Hydration of a GCL with powdered bentonite

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ABSTRACT: A series of laboratory experiments were conducted to study the isothermal and cyclic heating moisture uptake from silty sand subgrade soil by needle-punched and thermally-treated geosynthetic clay liners (GCLs) manufactured with powdered bentonite or fine-granular bentonite. The subgrade silty sand soil was compacted into PVC columns to dry density of 16.5 kN/m^3 at water content (W_{fdn}) of 10, 16, or 21% and then covered by a GCL. The confining pressure on GCLs was 2 kPa. Test results indicated that under isothermal conditions, there was more rapid uptake of moisture and a higher steady-state GCL water content with increasing subgrade soil water content. The structure of the bentonite after 35 weeks of contact with soil examined looked well hydrated with no cracks over the range of W_{fdn}. Under similar conditions, GCLs with powered bentonite achieved a higher water content and degree of saturation than GCLs with fine-granular bentonite in the short-term. In the longer-term both GCLs can achieve a similar degree of saturation. However, under cyclic heating conditions, the GCL with powdered bentonite demonstrated greater moisture retention than the GCL with fine-granular bentonite for one case examined.

Keywords: geosynthetic clay liners, hydration, laboratory experiments, silty sand subgrade

1 INTRODUCTION

The barrier system at the bottom of modern landfills typically incorporates a leachate collection system, a geotextile protection layer and a composite liner comprised of a geomembrane (GMB) over a clay liner (Rowe et al., 2004). Geosynthetic clay liners (GCLs) have been used widely in landfill liner systems over the last three decades (Podgorney and Bennett, 2006). This is because GCL is characterized by its very low hydraulic conductivity (*k*) when hydrated and permeated with water not containing significant cations under realistic confining pressures (Daniel at al., 1997; Petrov and Rowe, 1997; Lin and Benson, 2000; Jo et al., 2001; 2005; Lee and Shackelford, 2005; Shackelford et al., 2010).

Ideally for landfill base composite liner systems, the GCL is initially hydrated from moisture in the underlying subgrade soil. Afterwards, the hydrated GCL may be exposed to leachate from the overlying waste (e.g., from leakage through holes in the GMB). Jo et al. (2004) reported that the *k* values of GCL specimens prehydrated with deionized water for 40 days then permeated with 40 mM $CaCl_2$ solution for long-term (71-94 pore volumes) were about 3-4 times lower than non-prehydrated specimens permeated with the 40 mM $CaCl_2$ solution. Furthermore, at the end of permeation with the 40 mM $CaCl_2$ solution, the swell index (SI) values of the prehydrated specimens were much higher than those measured for non-prehydrated specimens (e.g., after 10 pore volumes, the SI of the prehydrated specimens was 16.5 mL/2 g versus 10 mL/2 g for non-prehydrated specimens). Therefore, the best case scenario for a GCL in a composite liner system is to be well hydrated first by up taking moisture from the subgrade before exposure to landfill leachate.

The rate of moisture uptake from the subgrade and the ultimate degree of hydration of GCLs manufactured with coarse- or fine-granular bentonite has been the subject of previous research (e.g., Daniel et al., 1993; Rayhani et al., 2011; Anderson et al., 2012). They concluded that the type of bentonite and the method of GCL manufacture both can affect the degree of hydration that can be achieved by GCL in contact with moist subgrade. However, there appears to be a paucity of data on hydration of GCLs manufactured with powdered bentonite. The objective of this paper is to first present experimental results examining the rate of moisture uptake by a GCL product manufactured with powdered bentonite from an underlying silty sand subgrade soil over 35 weeks under isothermal laboratory conditions. Second, the macrostructure of the GCL is examined for initial subgrade water contents of 10%, 16%, and 21%. The isothermal hydration results for the GCL with powdered bentonite are then compared with published results for hydration of a GCL with fine-grained granular bentonite. Finally, moisture retention of two GCLs (one with powdered bentonite and the other with fine-granular bentonite) when subject to thermal cycles is examined following isothermal hydration on silty sand at 16% initial subgrade water content for 4 weeks.

2 MATERIALS

2.1 *GCLs*

The GCL with powdered bentonite investigated in this paper had a slit-film woven carrier and needle-punched nonwoven cover geotextile. The GCL itself was needle-punched and the resulting needle-punched fibres from the cover geotextile were thermally melted to the carrier geotextile (i.e., thermal treatment). It is denoted herein as GCL6, following the nomenclature of Ashe et al. (2015). Comparisons are made with two similar needle-punched and thermally treated GCLs made with initial fine-grained granular bentonite, denoted as GCL1 and GCL2. Initial properties of the three GCLs are given in Table 1.

2.2 *Subgrade soil*

Soil used as the subgrade layer to hydrate the GCLs was obtained from the Queen's University Environmental Liner Test Site (QUELTS) located 40 km north of Kingston, Ontario, at a latitude of 44°34'14"N and longitude of 76°39'44"W (Brachman et al., 2007). According to the Canadian Foundation Engineering Manual (CFEM, Canadian Geotechnical Society, 2006), the subgrade soil is classified as silty sand based on the dry sieve analysis. Standard Proctor compaction tests gave a maximum dry density of 18.3 kN/m^3 at an optimum water content of 11.4% (Rayhani et al., 2011). The shake flask extraction technique (Price, 2009) was followed to measure the readily extractable elements from the soil. The average porewater Ca^{2+} concentration for soil samples collected from three different locations at site was 230±24 mg/L. The concentrations of Mg^{2+}, Na^{+}, and K^{+} were 35±4, 31±16, and 7±2 mg/L, respectively. No other cations were detected in the extracted water. The ionic strength of the porewater was 15±5 mM. The ratio of the monovalent soluble cations (in cmol/kg) to the divalent soluble cations (in cmol/kg) (MDR) was 0.27±0.08, and the total soluble cations per unit mass (TCM) was 1.7±0.4 cmol/kg.

Table 1. Initial properties of virgin needle-punched thermally treated GCLs examined

		Test method	GCLs examined		
			GCL6	GCL1	GCL2
Bentonite	Initial grain size	—	Powdered	Fine-granular	Fine-granular
	Dry mass/area (g/m^2)	ASTM D5993	5560 (± 250)	4500 (± 400)	4600 (± 600)
	Off-roll water content (%)	ASTM D4643	7	6	6
	Swell index (mL/2 g)	ASTM D5890	32	26	25
	CEC (cmol/kg)	ASTM D7503	105	75	78
Carrier GTX	Type	—	W*	W*	NWSR*
	Mass (g/m^2)	ASTM D5261	110	120	260
Cover GTX	Type	—	NW*	NW*	NW*
	Mass (g/m^2)	ASTM D5261	220	230	230
GCL	Needle punched	—	Yes	Yes	Yes
	Thermally treated	—	Yes	Yes	Yes
	Initial thickness (mm)	ASTM D5199	7.7	7.7	6.6
	W_{ref}**	—	222	150	120

*W = Woven geotextile, NW= nonwoven geotextile; NWSR= nonwoven scrim reinforced geotextile.
** Water content after two months hydration under 2 kPa confining stress with unlimited DI water supply.

3 EXPERIMENT DETAILS

To investigate the potential of GCLs to hydrate under isothermal conditions, a series of laboratory experiments were conducted using soil extracted from QUELTS as the subgrade. The extracted soil was compacted into PVC columns. The internal diameter of the columns was 150 mm and the thickness of the subgrade layer in each column was 450 mm. The subgrade soil was compacted in the columns to a dry density of 16.5 kN/m^3 (90% of Std Proctor maximum dry density) at subgrade soil water content (W_{fdn}) of 10% (~ optimum water content), 16% (average soil water content at the QUELTS), or 21% (field capacity water content). The subgrade in each column was then covered by a 150 mm diameter GCL sample followed by a GMB sample. A circular steel plate was place on the top of the GMB to apply a 2 kPa confining pressure. Finally, the columns were sealed and stored at a temperature of 22 ± 2°C. The water content of the GCL (W) was monitored with time for 35 weeks (approximately 9 months). The structure of the bentonite in each GCL sample was inspected using a Faxitron sealed X-ray cabinet designed to give high resolution radiographs for small to medium-size objects. In addition, cross section images of GCLs were captured using a high resolution digital camera.

4 RESULTS AND DISCUSSION

4.1 *Effect of subgrade water content on hydration of GCL6*

The water content attained by a GCL is a function of the suctions in the GCL and the suctions in the subgrade soil (foundation). As such, isothermal hydration may be expected to depend on time, the type of GCL, and the type and water content of the subgrade. To investigate the effect of W_{fdn} on moisture uptake by a GCL with powdered bentonite, the change in W with time for GCL6 over a range of subgrade soil water contents under a 2 kPa confining pressure is presented in Figure 1. The water content of the GCL is taken as the mass of water in the GCL (i.e., wet mass of the GCL – dry mass of the GCL) divided by the dry mass of the GCL. Test results show a larger steady-state GCL water content with increasing W_{fdn} with a measured W of 94%, 125%, and 176% when W_{fdn} was 10%, 16%, and 21%, respectively, after 35 weeks of contact with the subgrade soil. The increase in W with increasing W_{fdn} occurs because the soil suctions that resist moisture loss from the soil to the GCL becomes smaller at higher W_{fdn}. For example, Siemens et al. (2012) reported drying-curve suctions of around 400, 20, and 1 kPa for the silty sand soil with W_{fdn} equal to 10%, 16%, and 21%, respectively. There is also a more rapid moisture uptake with increasing W_{fdn}. This is also due to greater moisture availability and smaller sub-soil suctions at higher W_{fdn}.

Since the structure and manufacturing process of a GCL can affect its capacity to uptake moisture, the hydration results in Figure 1 are normalized by the hydration potential of the GCL (W_{ref}). Here, the hydration potential of a GCL is defined as the steady-state water content of the GCL for a specific stress and specific hydrating liquid. To measure W_{ref}, four coupons of GCL6 (each 100 x 100 mm) were submerged in deionized water (water head of 20 mm) under 2 kPa confining pressure. The reference water content of the GCL was measured after two months submerged in deionized water (i.e., at steady-state). The W_{ref} value of the thermally treated and needle-punched GCL6 was 222% (std dev. = 3%). The measured W_{ref} value for GCL6 with powdered bentonite is much higher than values measured for GCLs with the same general structure except having an initial fine-grained granular bentonite instead of powdered bentonite (150 and 120%, respectively for GCL1 and GCL2, Table 1). This difference in W_{ref} values is likely due to a combination of several factors: the lower specific surface area and suctions of GCLs with coarser size of bentonite, the type of bentonite, the difference in the mass per unit area of bentonite, and difference in peel strength. Water content values of GCL6 shown in Figure 1 were then normalized by diving W values by W_{ref} (222%) and represented in Figure 2. After 35 weeks of being in contact with the subgrade soil, W/W_{ref} values of GCL6 were 79%, 56%, and 42% when the W_{fdn} values were 21%, 16%, and 10%, respectively.

When GCL6 was in contact with soil compacted at W_{fdn} = 16% or 21% under 2 kPa confining stress, there was a rapid initial increase in the water content of the GCL followed by a decrease in the short-term. This behaviour could be from a transient moisture movement between the soil and GCL as they attain a suction equilibrium. Better understanding for the moisture uptake by GCL with powdered bentonite in contact with subgrade soil compacted at high W_{fdn} is under investigation. It should be also noted that the rapid increase followed by a decrease in the W had no discernable effect on the macrostructure of GCL6. For example, Figure 3a shows X-ray image for the bentonite structure of GCL6 after rapid peak to W = 147% (W/W_{ref} = 66% after 2 weeks of being in contact with soil) which was almost the same as that for GCL6 after a decrease in W to 132% (W/W_{ref} = 59%; after 10 weeks; Figure 3b).

On extraction from the PVC columns after 91 weeks on the subgrade, visual inspection indicated that the bentonite in GCL6 samples was well hydrated with no observed cracks (Figure 4) under all tested conditions. Therefore, it is expected with the bentonite structure shown in Figure 4, for GCL6 to perform well as a hydraulic barrier.

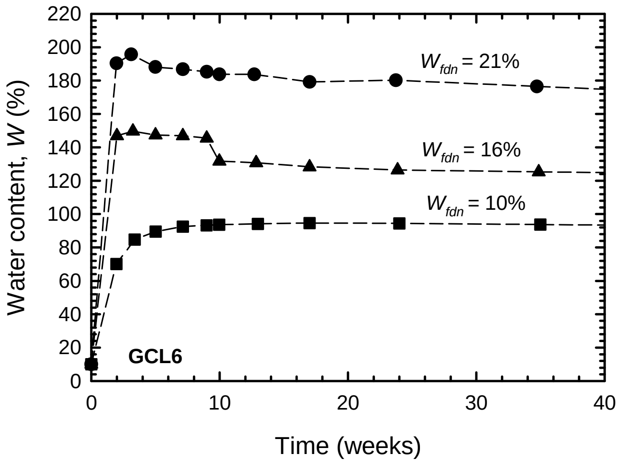

Figure 1. Water content (*W*) of GCL6 with time for three initial values of subgrade soil water content (W_{fdn})

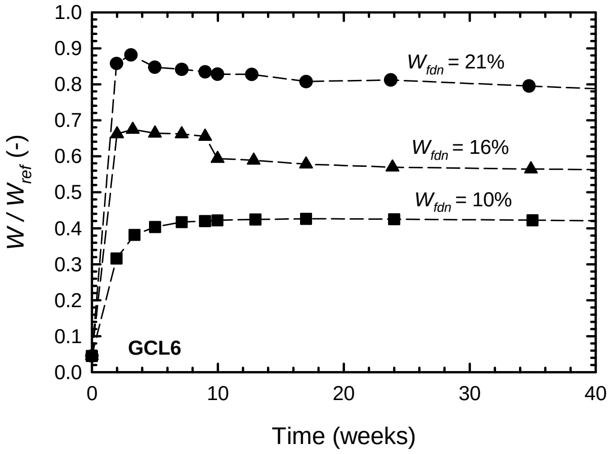

Figure 2. Normalized water content (W/W_{ref}) of GCL6 with time for three initial values of subgrade soil water content (W_{fdn})

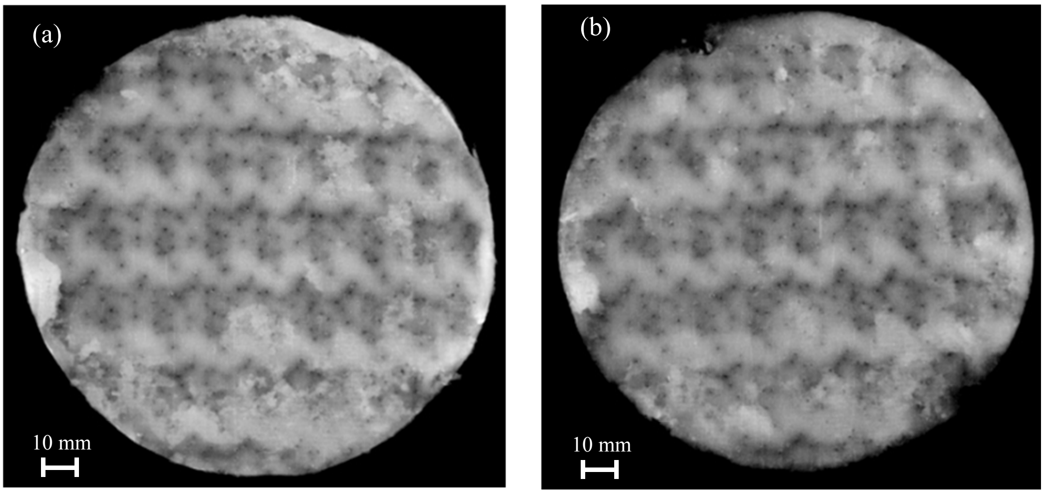

Figure 3. X-ray images of GCL6 with W_{fdn} = 16% after (a) 2, and (c) 10 weeks of hydration

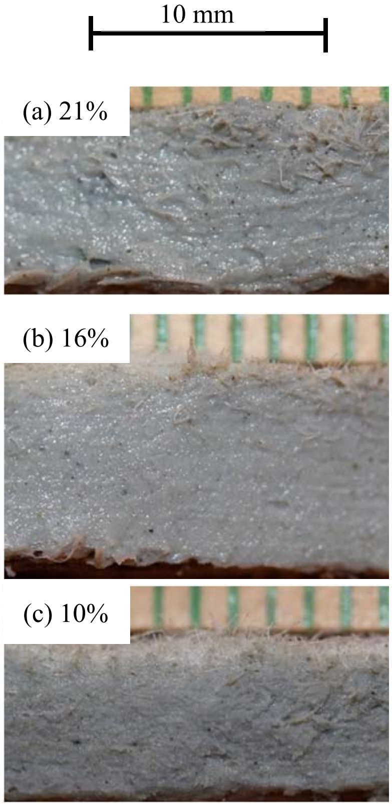

Figure 4. Photographs showing macrostructure of GCL6 after 91 weeks hydration for initial subgrade water contents of (a) 21%, (b) 16% and (c) 10%

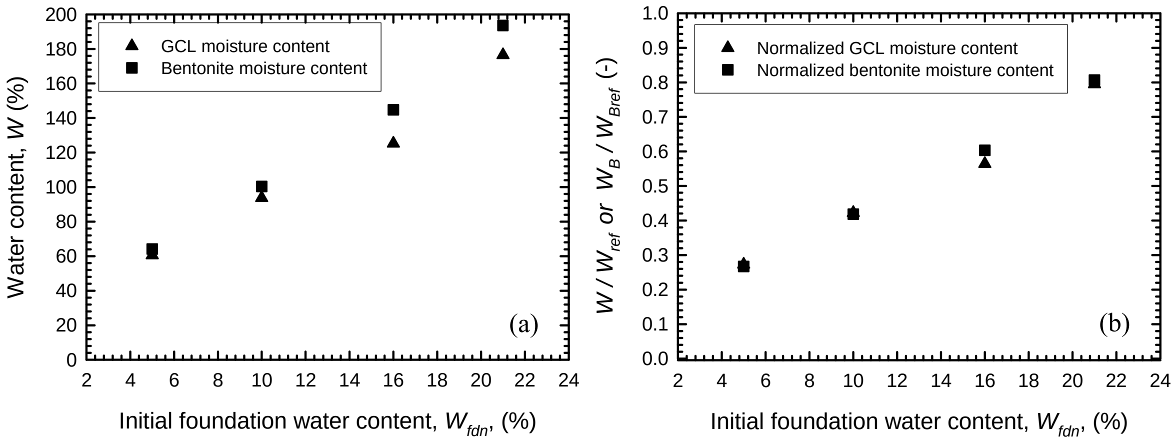

Figure 5. (a) GCL and bentonite water content, and (b) normalized GCL and bentonite water content of GCL6 vs. initial subgrade soil water content after 35 weeks hydration

Results for GCL6 after 35 weeks are summarized in Figure 5. If all of the hydrated water is attributed to the bentonite, the water content of the just bentonite (W_B, taken here as (wet mass of the GCL – dry mass of the GCL) divided by (dry mass of the GCL – mass of the geotextile components)) increases to around 195% for the wettest subgrade soil (Fig. 5a). However, there is no substantive difference when normalized by the reference GCL water content (W_{ref}), or corresponding reference bentonite water content (W_{Bref}=240%), Figure 5b.

Figure 5 also shows the results for a test configuration with a much drier subgrade soil with W_{dfn}=5%. Together with the wetter subgrade soil results, a near linear relationship between GCL water content after 35 weeks and initial subgrade soil water can be observed. Work is ongoing to investigate the macrostructure of the GCL at such a low subgrade soil water content.

4.2 *Effect of the bentonite grain size on GCL hydration*

The moisture uptake with time of GCL6 is compared with that for a very similar needle-punched thermally treated GCL with fine-granular bentonite, denoted as GCL1 (as reported by Rayhani et al., 2011) in Figure 6. GCL6 with powdered bentonite showed a much more rapid rate of initial hydration than GCL1. After 2 weeks of hydration, the water content of GCL6 reached 146%, while it was 60% for GCL1. As time increased, GCL6 showed the slight decrease in water content as previously noted, while GCL1 continued to slowly increase its water content. After 35 weeks, the water content of GCL6 (125%) was still higher than that for GCL1 (102%). At this time, both GCLs attained a similar normalized water content (W/W_{ref}) between 0.6 and 0.7 and appeared well-hydrated with gel-like macrostructures. The faster rate of initial hydration of GCL6 is most likely from having initial powdered bentonite; but overall, both GCLs attain a good degree of hydration after 35 weeks. Results in Figure 6 are compared at an initial subgrade water content of 16%. Similar comparisons were also found at water contents of 10 and 21%.

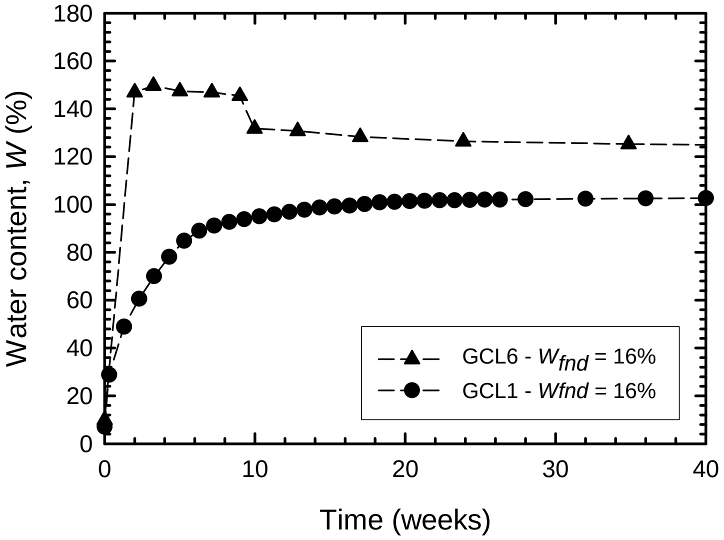

Figure 6. Comparison of GCL water content (W) for GCL6 (with powdered bentonite) with GCL1 (with fine-granular bentonite). GCL1 results obtained from Rayhani et al. (2011)

4.3 *GCL hydration under cyclic heating conditions*

The isothermal hydration results presented earlier provide insight into the net effects of GCL and soil suctions under constant temperature conditions. In some field applications with low soil cover, or in cases where the GCL may be covered by a geomembrane but the composite liner is left exposed, in addition to moisture uptake from the subgrade soil, the GCL may also experience moisture loss to an airspace above the GCL (e.g., the GCL is covered by an exposed GMB that develops some wrinkles) from temperature cycles. The moisture lost by the GCL may be expected to depend on the magnitude of the thermal gradient and the ability of the GCL to retain moisture. Field evidence from QUELTS (Rowe et al., 2016) suggests that GCL6 (with powdered bentonite) demonstrated greater moisture retention than GCL2 (with fine-granular bentonite; Table 1). To help explain this behaviour, cyclic hydration experiments under controlled laboratory conditions were designed and conducted as part of this project to examine the moisture retention behaviour of GCL6 relative to GCL2.

For the first 4 weeks of hydration, these experiments mimicked the isothermal hydration tests (i.e., moisture uptake by the GCL from moisture in the subgrade soil); however, subsequently, the air space above the GCL was subjected to a daily thermal cycle. The air space was heated to 60°C over 6 hours and then allowed to cool to around 30°C, until the next cycle was applied. These temperatures approximate summer exposure as measured at QUELTS.

Preliminary results for the cyclic heating hydration of GCLs 6 and 2 are shown in Fig 7. In these tests, the air space was intentionally vented at the end of each heating cycle to remove any moisture lost by the GCL to the air space prior to cooling. GCL6 reached a gravimetric water content of around 140% (W/W_{ref} = 0.63) after 4 weeks of isothermal hydration (Fig. 7a). After 3 additional weeks with thermal cycles, the water content did not decrease, but actually increased slightly to 155% (W/W_{ref} = 0.70). This is in stark contrast to the response of GCL2 plotted in Fig. 7b where, after reaching an isothermal water content of 83% (W/W_{ref} = 0.70), the water content decreased to 20% (W/W_{ref} = 0.17) after the same thermal cycles. Similar to what was qualitatively observed at QUELTS, these preliminary results strongly suggest greater moisture retention under a thermal gradient of the initial powdered bentonite in GCL6 relative to GCL2 under the same thermal cycling. Additional work is currently underway to better understand the mechanisms leading to the greater moisture retention.

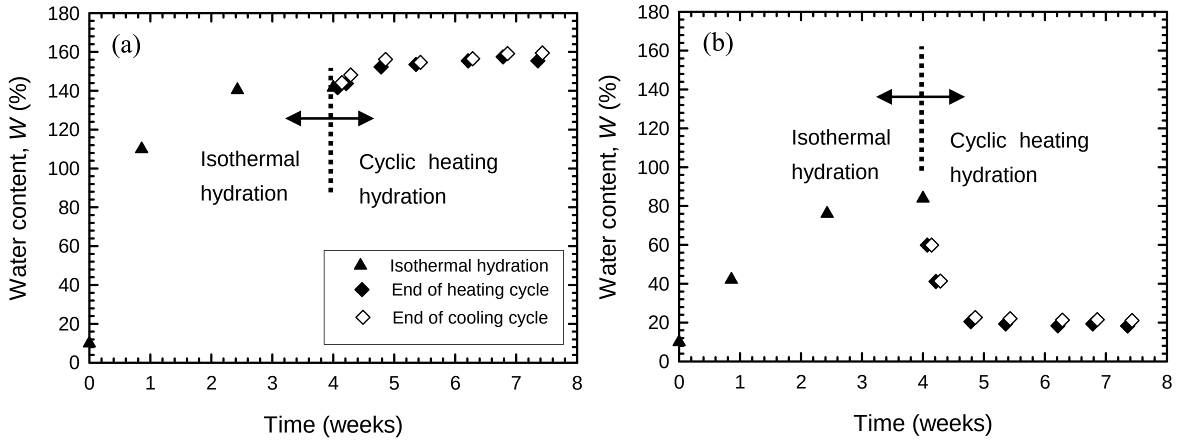

Figure 7. Comparison of moisture retention of (a) GCL6 and (b) GCL2 under daily thermal cycles (30-60°C) following 4 weeks of isothermal hydration

5 SUMMARY AND CONCLUSION

Results from isothermal hydration experiments have investigated the moisture uptake of a needle-punched and thermally treated GCL with powdered bentonite from a silty sand subgrade. Normalized degrees of hydration (W/W_{ref}) of around 40 to 80% were reached for initial silty sand subgrade water contents of 10 to 21% after 35 weeks and the GCLs had a well hydrated, gel-like structure. When compared to a very similar GCL but with initial fine-granular bentonite, the GCL with initial powdered bentonite hydrated at a much faster rate but after 35 weeks both attained a similar normalized degree of hydration (W/W_{ref}) of 0.6 to 0.7 for an initial subgrade water content of 16%. Preliminary results were also reported that strongly suggest greater moisture retention by a GCL with initial powdered bentonite than another with fine-granular bentonite when subjected to a few daily thermal cycles after being allowed to hydrate under isothermal conditions for four weeks. Additional experiments are currently underway to further examine the moisture uptake and retention of these GCLs.

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