GCL hydration under simulated daily thermal cycles

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ABSTRACT: The hydration of three different geosynthetic clay liners (GCLs) subjected to daily thermal cycles was examined for a range of subsoil conditions. It was shown that daily thermal cycles can significantly decrease the equilibrium gravimetric moisture content of the GCL to as low as 15% of that under isothermal conditions in the worst case. For silty sand (SM) foundation soil with an initial gravimetric moisture content of 16%, the type of GCL had a significant effect on the daily variation in moisture content which ranged between 13% for one type of GCL and only 2% for another. The effect of these daily variations in moisture content on susceptibility to shrinkage is discussed. The initial moisture content and associated matric suction of the foundation soil was shown to have the dominant effect on GCL hydration. For GCLs over silty sand with initial moisture contents, w_{fdn}, of 5, 10 and 16% and initial suction levels greater than their air entry value, the daily thermal cycles controlled GCL hydration at the end of the thermal cycle to moisture contents of between 14 and 30% and the GCL equilibrium moisture content was relatively insensitive to the initial foundation moisture content over this range. However when the foundation moisture content increased to $w_{\mathrm{fdn}} = 21\%$ (just below field capacity and the saturated moisture content) the GCL moisture contents increased to 113 to 127% (depending on GCL). Results are also reported for a GCL on poorly graded sand (SP) at 10% initial moisture content and the effect of the grading curve (and the related water retention curve) is discussed. The results of this study highlight the potential complexity of interpreting shrinkage of GCLs at the same site let alone at different sites.

KEYWORDS: Geosynthetics, Geosynthetic clay liners (GCL), Hydration, Thermal cycles

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1. INTRODUCTION

Geosynthetic clay liners (GCLs) have been extensively used as part of composite liners in modern solid waste landfills. However to be most effective they need to be adequately hydrated with water before contact with leachate (e.g. Petrov and Rowe 1997; Petrov *et al.* 1997) or exposure to harsh field conditions (e.g. Benson *et al.* 2010). It is generally accepted that this hydration typically occurs due to moisture uptake from the underlying foundation soil; however the rate of hydration of a GCL from the underlying foundation soil has received very little attention. Daniel *et al.* (1993) showed that, when placed on one specific sand ($D_{10} = 0.2$ mm, $D_{60} = 0.5$ mm, $D_{85} = 0.7$ mm) at 3% moisture content, an initially air dry GCL reached 88% moisture content after 40 to 45 days under isothermal conditions. Eberle and von Maubeuge (1997) reported that an initially dry GCL placed over well graded sand (90% passing 4.75 mm sieve) with an initial moisture content of 8–10%, reached a moisture content of 100% in less than 24 h and 140% after 60 days under isothermal conditions (23°C). Rayhani *et al.* (2011) investigated the hydration of the three types of GCLs listed in Table 1 when placed in contact with a sand and silty sand foundation soil under isothermal conditions at room temperature. They reported that the GCL type, foundation soil particle size distribution (and hence water retention curve) and the matric suction associated with the initial moisture content of the foundation soil have a great effect on the hydration of the GCL.

The moisture uptake data for isothermal conditions noted above provides insight as to the likely hydrated moisture content for the GCLs and foundation soils examined under conditions where the composite liner is promptly covered with a leachate collection layer that protects the liner from significant thermal cycles. However, it is not uncommon for a composite liner to be left exposed to solar radiation for a period of time (weeks, months and in some cases years depending on the situation) before being covered (Thiel *et al.* 2006). Under these circumstances the liner may be subjected to both daily and, if left exposed long enough, seasonal thermal cycles. To date there is no data in the literature examining the effect of thermal cycles on GCL hydration. It has been postulated that the daily thermal cycles could contribute to the shrinkage of GCLs that has been reported in the literature (Thiel and Richardson 2005; Thiel *et al.* 2006) for exposed composite liners. Based on this hypothesis, several laboratory studies (Thiel *et al.* 2006; Bostwick *et al.* 2010; Rowe *et al.* 2010, 2011) have shown that GCLs can lose dimensional stability and shrink when subjected to severe moisture and thermal cycles. However, despite this work, there is continued uncertainty regarding whether the thermal and moisture cycles most critical to the observed shrinkage behaviour are daily or seasonal. If seasonal, a typical exposed composite liner would only experience several cycles per year of exposure. If daily, the frequency of cycling and the rate of accumulation of shrinkage strain would be much higher. However, to undergo daily wetting and drying cycles the GCL must first hydrate sufficiently overnight to allow drying and shrinkage the next day, but the extent to which the GCL will hydrate or experience wet–dry cycling when subjected to thermal cycles has not been investigated.

To investigate this phenomenon, Brachman *et al.* (2007) described a field study being conducted to examine the shrinkage of different GCLs placed on a silty sand foundation soil under exposed field conditions in Godfrey Ontario (Canada). To assist in understanding the observed field behaviour at this site and, more generally, to provided insight regarding the moisture uptake and loss from GCLs, it was considered beneficial to conduct a number of controlled laboratory experiments to understand (*a*) the difference in the water retention curves (WRCs) of the GCLs examined (Beddoe *et al.* 2011), (*b*) the hydration of the GCLs under isothermal conditions (Rayhani *et al.* 2011), and (*c*) hydration of the GCLs under daily thermal cycles. The objective of this study was to investigate the hydration of GCLs when subjected to daily thermal cycles similar to those that can be experienced in the field. In particular, the effect of foundation soil and especially the initial foundation moisture content on moisture uptake were investigated for three different GCLs.

2. MATERIALS

2.1. Geosynthetic clay liners

Three GCL products from two different North American manufacturers were examined (Table 1): Bentofix NSL (GCL1 in this paper), Bentofix NWL (GCL2) and Bentomat DN (GCL3). All GCLs contained granular sodium bentonite and had montmorillonite contents of 50–58%. The swell index was 26, 24 and 23 ml/2 g for GCLs 1, 2 and 3, respectively, and the cation exchange capacities were 81, 78 and 103 meq/100 g for GCLs 1, 2 and 3, respectively. GCL3 contained coarse granular bentonite with D_{60} of 1.1 mm, whereas the other GCLs contained fine-grained bentonite with D_{60} of about 0.35 mm (Rowe *et al.* 2011). The WRCs for the three GCLs have been presented by Beddoe *et al.* (2011) for both the wetting and drying paths. They demonstrated that different GCL products had different WRCs with the scrim reinforced, thermally treated GCL (GCL2) having a much smaller difference between the wetting and drying curves (and hence less hysteretic effects on wetting and drying) than the other two GCLs. Furthermore, GCL2 achieved a fully hydrated state at lower moisture content and much lower bulk void ratio than the other two GCLs due to the better anchorage of the needle-punched fibres.

2.2. Soil properties

Silty sand (SM in USCS classification, ASTM D 2487) from the Queen's geosynthetic liner experimental field site in Godfrey Ontario (Brachman *et al.* 2007) was used as

Table 1. Description of GCLs examined in this study

GCL	Total dry mass/area (g/m^2)	Carrier GT		Cover GT		Construction	Average peel strength: N	Symbol in paper
		Type	Mass (g/m^2)	Type	Mass (g/m^2)			
NSL	4023–4967	W	120–126	NW	216–258	NPTT	94 ± 16	GCL1
NWL	3411–4468	SRNW	230–253	NW	200–224	NPTT	260 ± 17	GCL2
DN	4512–4972	NW	200–283	NW	226–263	NP	219 ± 30	GCL3

W, woven; NW, nonwoven; SRNW, scrim-reinforced nonwoven; NP, needle-punched; NPTT, needle-punched and thermally treated. The geotextile masses were measured by N. Arnepalli, Queen's University. Peel strength tests performed by M. Hosney, Queen's University.

the foundation soil for all experiments except for one conducted on poorly graded sand (SP) as indicated in Table 2. The particle size distributions for both sands are given in Figure 1a. The silty sand had about 35% fines (passing the 0.075 mm sieve) and the sand had about 5% fines. In both cases, these fines were non-plastic. The standard Proctor maximum dry density was 1.83 and 1.89 Mg/m^3 at optimum moisture contents of 11.4 and 10.3% for the silty sand (SM) and sand (SP), respectively. The WRCs for both sands are given in Figure 1b (based on Geo-Slope International Ltd 2007). In the silty sand, four moisture contents were selected for testing to cover the full range of water-retention behaviour of this foundation soil. These consisted of a moisture content near saturation (21%), two moisture contents on the steep portion of the drying curve (16 and 10%), and a moisture content near the residual moisture content (5%).

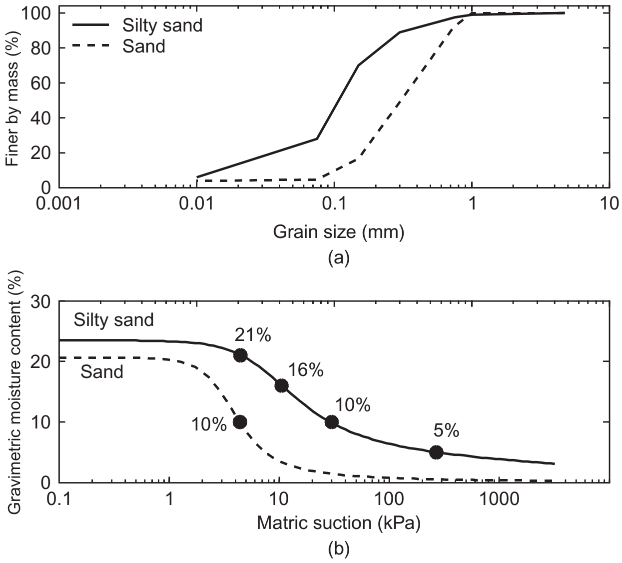

Figure 1. (a) Particle size distribution and (b) water retention curves of foundation soils highlighting the foundation water contents selected for testing

3. EXPERIMENTAL METHOD

3.1. Instrumented columns

The objective of the present study was to investigate the hydration of GCLs when subjected to daily thermal cycles that were representative of typical field exposure conditions. Experiments were designed in which a typical composite liner profile was re-created in 150 mm diameter by 500 mm high polyvinyl chloride (PVC) cells. As shown in Figure 2, this profile consisted of a heating pad to apply the daily thermal boundary condition, a steel block to provide 2 kPa of normal stress on the GCL, a geomembrane, a GCL, and 450 mm of foundation soil compacted to a specific target moisture content.

Bulk samples of the Godfrey silty sand were mixed with tap water with an average calcium concentration of 40 mg/L to bring its moisture content (w_{fdn}) to 10, 16 and 21%, which correspond to the lower, average, and higher moisture content observed during GCL installation at the Godfrey field site (Brachman *et al.* 2007). The moisture content of 21% is approximately field capacity for the silty sand. A series of tests with subsoil samples at a much drier initial moisture content of 5% were conducted to study GCL hydration close to the residual moisture content. The sand experiments were prepared at a moisture content of about 10% (i.e. at about standard Proctor optimum and just below field capacity for this soil). The foundation soil was compacted into the PVC cylinders to a dry density of 1.65 Mg/m^3, sealed to provide a closed-system (i.e. constant mass of moisture within the cell), and left for 2–3 h before the GCL sample was placed on top of the soil.

GCL samples were taken from the roll at its initial moisture content, cut to a diameter of 150 mm, and placed on the foundation soil. Details regarding the initial

Table 2. Details of cyclic thermal experiments. The silty sand (SM) and sand (SP) were both compacted to a dry density of 1.65 Mg/m^3

GCL type	Foundation soil*	GCL	GCL moisture content			Normalised GCL moisture content:† w/w_{ref}		GCL moisture content at 30 weeks isothermal (Rayhani *et al.* 2011) (%)
	Initial moisture content (%)	Total air-dry mass/ unit area: (g/m^2)	Initial: %	After 1 week (%)	After 7 weeks (%)	After 1 week (%)	After 7 weeks (%)	
GCL1	5	4503	8.2	20.5	22.8	14.6	16.3	33.5
	10	4023	8.1	32.4	34.7	23	24.8	86.4
	16	4314	8.1	33.4	30.4	23.8	21.7	102
	21	4967	8.3	73.4	113	52.4	80.8	141
GCL2	5	4455	6.2	18.4	16.0	16	14	39.6
	10	3411	6.3	17.3	16.3	15	14.2	85.4
	16	4432	5.0	22.4	27.4	19.5	23.8	88
	21	4263	6.2	77.6	117	66.3	100	116
	10*	4468	6.2	22.9	20.5	20	17.8	90
GCL3	5	4512	10	19.4	14.0	13	9.3	83
	16	4972	4.5	14.8	16.8	10	11.2	114
	21	4665	4.5	67.4	127	45	84.5	149

*All on silty sand except experiment C2–1.
†w_{ref} (mean, standard deviation sd); GCL1 (140%, 4%), GCL2 (115%, 3%), GCL3 (150%, 5%).

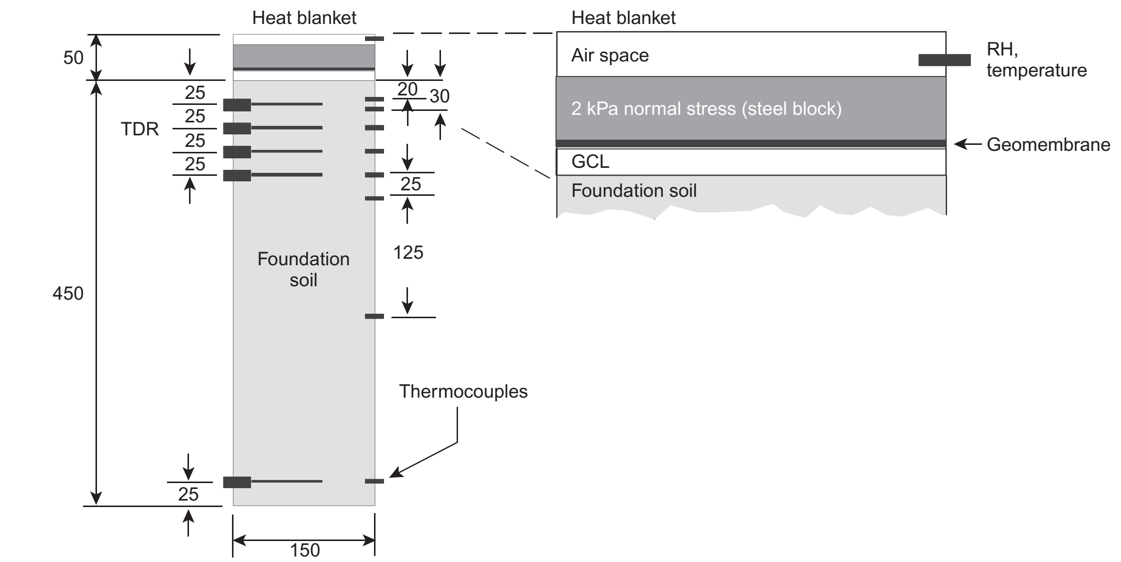

Figure 2. Geometry of instrumented soil column for investigating the effect of daily thermal cycles on GCL hydration

moisture content of the foundation soil and GCL specimen as well as the initial GCL mass per unit area are presented for each test in Table 2. After installation, a geomembrane was placed on top of the GCL to minimise potential evaporation into the headspace above the GCL. A steel seating block of 25 mm thickness was placed over the geomembrane to apply a 2 kPa stress to encourage contact between the GCL and the foundation soil. The conditions simulated in these experiments represent the case of an exposed composite liner in which the geomembrane is in direct contact with the GCL (i.e. there is no airspace above the GCL as there would be below a wrinkle in the geomembrane).

3.2. Monitoring

Two types of instrumentation were used to monitor each experiment: (1) time domain reflectometers (TDR) were used for measuring moisture content at up to five locations in the soil, and (2) thermocouples were used for measuring temperature at eight elevations in the soil and one in the headspace above the steel block (Table 3, Figure 2). The TDR equipment consisted of a Campbell Scientific TDR100 system with 75 mm long waveguide probes sealed into the side of the columns to ensure that the waveguides were located at the centre of the column. During installation, care was taken to ensure contact between the probe rods with the surrounding soil mass during the insertion process, as air-filled gaps can have a significant effect on the calibration relationship (e.g. Siddiqui *et al.* 2000). TDR readings were taken during installation of the probes to verify the initial moisture content readings in the column against the target prepared moisture content of the foundation soil. Subsequent TDR readings were then taken after each daily cycle. Thermocouples were placed at eight different depths in the foundation soil (Table 3). A VAISALA HMP45A probe was positioned in the small air gap above the geomembrane to measure the temperature in the headspace above the composite liner.

Table 3. Location of TDR probes and thermocouples placed within the soil (relative to top of foundation soil)

TDR probes	Z (mm)	Thermo-couple	Z (mm)
		RH	0
		TC1	20
TDR1	25	TC2	30
TDR2	50	TC3	50
TDR3	75	TC4	75
TDR4	100	TC5	100
		TC6	125
		TC7	250
TDR5	425	TC8	425

3.3. Experimental procedure

Once the composite liner profile had been constructed in each cell, the cells were inserted into a thermally isolated box, surrounded with Styrofoam insulation and heated at the top using a heating blanket system to provide one-dimensional thermal and moisture migration conditions. To investigate the effect of daily thermal cycles on GCL hydration, the temperature controller was programmed to generate realistic geomembrane temperature cycles in southern Ontario, Canada (20–60°C). The bottom of the cell was kept at a constant lower temperature to simulate the thermal gradients that develop in the field. Heat was typically applied for 12 h and the cells were allowed to cool for 12 h. Typical cycles of the applied daily thermal boundary conditions are shown in Figure 3. In this figure, the applied temperature is the temperature measured in the air gap, and the thermal response of silty sand foundation is shown at depths of 20, 50, 100 and 425 mm. This data indicates that the heights of the cells were sufficient to capture the daily thermal response of the soil profile with only a small accumulation of heat at the base of the cells. These thermal cycles were applied daily, and cells were opened weekly to measure the moisture content of the

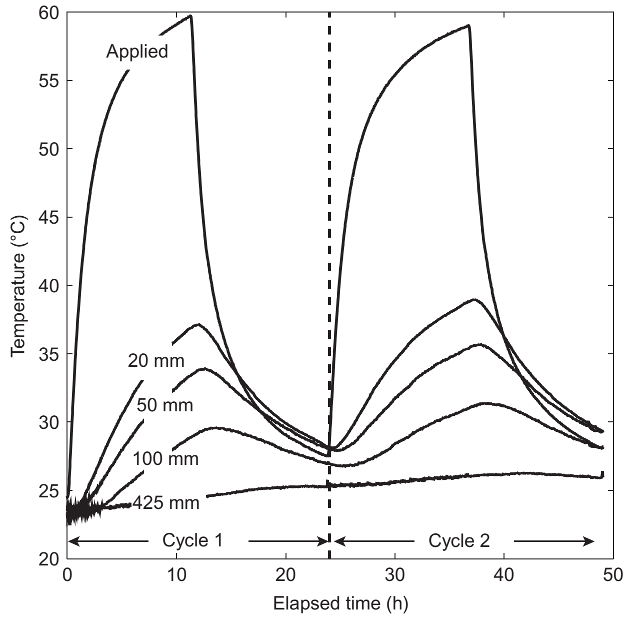

Figure 3. Applied thermal cycles and thermal response of silty sand foundation

GCL. This involved temporarily removing the GCL and quickly measuring its thickness and mass before returning it to the column. Each cell was subjected to a minimum of 7 weeks of daily thermal cycles.

4. RESULTS

4.1. Temperature profile

Figure 4 shows the initial temperature and the temperature profile at the end of the heating and cooling portion of the 50-th cycle for silty sand foundation moisture contents of 5 and 21%. In both tests, the initial temperature was approximately 24°C. As was observed in Figure 3, the base temperature boundary condition in the foundation soil slowly accumulated heat, with a result that by the 50-th cycle its temperature was 27°C During a heating cycle, the temperature in the air space above the composite liner was slowly raised to 57–60°C (Figure 3) and is plotted in the temperature profile of Figure 4 at depth of 0 mm. The temperatures measured in the soil decreased with depth, with the majority of the daily thermal change occurring in the upper 100 mm of the soil. Despite the difference in foundation moisture contents between the two tests presented in Figure 4, there was no significant difference in the magnitude of the thermal cycle between these two configurations. The data would suggest that if anything the thermal profile extended a little deeper for the soil at 5% moisture content than for that at 21% despite the fact the thermal conductivity would be expected to be higher for the soil at the higher moisture content.

4.2. Moisture content profile in subsoil

The initial profile and profile of volumetric moisture contents (VMC) at the end of the heating and cooling portion of the 50-th cycle for silty sand foundation moisture contents of 5 and 21% are presented in Figure 5, respectively. In both cases, the volumetric moisture content of the foundation soil within the soil column was observed to slightly decrease under the action of daily thermal cycles. For the case of the gravimetric foundation water content, w_{fdn}, of 5%, this consisted of a drop from 8% VMC to 7%. For the soil column with $w_{fdn} = 21\%$, the VMC dropped from an initial value of about 31% to about 28% after 50 heat/cool cycles. This small amount of moisture was either lost to gravity and retained in the bottom 50 mm of soil below the lowest TDR measurement location, or was lost as the air in the small airspace above the composite liner was exchanged once each week during GCL moisture content measurement.

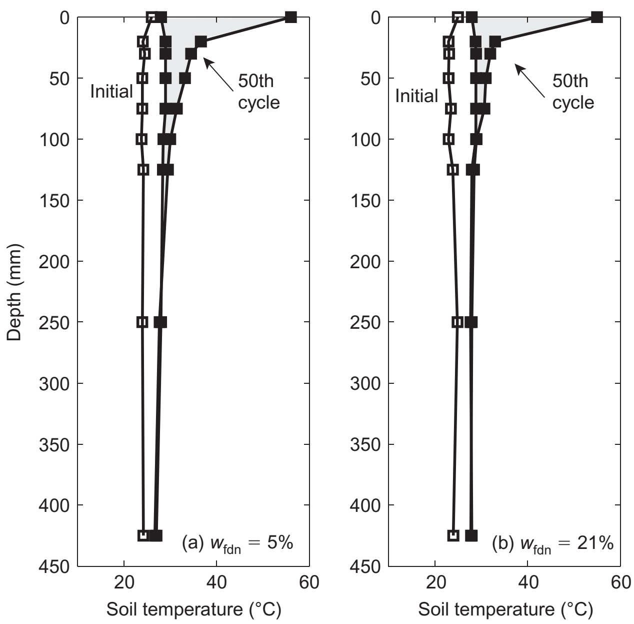

Figure 4. Thermal profiles in the soil column before test and at beginning and end of 50th daily thermal cycle

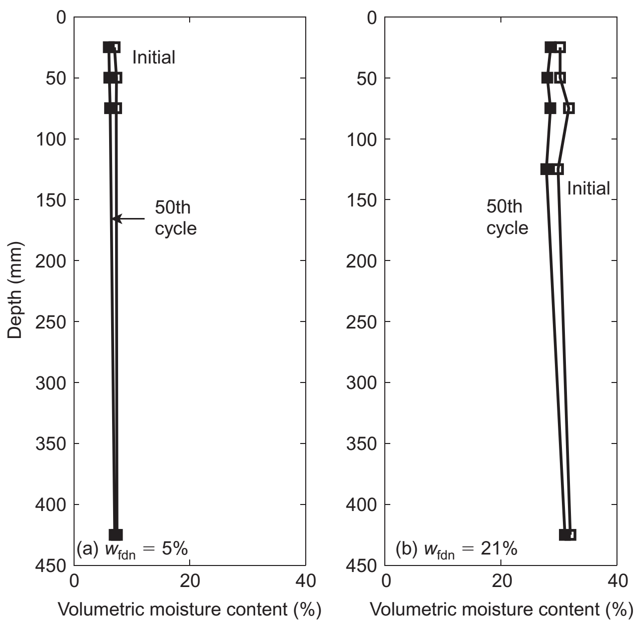

Figure 5. Volumetric moisture content profiles in the soil column before test and end of 50th daily thermal cycle

4.3. Moisture uptake

The GCL moisture uptake was monitored for 7 weeks, by which time equilibrium in moisture migration between the foundation soil and the GCL was achieved. Table 2 shows the GCL initial moisture content and moisture content after 1 and 7 weeks of daily thermal cycles for all samples. Figures 6–11 show different aspects of the variation in the GCL moisture content with time and will be discussed in the following section.

5. ANALYSIS AND DISCUSSION

5.1. GCL hydration subject to daily thermal cycles on silty sand ($w_{fdn} = 16\%$)

The GCL moisture content reached a minimum at the end of each heating cycle and increased with moisture uptake overnight during the cooling cycle (Figure 6). However, the difference in moisture at the end of the heating and cooling cycle depended on the GCL type as shown in Figure 6 for GCLs resting on silty sand at an initial 16% moisture content. After about 2 weeks, there was a fairly consistent 10% difference in gravimetric moisture content between the end of the heating and cooling cycle for GCL3 (Figure 6c). For GCL1 the difference was negligible after 1 week but increased to about 13% after about 5 weeks and stayed at about 13% subsequently. For GCL2 the difference was consistently about 2% gravimetric moisture content. These differences are related to the difference in the level of interlock of the needle-punched fibres of the GCLs and hence the resistance to swelling of

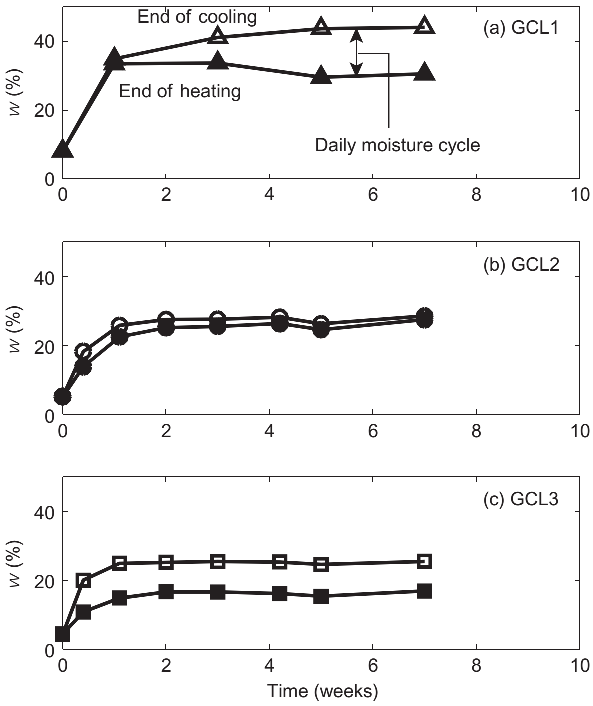

Figure 6. Hydration of (a) GCL1, (b) GCL2, and (c) GCL3 under simulated daily thermal cycles (silty sand foundation soil, $w_{fdn} = 16\%$)

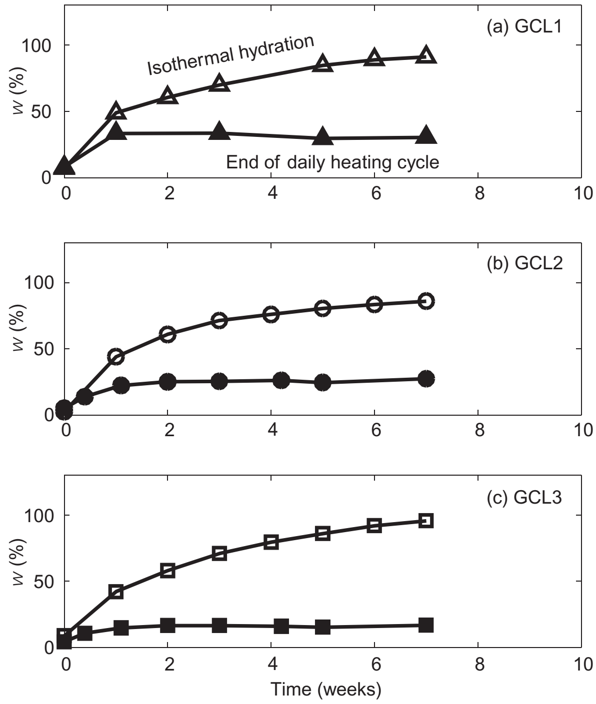

Figure 7. GCL moisture uptake under isothermal conditions (room temperature) and at the end of a heating cycle when subjected to daily thermal cycles (silty sand foundation soil, $w_{fdn} = 16\%$)

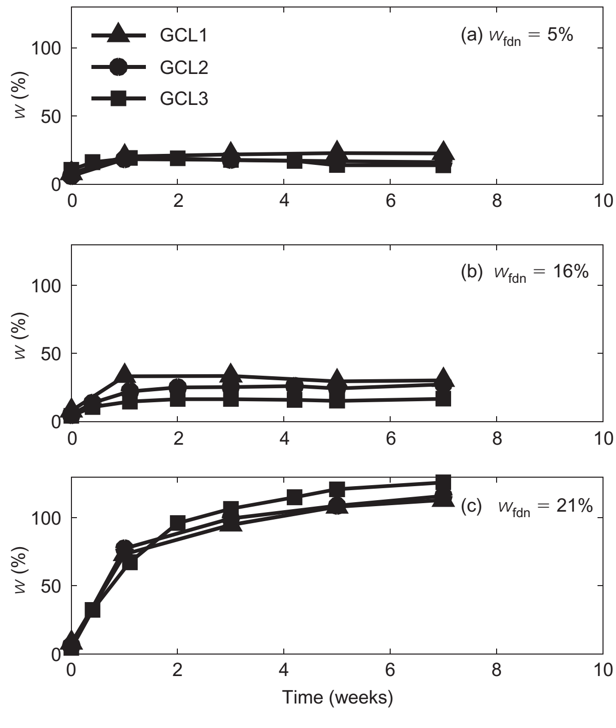

Figure 8. Effect of initial moisture content of silty sand foundation on GCL hydration measured at the end of a daily heating cycle

the bentonite which affects the water retention curves for these GCLs (Beddoe *et al.* 2011). It is of note that after a few weeks, GCL1 had the greatest daily variation in moisture content (13%), GCL3 the second most (10%)

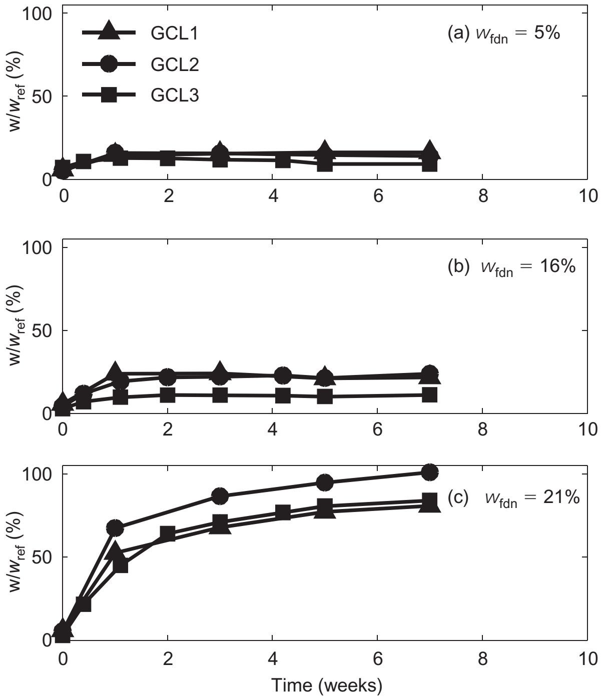

Figure 9. Effect of initial moisture content of silty sand foundation on normalised hydration (w/w_{ref}) measured at the end of a daily heating cycle

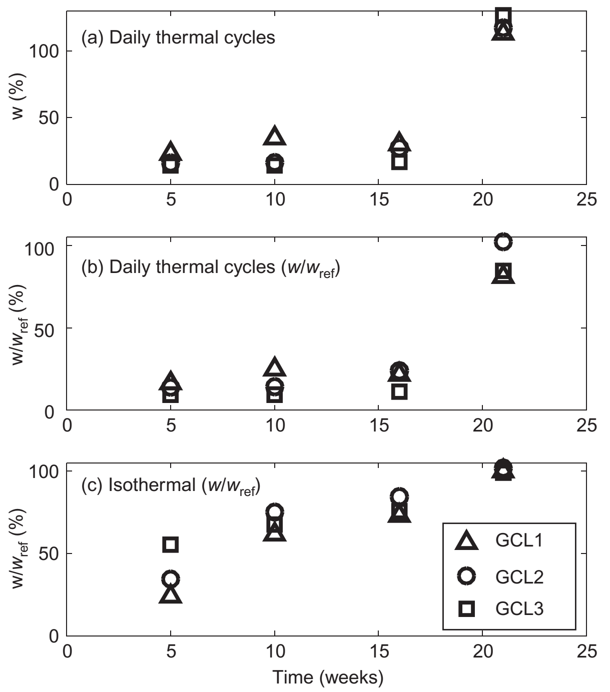

Figure 10. Effect of initial moisture content of silty sand foundation on GCL final equilibrium moisture content under isothermal conditions and daily thermal cycles (at end of heating cycle)

and GCL2 the least (only about 2%). Thus to the extent that shrinkage is a function of daily moisture cycles, susceptibility to shrinkage would be GCL1 $\geqslant$ GCL3 > GCL2 for the conditions examined here.

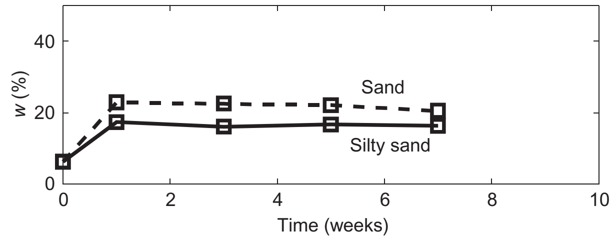

Figure 11. Comparison of GCL2 hydration on sand and silty sand foundation soils under simulated daily thermal cycles, $w_{fdn} = 10\%$

5.2. Hydration under daily thermal cycles compared to isothermal conditions on silty sand ($w_{fdn} = 16\%$)

The performance of a GCL in a barrier system is dependent on the degree of saturation of the bentonite in the GCL. At low applied confining stress (2 kPa), the constraint provided by the needle punching is dependent on the method of GCL manufacture and different GCLs experience different swelling characteristics during moisture uptake until they reach equilibrium under low stress (Lake and Rowe 2000; Beddoe *et al.* 2011). Consequently, the final equilibrium moisture content for GCLs immersed in water (denoted w_{ref} herein) varied significantly for the three GCLs examined (Table 2). Thus the degree of saturation of GCL2 at $w = 115\%$ gravimetric moisture content ($w/w_{ref} = 100\%$) would be substantially higher than that for GCL3 at the same moisture content of 115% ($w/w_{ref} = 77\%$). Hence simply comparing moisture content when comparing the performance of different GCL products can be misleading if not viewed in this context and so in the discussion below reference is made to both the absolute gravimetric moisture content and the moisture content normalised with respect to w_{ref}.

In a previous study, the moisture uptake of the same three GCLs on the same foundation soils was examined under isothermal conditions at room temperature (Rayhani *et al.* 2011). Figure 7 compares the results obtained by these researchers under isothermal conditions at room temperature with those obtained for daily thermal cycles of 25 to 60°C under otherwise identical conditions (silty sand, $w_{fdn} = 16\%$). Despite the fact that all three GCLs had a fairly similar uptake of moisture in the first week (42, 45 and 38% for GCL1, 2 and 3, respectively) under isothermal conditions, the rate of hydration when exposed to daily thermal cycles was less and quite different for the three GCLs (i.e. 33, 22 and 15% for GCL1, 2 and 3, respectively; Figure 7 and Table 2). In each case the moisture uptake and loss over a daily thermal cycle stabilised after only a few weeks (Figures 6 and 7) whereas under isothermal conditions the moisture content was still rising in all cases after 7 weeks (Figure 7). Table 4 shows a comparison of the moisture at 7 weeks and the equilibrium moisture for the case with daily thermal cycles and isothermal conditions. GCL2 achieved the highest moisture content relative to its potential (w/w_{ref}) of 24 and 77% at equilibrium with and without thermal cycles. In contrast, GCL3 had the lowest equilibrium moisture content relative to its potential ($w/w_{ref} = 11\%$)

Table 4. Comparison of moisture content after 7 weeks and at equilibrium with daily thermal cycles and under isothermal conditions (foundation soil–silty sand at 16% initial moisture content)

GCL	GCL moisture content			Normalised GCL moisture content (w/w_{ref})		
	Thermal cycles*	Isothermal		Thermal cycles*	Isothermal	
	7 weeks (equilibrium) (%)	7 weeks (%)	Equilibrium (%)	7 weeks (equilibrium) (%)	7 weeks (%)	Equilibrium (%)
GCL1	30.4	90	102	22	64	73
GCL2	27.4	78	88	24	68	77
GCL3	16.8	95	114	11	63	76

*At end of heating cycle.

with thermal cycles (c.f. 76% under isothermal conditions)

The difference in hydration of the three GCLs when subjected to isothermal hydration was primarily considered to be related to the difference in the shape and final equilibrium wetting curve moisture content of the three GCLs (Beddoe *et al.* 2011), as discussed later. However, these differences were not significant enough to prevent suppression of hydration under the action of daily thermal cycles and in all cases the final equilibrium moisture content at the end of the heating cycle was 30% or less of that expected under isothermal conditions.

5.3. Influence of foundation soil moisture content and GCL type on GCL hydration

The effect of thermal cycles on GCL hydration was highly dependent on the initial moisture content and associated matric suction of the foundation soil (Figure 8). For silty sand with an initial soil moisture content close to the field capacity and its saturated moisture content ($w_{fdn} = 21\%$), there is significant uptake of moisture by all three GCLs and after about 7 weeks GCL2 had reached the same moisture content (117%) as it would under isothermal conditions. GCL1 and GCL3 appeared to be approaching equilibrium at a moisture content of 113–126%.

The results presented in Figure 8 are replotted relative to w_{ref} (i.e., the moisture content achieved under isothermal conditions if there is no limit on available moisture) in Figure 9. Rayhani *et al.* (2011) reported that, under isothermal conditions, all three GCLs hydrated to the maximum possible ($w/w_{ref} = 100\%$) on the silty sand at $w_{fdn} = 21\%$. Under similar conditions but with daily thermal cycles, GCL2 again approached the maximum expected hydration ($w/w_{ref} = 100\%$) after about 7 weeks (Figure 9c and Table 2). However, although GCL 1 and GCL3 also approached their equilibrium moisture content at about the same time, this equilibrium value was affected by the thermal cycles and was only about 80–85% of that expected with no limit on the available moisture (i.e. $w/w_{ref} = 80–85\%$). Thus there was sufficient moisture available to satisfy GCL2 but the thermal cycles limited the moisture uptake in GCL1 and GCL3. Comparing the shape of the GCL WRCs (Beddoe *et al.* 2011) indicated that GCL 1 and GCL3 have a relatively steeper transition zone in comparison with GCL2. The thermal cycles increase the resultant suction in comparison with the isothermal case. Due to the steepness of the WRCs the increase in suction had a greater effect on the equilibrium water content on GCL1 and GCL3 compared with GCL2 which has a flatter WRC. As such, the final water content relative to w_{ref} was essentially unchanged for GCL2; however, GCL1 and GCL3 experienced a significant decrease in moisture content.

As noted earlier, for an initial foundation soil with $w_{fdn} = 16\%$ (Figures 8b and 9b; Table 2), GCL1 experienced the greatest increase in moisture content (to 33%; $w/w_{ref} = 24\%$) but decreased to about 30%; $w/w_{ref} = 22\%$) at equilibrium. GCL2 and GCL3 increased monotonically to equilibrium values of about 27 and 17% ($w/w_{ref} = 24$ and 11%), respectively.

For the case with $w_{fdn} = 5\%$ (Figures 8a and 9a; Table 2), the moisture content of GCL1 increased monotonically to about 20.5% ($w/w_{ref} = 15\%$) between 1 and 2 weeks and then slightly increased to its equilibrium value of 23% ($w/w_{ref} = 16\%$) (this is in contrast to the behaviour at $w_{fdn} = 16\%$). In this case GCL2 and GCL3 both increased to a peak moisture content of about 18 to 19% ($w/w_{ref} = 16$ and 13%, respectively) and then decreased to their equilibrium values of 16 and 14% ($w/w_{ref} = 14$ and 9%, respectively).

Rayhani *et al.* (2011) demonstrated that the final equilibrium hydration of GCLs under isothermal conditions was highly dependent on the foundation soil moisture content, w_{fdn} (Figure 10c) and associated matric suction (Figure 1b). The results from the present study (Figure 10a,b), confirm the important role of the foundation soil on GCL hydration but are in many respects quite different to those for isothermal conditions. With daily thermal cycles and foundation soil moisture contents of 5 to 16% which are associated with suction levels greater than the air entry value, there was relatively little hydration of the GCLs. Over this range, GCL1 had equilibrium moisture contents between 23 and 30%, GCL2 between 16 and 27%, and GCL3 between 14 and 17% (Figure 10a and Table 4). However, when the foundation soil moisture content increased to 21%, which is very close to the saturated water content, the behaviour changed substantially and the GCL moisture uptake was significantly increased to between 113 and 127% and reached 81 to 100% of the maximum possible (Figure 10b).

Thus the shift in the initial foundation soil moisture content from 21% (the typical highest values for this soil at the Godfrey field site: Brachman *et al.* 2007) to 16% (the average value for this soil at the Godfrey field site) and 10% (the lowest value observed at the Godfrey field site) had a profound effect on the hydration of the three GCLs used at the Godfrey site.

This data indicates that the most important parameter when considering the hydration of GCLs under daily thermal cycles is the availability of moisture for hydration as determined by the water retention curve of the foundation soil.

5.4. Effect of soil type on GCL hydration under thermal cycles

To illustrate the possible effect of foundation soil type, an experiment was conducted on a poorly graded concrete sand (SP) at an initial moisture content of 10%. As shown in the WRCs for these two materials provided in Figure 1b, the initial suction in the soil was higher in the silty sand. The observed hydration response for these two test cells is shown in Figure 11. In both cases the hydration of GCL2 was suppressed under the action of daily thermal cycles. As anticipated the lower suction supplied by the sandy foundation soil is reflected in the higher equilibrium moisture content. The difference in equilibrium moisture content is relatively small and this is due to the flat WRC of GCL2.

6. CONCLUSIONS

Experiments were conducted to investigate the hydration of three different GCLs under simulated daily thermal cycles. It was shown that the daily thermal cycle significantly decreased the equilibrium moisture content of the GCL to as low as 15% of that under isothermal conditions at room temperature in the worst case. The significant difference in moisture uptake of the GCL on the same silty sand foundation soil underscores the importance of exposure conditions on the hydration of GCLs.

The type of GCL had a significant effect on the change in moisture content during a heating cycle. For example, for a silty sand foundation soil with initial moisture content of 16%, at equilibrium (after a few weeks of daily thermal cycles), one GCL had a daily variation in gravimetric moisture content of 13%, another GCL had 10%, and the third GCL had only about 2%. Thus to the extent that shrinkage is a function of daily moisture cycles, susceptibility to shrinkage would be expected to be greatest for the GCL with the largest daily cycle and smallest for that with the smallest daily thermal cycle (other things being equal).

The initial moisture content and associated matric suction of the foundation soil was also shown to have a significant effect on GCL hydration. For GCLs over silty sand with initial moisture contents, w_{fdn}, of 5, 10 and 16% and suctions greater than their air entry value, the daily thermal cycles controlled GCL hydration at the end of the thermal cycle to values of between 14 and 30% and the GCL equilibrium moisture content was relatively insensitive to the initial foundation moisture content over this range. However, when the foundation moisture content increased to $w_{fdn} = 21\%$ (just below field capacity and saturated moisture content) the GCL moisture contents increased to 113 to 127% (depending on GCL). In contrast, the GCL equilibrium moisture content under isothermal conditions at room temperature was more variable ranging (depending on the GCL) from 33 to 83% at $w_{fdn} = 5\%$, to 85 to 102% at $w_{fdn} = 10\%$, 88 to 114% at $w_{fdn} = 16\%$, and 115 to 149% at $w_{fdn} = 21\%$.

The GCL moisture uptake was affected by the grading curve (and the related water retention curve) of the foundation soil with the hydration of a GCL on a poorly graded on sand (SP) at 10% initial moisture content being slightly higher than that of silty sand (SM) under otherwise similar conditions. From an unsaturated soil mechanics perspective initially the GCL has an extremely high suction (on the order of 10^5 kPa suction) and the foundation soil has a much lower suction (order of 10^1 to 10^2 kPa suction). As the quantity of water taken up by the GCL is minor compared with the volume within the foundation soil mass, the equilibrium suction is very close to the initial suction in the soil. Thus the foundation soil's initial moisture condition sets the target suction of the GCL. The GCL follows a wetting curve to the equilibrium moisture content.

These observations underscore the effect that: (*a*) the soil moisture content and suction, (*b*) soil grain-size distribution, and (*c*) the thermal exposure conditions can have on GCL hydration. Thus it may be inferred that shrinkage of a given GCL may vary substantially depending on the grain-size and moisture content of the foundation soil and their variability over the site as well as the nature of the daily thermal cycles. This highlights the potential complexity of interpreting shrinkage of GCLs at the same site let alone at different sites

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