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# Laboratory investigation of GCL hydration from clayey sand subsoil[☆]

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ABSTRACT

The hydration of Geosynthetic Clay Liners (GCLs) from underlying clayey sand subsoil (SC) is studied. The effect of product type and initial subsoil moisture content on GCL hydration is examined for both isothermal conditions at room temperature and for daily thermal cycles over several months. GCL hydration is shown to be highly dependent on the initial moisture content of the subsoil. For a subsoil initial moisture content of 5%, GCLs were only able to reach 12–18% of maximum hydration in over 22 weeks. For a subsoil initial moisture content close to field capacity (20%), GCLs were able to reach 90–91% of maximum hydration over 22 weeks. The method of GCL manufacture is shown to greatly affect the maximum hydration reached as well as the swelling of the respective GCLs. Daily thermal cycles greatly reduced hydration and kept the gravimetric moisture content of the GCLs below 30% of what was reached under isothermal conditions at room temperature. Compared to sand (SP) and silty sand (SM) subsoils, clayey sand (SC) slowed the rate of hydration of the GCLs and reduced the final equilibrium moisture content attained.

## 1. Introduction

Geosynthetic clay liners (GCLs) are often used together with a geomembranes to form a composite liner system at the base of modern landfills, heap leach pads and many other fluid containment applications (Rowe, 2005; Benson et al., 2010a, b; Gates and Bouazza, 2010; Hornsey et al., 2010; Lange et al., 2010; Roisin-Paumier et al., 2010, 2011; Shackelford et al., 2010; Chen et al., 2010). Being used as an effective barrier to advective transport of contaminants, GCLs must be adequately hydrated prior to contact with leachate (Rowe, 2005). After placement, the GCL takes up pore water from the underlying soil. While it is accepted that GCL performance is, at least partially, based on degree of hydration before it comes into contact with leachate (Rowe et al., 2004), there is very limited data regarding the hydration of a GCL from subsoil and it is generally not known to what extent a GCL will be hydrated by the time it is covered with waste.

A few researchers have investigated the hydration of GCLs from sand subsoil under isothermal conditions at room temperature (Daniel et al., 1993; Eberle and von Maubeuge, 1997; Chevrier et al., 2010; Rayhani et al., 2011a). Daniel et al. (1993) showed that, GCL could reach up to 88% moisture content after 40–45 days, when placed on sand at 3% moisture content. Eberle and von Maubeuge (1997) reported that an initially air dry GCL absorbed a moisture content of 100% in less than 24 h and 140% after 60 days, when placed in contact with a sand subsoil with a moisture content of 8–10%. Both the method of manufacture (Beddoe et al., in press; Rayhani et al., 2011a) and the type of bentonite (Bouazza et al., 2006) have also shown to affect GCL hydration. Rayhani et al. (2011a) also reported that the subsoil grain size distribution and initial moisture content influence the rate and degree of hydration of GCLs, when placed over a sand (SP) and silty sand (SM) subsoil under isothermal condition at room temperature. The rate of GCL hydration from a sand (SP) subsoil was slightly higher than that for a silty sand (SM) subsoil. Chevrier et al. (2010) showed that the equilibrium water content of the GCL, from a sand subsoil, decreased by about 12.5% as the confining pressure increased from 7 to 28 kPa.

It is good practice in landfill construction to cover the composite liner with the leachate collection system shortly after placement of the liner. However, it is not uncommon for a composite liner to be left exposed to thermal cycles due to daily heating and cooling of the geomembrane for periods that may range from weeks to years before it is covered (Thiel and Richardson, 2005). However, except for the study by Rowe et al. (2011), the effect of thermal cycles on GCL hydration is not sufficiently documented. Rowe et al. (2011) showed that daily thermal cycles similar to that which might experienced by a composite liner left exposed to the sun

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significantly affected the hydration of GCLs from silty sand and sand subsoil.

The objective of this paper is to investigate the hydration of GCLs from a clayey sand subsoil under both isothermal conditions at room temperature and daily thermal cycles. Consideration will be given to the effect of subsoil particle size distribution and the initial moisture content of the subsoil on the rate of moisture uptake by three different GCLs. Some of the results reported herein were previously reported briefly in a conference paper by Rayhani et al. (2011b). This paper goes beyond that work by describing all experimental details and discusses the effect of seasonal thermal cycles on the rate of hydration for a range of different conditions, and compares the GCL hydration from clayey sand with other previously studied subsoils.

## 2. Material properties

### 2.1. Geosynthetic clay Liners

Three GCLs, Bentofix NSL (denoted as GCL1 henceforth), Bentofix NWL (GCL2) and Bentomat ST (GCL3) were studied. The index characteristics of the three GCLs are shown in Table 1. The granular sodium bentonite in the three GCLs had a similar smectite content (50–58%) and swell index. GCL1 and GCL2 contained fine grained bentonite with $D_{50}$ of about 0.33 mm, while GCL3 contained coarse granular bentonite with $D_{60}$ of 0.9 mm GCL3 had a higher cation exchange capacity (103 meq/100 g) than the other GCLs (78–81 meq/100 g). The water retention curves for the three GCLs also differed significantly as described by Beddoe et al. (in press).

### 2.2. Soil characteristics

The grain size distribution of the clayey sand subsoil (SC, ASTM D2487, 2005) determined according to ASTM D 422 is shown in Fig. 1a. A hydrometer test (ASTM D422, 2005) was also conducted to obtain the grain size distribution of the fine portion of the soil (Fig. 1a). The grain size distribution curve indicates that the soil has about 21% fines (passing the 0.075 mm sieve) and about 12% clay size. The plasticity index (ASTM D4318, 2005) of the fine fraction was about 4%. The maximum dry density of the soil was 1.96 mg/m$^3$ at a gravimetric water content of 11.3% based on standard Proctor compaction (ASTM D698, 2005). The saturated hydraulic conductivity of the soil was 3.9 10$^{-6}$ m/s. The subsoil water retention curve was estimated using the data point function (GeoStudio, 2007) is shown in Fig. 1b. Four subsoil moisture contents were examined (Fig. 1b): field capacity (i.e., the water content held in soil after excess water is drained) (20%), two moisture contents on the steep portion of the drying curve (15% and 10%), and a moisture content near the residual moisture content (5%).

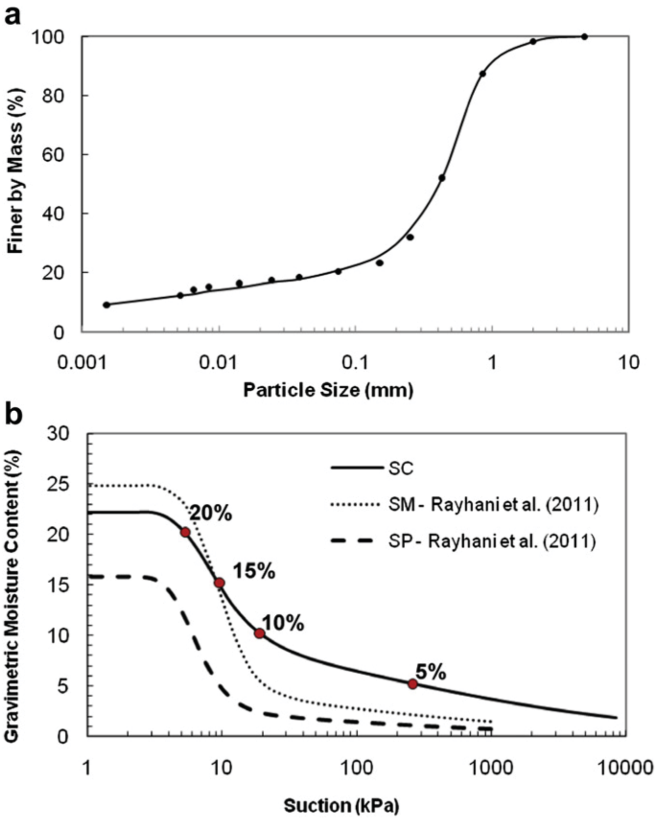

**Fig. 1.** (a) Particle size distribution and (b) inferred water retention curve for the subsoil examined.

**Table 1**
Basic properties of GCLs tested.

| GCL properties | | | GCL1 | GCL2 | GCL3 |
|---|---|---|---|---|---|
| Mass/area | Avg. dry mass/area (g/m$^2$) | | 4509 | 3896 | 5438 |
| Carrier | Type | | W | SRNW | W |
| | Avg. mass/area (g/m$^2$) | | 123 | 241 | 121 |
| Cover | Type | | NW | NW | NW |
| | Avg. mass/area (g/m$^2$) | | 237 | 212 | 275 |
| Structure | Construction | | NPTT | NPTT | NP |
| | Avg. peel strength (N)[a] | | 94 16 | 260 17 | 204 35 |
| Bentonite | Aggregate size distribution (mm) | $D_{10}$ | 0.1 | 0.15 | 0.4 |
| | | $D_{30}$ | 0.28 | 0.3 | 0.65 |
| | | $D_{60}$ | 0.35 | 0.35 | 1.0 |
| | Smectite content (%)[b] | | 50–55 | 50–55 | 53–58 |
| | Swell Index (ml/2 g)[a] | | 26 | 24 | 23 |
| | Liquid limit (%)[c] | | 278 | 265 | 334 |
| | Plasticity index (%)[c] | | 227 | 216 | 262 |
| | Cation exchange capacity (meq/100 g)[a] | | 81 | 78 | 103 |

W, woven; NW, nonwoven; SRNW, scrim-reinforced nonwoven; NP, needle punched; NPTT, needle punched & thermally treated.

[a] Tests performed by M. Hosney, Queen's University.

[b] Data from Bostwick et al. (2010).

[c] Tests performed by H. Sarabadani, Carleton University.

## 3. Experimental method

### 3.1. Experimental procedure

The clayey sand (Fig. 1) was mixed with tap water with an average calcium concentration of 40 mg/L (similar to that reported by Rayhani et al., 2011a, b and Rowe et al., 2011) to bring its moisture content to the appropriate subsoil moisture content ($w_{fdn}$) of 5%, 10%, 15%, and 20%. Once thoroughly mixed, the soil samples were left to cure for 24 h in sealed plastic bags. The prepared clayey sand was then compacted using a compaction hammer in three layers into 150 mm diameter and 300 mm in height polyvinyl chloride (PVC) test cells (Fig. 2) to a dry density of 1.75 mg/m$^3$ (approximately 90% of the maximum dry density). The soil porosity was about 34%.

GCL specimens with 150 mm diameter were placed on top of the soil and a geomembrane was placed over the GCL. The geomembrane simulated composite liner field conditions and minimized evaporation of soil moisture. A 15 mm thick steel seating block (1 kPa) was placed on top of the geomembrane to ensure good contact between the GCL and the soil. The test cells were sealed to prevent moisture loss (Fig. 2). The initial moisture content of the subsoil and GCL specimens as well as the initial GCL mass per

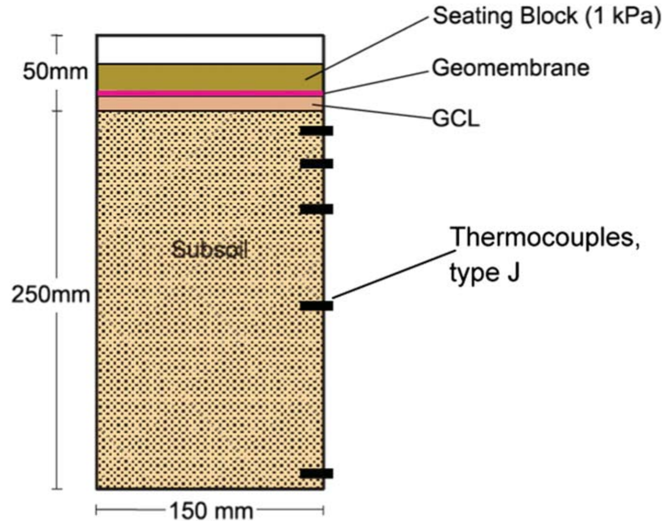

**Fig. 2.** Geometry of instrumented soil column used for investigating GCL hydration.

**Table 3**
Details of GCL hydration under daily thermal cycles.

| GCL type | Subsoil | GCL | GCL moisture content (w) | | | Normalized GCL moisture content[a] ($w/w_{ref}$) | | |
|---|---|---|---|---|---|---|---|---|
| | Initial moisture content (%) | Total air dry mass/unit area (g/m$^2$) | Initial (%) | After 1 week (%) | After 6 weeks (%) | Initial (%) | After 1 week (%) | After 6 weeks (%) |
| GCL2 | 5 | 3747 | 5.0 | 12.8 | 13.2 | 4.2 | 10.8 | 11.2 |
| | 10 | 3490 | 5.0 | 13.4 | 15.5 | 4.2 | 11.3 | 13.1 |
| | 15 | 3872 | 5.0 | 13.7 | 16.3 | 4.2 | 11.6 | 13.8 |
| | 20 | 3932 | 5.0 | 24.6 | 65.6 | 4.2 | 20.8 | 55.6 |
| GCL3 | 5 | 5522 | 10.6 | 17.2 | 16.2 | 6.2 | 9.05 | 8.5 |
| | 10 | 5540 | 10.6 | 17.4 | 19.5 | 6.2 | 9.15 | 10.3 |
| | 15 | 5414 | 10.6 | 16.8 | 18.0 | 6.2 | 8.8 | 9.5 |
| | 20 | 5402 | 10.6 | 46.6 | 91.7 | 6.2 | 24.5 | 47.8 |

[a] $w_{ref}$ (mean, standard deviation, sd) : GCL1 (145%, 8%), GCL2 (118%, 5%), GCL3 (190%, 10%).

unit area for the isothermal hydration experiments are presented in Table 2 and those for the daily thermal cycles experiments are given in Table 3. In all, 20 test cells were used. Of these cells, 12 were conducted at room temperature as part of an isothermal hydration test. The remaining 8 cells were used to study the effects of cyclic heating conditions on GCL hydration.

### 3.1.1. *Isothermal test conditions*

Isothermal hydration tests were conducted for all three types of GCLs (Table 2) at room temperature (22 °C).

### 3.1.2. *Cyclic heating conditions*

Two GCL types (GCL2 and GCL3) were used to study the effect of cyclic heating on GCL hydration (Table 3). The test 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. The temperature controller was programmed to generate thermal cycles representative to exposed geomembrane to sun (20–60 °C), whilst the bottom of the cell was kept at a constant lower temperature to simulate the thermal gradients that develop in the field. Heat was applied for 8 h and the cells were allowed to cool for 16 h before the cycle was repeated.

During a three week span in the second month of testing, the blanket was left off to study the effect of long-term cooling cycle on GCL hydration. This time span with no heating provides an indication of the effect of seasonal temperature changes on GCL hydration.

At termination of the tests, a final moisture content profile was obtained for each cell for comparison with the initial moisture content profile.

## 3.2. *Monitoring*

The PVC cells were opened once a week and the GCLs were removed for weighing and thickness measurement to evaluate the progression of GCL hydration and track changes in thickness. Thickness was measured using callipers, by taking the average of three different measurements at different points on the GCL. After measurement, the GCLs were placed back in their cell and the cells were resealed. To minimize moisture loss, the process was completed for each cell in less than 5 min.

For the cyclic heating experiments, the temperature profile with depth was monitored using thermocouples. Fig. 3 shows the applied temperature and the thermal response of subsoil at depths of 10, 60, 150, and 240 mm. During a heating cycle, the temperature in the air space above the composite liner increased to 55–60 °C. The temperatures in the soil decreased with depth, with the majority of the daily thermal change occurring in the upper 100 mm of the soil. Thus the height of the cells was sufficient to capture the daily thermal response of the soil profile with only a small accumulation of heat at the base of the cells. Each week, the test cells were opened and the GCL mass was measured

**Table 2**
Details of isothermal hydration experiments.

| GCL type | Subsoil | GCL | GCL moisture content (w) | | | Normalized GCL moisture content[a] ($w/w_{ref}$) | | |
|---|---|---|---|---|---|---|---|---|
| | Initial moisture content (%) | Total air dry mass/unit area (g/m$^2$) | Initial (%) | After 1 week (%) | After 22 weeks (%) | Initial (%) | After 1 week (%) | After 22 weeks (%) |
| GCL1 | 5 | 4249 | 9.2 | 24.2 | 23.6 | 6.6 | 16.7 | 16.3 |
| | 10 | 4398 | 9.2 | 37.3 | 85.4 | 6.6 | 25.7 | 58.9 |
| | 15 | 4243 | 9.2 | 40.0 | 97.5 | 6.6 | 27.6 | 67.3 |
| | 20 | 4506 | 9.2 | 41.5 | 130 | 6.6 | 28.6 | 90.0 |
| GCL2 | 5 | 4022 | 5.0 | 20.7 | 21.5 | 4.2 | 17.5 | 18.2 |
| | 10 | 3723 | 5.0 | 31.0 | 78.9 | 4.2 | 26.3 | 66.9 |
| | 15 | 4183 | 5.0 | 32.1 | 87.8 | 4.2 | 27.2 | 74.5 |
| | 20 | 3788 | 5.0 | 34.7 | 106 | 4.2 | 29.4 | 90.1 |
| GCL3 | 5 | 5545 | 10.6 | 25.1 | 23.3 | 6.2 | 13.2 | 12.3 |
| | 10 | 5498 | 10.6 | 40.5 | 90.4 | 6.2 | 21.3 | 47.6 |
| | 15 | 5211 | 10.6 | 40.9 | 99.4 | 6.2 | 21.5 | 52.3 |
| | 20 | 5384 | 10.6 | 45.8 | 174 | 6.2 | 24.1 | 91.5 |

[a] $w_{ref}$ (mean, standard deviation, sd) : GCL1 (145%, 8%), GCL2 (118%, 5%), GCL3 (190%, 10%).

immediately following a heat cycle (in the evening), and then the next morning after nightly cooling just before heat was re-applied.

### 3.3. Reference (maximum) GCL hydration moisture content

The maximum hydration moisture content ($w_{ref}$) for each of the three GCLs was taken to be the final equilibrium moisture content after submerging a GCL specimen in water with a 1 kPa seating load. The equilibrium moisture content (145% ± 8% for GCL1, 118% ± 5% for GCL2 and 190% ± 10% for GCL3) was reached within a week in each case.

## 4. Results and discussion

The hydration of the GCLs under isothermal conditions and thermal cycles are presented in terms of gravimetric moisture content ($w$) and normalized hydration in Tables 2 and 3 and Figs. 4–9. The normalized hydration ($w/w_{ref}$) is the moisture content of a GCL at a given time divided by the maximum hydration moisture content for that GCL (i.e., the moisture content achieved under isothermal conditions if there is no limit on available moisture as discussed earlier).

### 4.1. Effect of subsoil moisture content on isothermal GCL hydration

Fig. 4 shows the effect of initial moisture content of the subsoil on GCL hydration. Hydration of the GCLs is expressed in terms of gravimetric moisture content ($w$) on the left axis and normalized hydration on the right axis. Higher initial moisture content in the subsoil yielded higher GCL hydration. The gravimetric moisture content stabilized, or nearly stabilized within about 22 weeks for the three GCLs. However, the rate at which the GCLs reached final equilibrium depended on the initial moisture content of the subsoil.

At an initial subsoil moisture content of 5% ($w_{fdn}$ 5%), the GCL equilibrium moisture content was only 21–24% (Table 2) and the normalized moisture content ($w/w_{ref}$) only ranged from 12% to 18%. At 10% and 15% initial subsoil moisture content, the GCL equilibrium gravimetric moisture content ranged between 79–90% and 88–99% respectively, and the normalized moisture content ($w/w_{ref}$) ranged from 47 to 67% and 52–75% of the fully hydrated values respectively. For an inital subsoil moisture content of 20%, the GCLs approached full hydration and ranged from 90 to 91.5% of reference value ($w/w_{ref}$). Thus there was a very large difference in the final moisture content reached for 5% and 20% subsoil moisture content, while the difference for 10% and 15% subsoil initial moisture

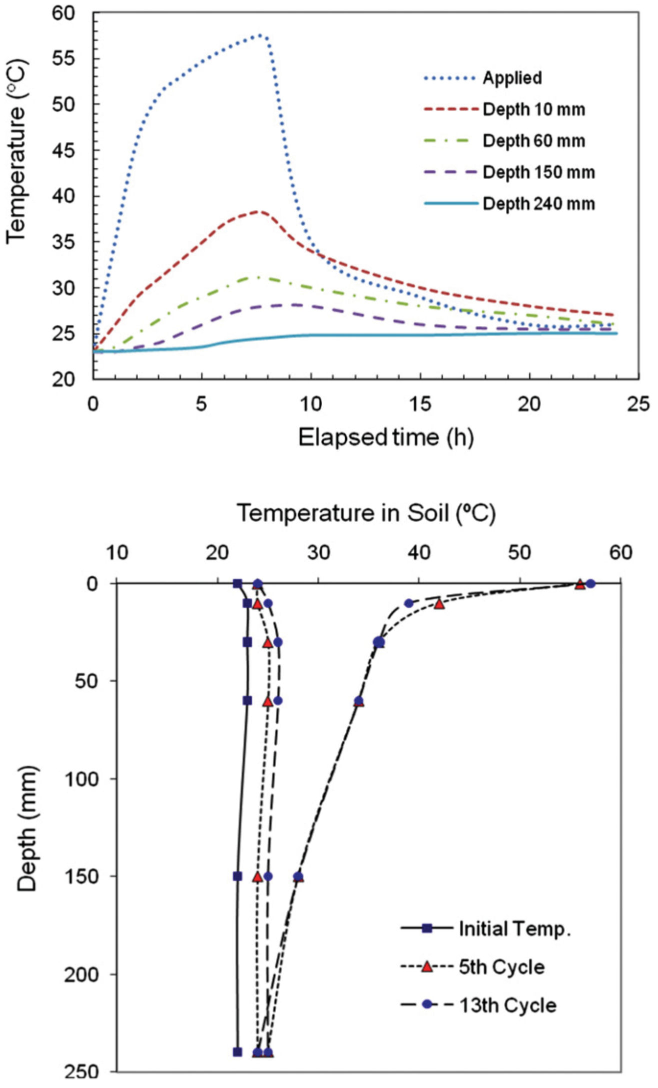

**Fig. 3.** Temperature profile in subsoil at the end of the heating (higher values) and cooling (lower values) cycles ($w_{fdn}$ 10%).

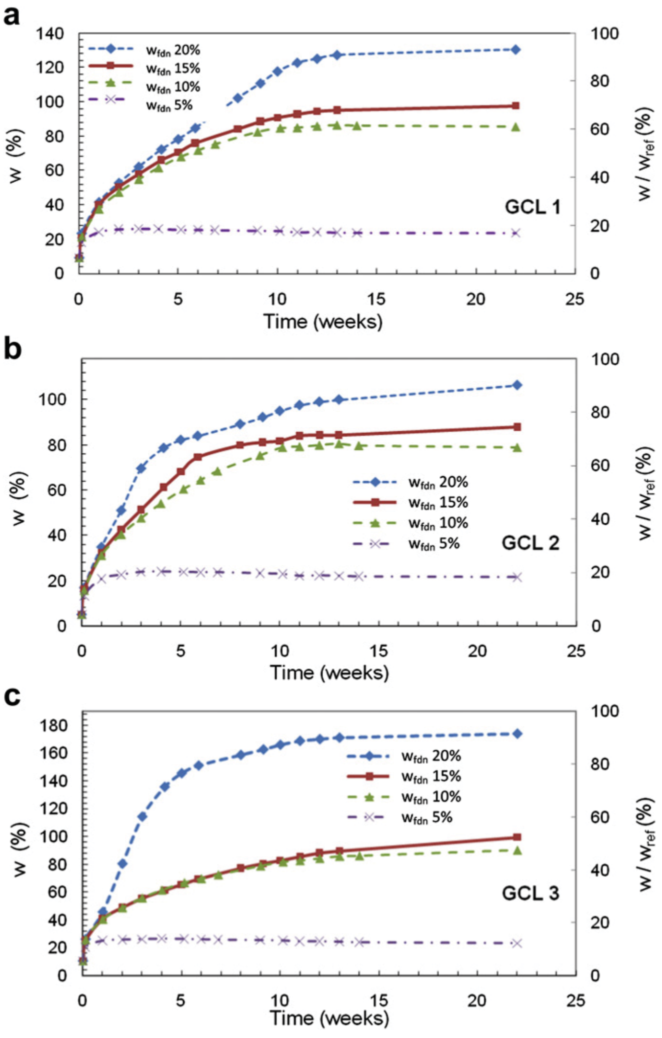

**Fig. 4.** Hydration of GCLs under isothermal conditions: (a) GCL1, (b) GCL2, and (c) GCL3. $w_{fdn}$ is initial water content of subsoil.

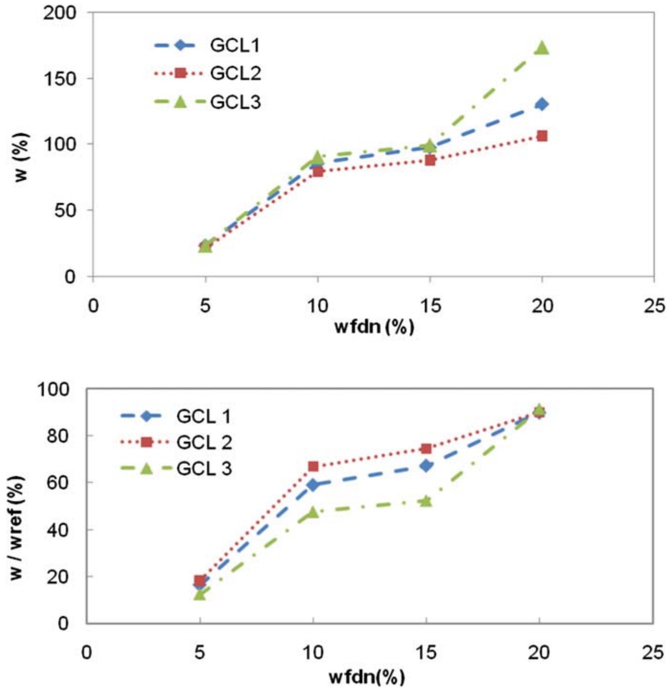

**Fig. 5.** Effect of GCL type and subsoil initial moisture content on normalized final equilibrium moisture content ($w/w_{\mathrm{ref}}$) of three GCLs.

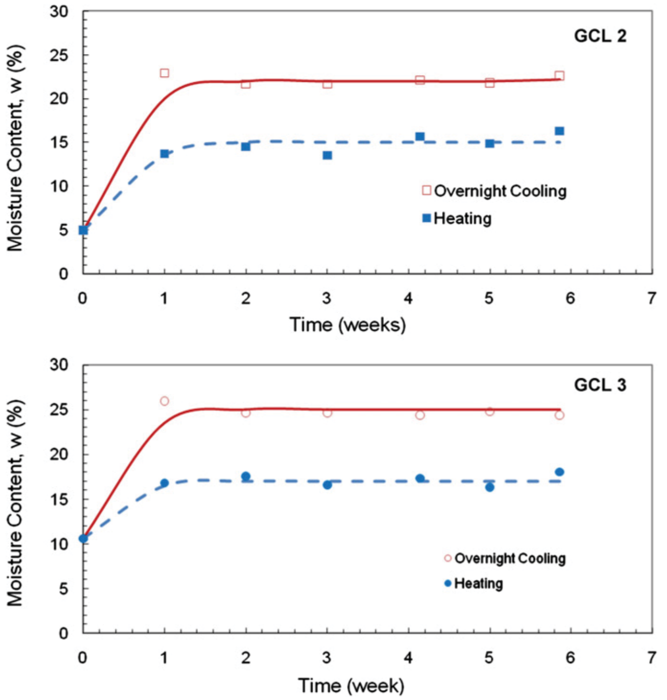

**Fig. 7.** GCL gravimetric moisture content at the end of heating and cooling cycles ($w_{\mathrm{fdn}} = 15\%$).

contents was much less. However, it was only for a subsoil moisture content of 20%, (i.e., near field capacity) that the GCLs approached full hydration.

### 4.2. Effect of GCL type on hydration

The GCL with the highest equilibrium moisture content on a subsoil at a given subsoil moisture content (Fig. 5a) does not necessarily correspond to the GCL that reaching the highest degree of saturation (Fig. 5b) which is the important quantity. GCL3 usually reached the highest moisture content. However GCL2 usually reached the highest normalized hydration (and hence degree of saturation). GCLs 1 and 2 had maximum normalized hydration usually falling within 5–10% of each other for each subsoil moisture content. On subsoil with moisture content 5–15%, the maximum normalized hydration of GCL3 was significantly less than that for GCLs 1 and 2 (Fig. 5). Only for the subsoil at 20% moisture content (i.e., close to field capacity), was the normalized hydration value for all GCLs similar (90–91.5%). This can all be attributed to the properties of the GCLs. GCLs 1 and 2 came from the same manufacturer and had the same type of bentonite clay and were thermally treated. Any differences between the two GCLs would result from the performance difference between the woven and nonwoven carrier geotextiles. The anchorage of the needle punched fibres by the thermally treated scrim-reinforcesd GCL2 (peel strength 260 N, Table 1) was effective in constraining the

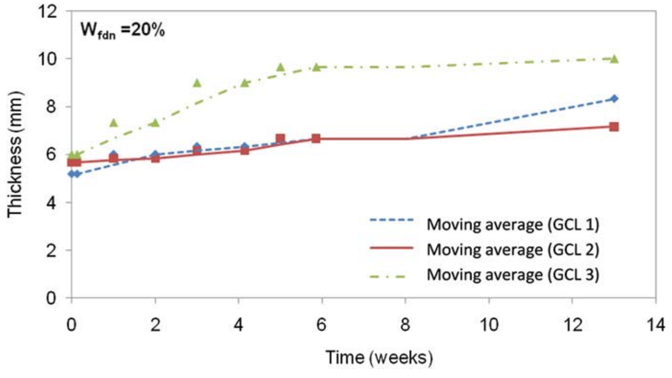

**Fig. 6.** Change in GCL thickness during hydration.

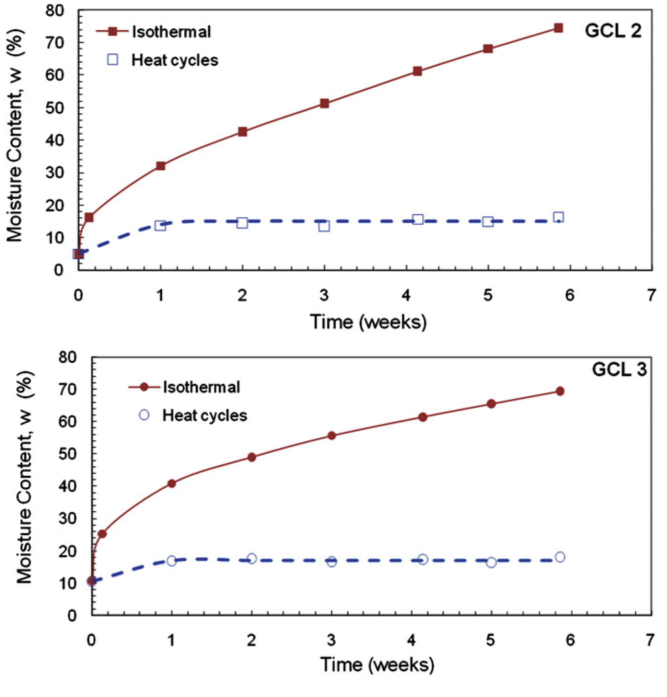

**Fig. 8.** GCL gravimetric moisture content under isothermal conditions and after cyclic heating ($w_{\mathrm{fdn}}$ 15%).

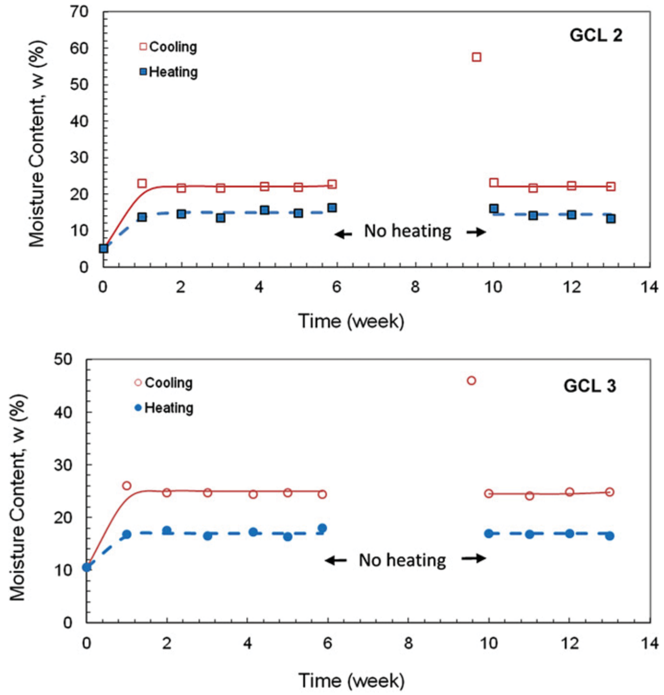

**Fig. 9.** Effect of long-term cooling cycle on GCL gravimetric moisture content ($w_{\text{fdn}}$ 15%). Note: between 6 and 10 weeks there were no heating cycles and the GCL was allowed to hydrate form the subsoil under isothermal conditions. Results at 10 weeks are after the first subsequent heating and cooling cycle.

maximum moisture content when immersed in water ($w_{\text{ref}}$ 118%) and provided less void ratio and better hydration performance. The woven thermally treated carrier geotextile in GCL1 (peel strength 94 N, Table 1) provided much less effective anchorage and therefore was less effective at limiting the maximum moisture uptake ($w_{\text{ref}}$ 145%) and the normalized moisture content was slightly less than that for GCL2. Despite a high peel strength of 204 N (Table 1), GCL3 showed the least effective anchorage of fibres and the highest maximum moisture content ($w_{\text{ref}}$ 190%) leading to the least normalized hydration values. Thus the peel strength is not a good indicator of how well the needle punched fibres will constrain the swelling of the bentonite at low stress. This is likely because peel strength is mobilized at large deformations whereas the ability to constrain swelling is mobilized at low deformations.

The GCLs performance can also be examined in terms of changes in thickness during hydration. Fig. 6 shows the change of thickness for each GCL on the subsoil at 20% moisture content. The final thickness of GCLs 1, 2 and 3 was 8.3 ± 0.3 mm, 7.2 ± 0.3 mm and 10.0 ± 0.5 mm, respectively. GCL3 had the least effective anchorage of the needle punched fibres and the higher mass of bentonite contained in the GCL. This combination resulted in more fibre pull-out and greater swelling (thicker GCL) but lower bulk voids ratio and degree of saturation (the two important engineering parameters). The thermal treatment of GCLs 1 and 2 limited the swelling of the bentonite and GCL thickness. The scrim-reinforced nonwoven carrier geotextile in GCL 2 reduced swelling even more effectively that the woven carrier in GCL 1. The superior anchorage of the needle-punching in GCL 2 results in a lowered bulk void ratio of the hydrated GCL, which has shown to lower hydraulic conductivity and lower diffusion coefficients (Petrov and Rowe, 1997; Lake and Rowe, 2000a, b; Beddoe et al., in press).

### 4.3. *Effect of daily and seasonal thermal cycles on GCL hydration*

When subjected to thermal cycles, the heat influx into the subsoil (Fig. 3) increased the subsoil temperatures at shallow depths (0–10 mm) to 56–57 °C. After 6 weeks, and the end of the daily cooling cycle, the subsoil temperatures were within a couple of degrees of initial temperatures. However, after 13 weeks, a significant amount of heat remained in the subsoil between depths of 30–150 mm at the end of the cooling cycle, but toward the bottom of the cell (240 mm) there was relatively little change due to the daily heating cycles with the temperature only increasing by 2 °C from initial conditions.

The gravimetric moisture content of the GCLs on a subsoil with 15% initial moisture content and undergoing daily heat cycles is shown in Fig. 7 both at the end of the heating cycle and end of the subsequent cooling (and rehydration) cycle. After one week, the moisture contents of the respective GCLs had reached their maximum values and then stabilized with just minor fluctuations over the next five weeks. For GCL 2, the daily heat cycle kept the GCL from reaching more than 15% moisture content. For GCL 3, the heat cycle had the moisture content hovering around 17%. Overnight cooling consistently increased the moisture content of both GCLs by approximately 7%, but the GCLs were never remotely close to reaching full saturation. This shows that with similar daily heating cycles the ability of GCLs to hydrate from subsoil is lost.

Table 4 and Fig. 8 compare the hydration observed with daily heat cycles to that under isothermal conditions. After 6 weeks the isothermal tests had yet to reach equilibrium and the GCLs had both reached around 60% gravimetric moisture content. Under cyclic heating, however, GCLs 2 and 3 had only reached equilibrium at 15% and 17% moisture content, respectively. This shows that daily cyclic heating greatly affects the hydration of GCLs.

To examine the effect of seasonal thermal cycles, the heating blanket was turned off between weeks 6–9 to allow the GCL three weeks to hydrate before the cycles were recommenced. This simulated the effect of shifting from sunny days to a block of overcast days. Fig. 9 shows hydration for GCLs 2 and 3 over subsoil

**Table 4**
Comparison of GCL moisture content for hydration with daily thermal cycles and under isothermal conditions.

| GCL | Subsoil | GCL moisture content (%) | | | Normalized GCL moisture content ($w/w_{\text{ref}}$) (%) | | |
|---|---|---|---|---|---|---|---|
| | Initial moisture content (%) | Thermal cycles | Isothermal | | Thermal cycles | Isothermal | |
| | | 6 Weeks (equilibrium) | 6 weeks | Equilibrium | 6 weeks (equilibrium) | 6 Weeks | Equilibrium |
| GCL2 | 5 | 13.2 | 23.7 | 22.3 | 11.2 | 20.0 | 18.9 |
| | 10 | 15.5 | 64.4 | 78.9 | 13.1 | 54.6 | 66.9 |
| | 15 | 16.3 | 74.5 | 87.8 | 13.8 | 63.1 | 74.5 |
| | 20 | 65.6 | 83.9 | 106 | 55.6 | 71.1 | 90.1 |
| GCL3 | 5 | 16.2 | 26.1 | 24.0 | 8.5 | 13.7 | 13.0 |
| | 10 | 19.5 | 69.8 | 90.4 | 10.3 | 36.7 | 47.6 |
| | 15 | 18.0 | 70.4 | 99.4 | 9.5 | 37.0 | 52.3 |
| | 20 | 91.7 | 151 | 174 | 47.8 | 79.5 | 91.5 |

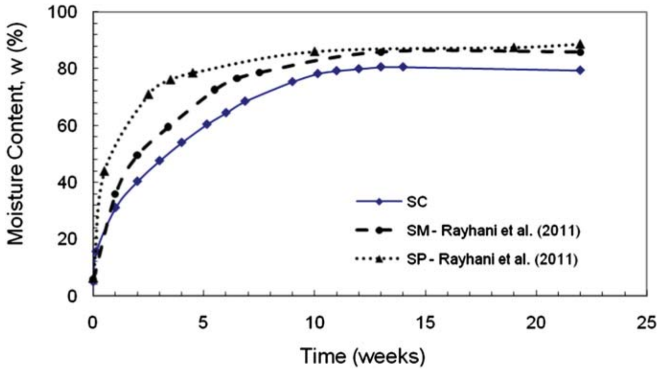

**Fig. 10.** Hydration of GCL 2 over three different subsoils under isothermal conditions at $w_{\mathrm{fdn}}$ 10%.

with an initial 15% moisture content over 13 weeks with cyclic heating and cooling between weeks 0–6 and 10–13.

During the 3 week without heating, the GCL moisture content for GCL 2, increased from around 23% at the end of 6 weeks to 58% at the end of 9 weeks while for GCL 3 there was an increase from 24% to 46% over the same period. Once heating cycles resumed after week 9, however, the moisture recovered by the GCLs was quickly lost. Between weeks 10 and 13, the moisture of the GCLs equilibrates at the same levels observed prior to the long cooling span. This shows the susceptibility of GCLs that have experienced partial hydration to moisture loss once heating conditions are experienced.

### *4.4. Effect of grain size distribution of subsoil on isothermal GCL hydration*

Rayhani et al. (2011a, b) reported that GCL moisture uptake was higher over a sand (SP) than silty sand subsoil (SM). This was attributed to the fact that the sand had much lower suction at a given moisture content than the silty sand, and hence there was a greater difference in suction between the sand and the GCL, allowing quicker moisture uptake from the sand than the silty sand. It was found that for subsoils with an initial 10% moisture content, GCL 2 over sand reached 60% saturation ($w/w_{\mathrm{ref}}$) in 2 weeks compared to 5 weeks for the silty sand. The final equilibrium moisture content also was slightly higher for the GCL over sand (88%) than over the silty sand (85%).

Fig. 10 and Table 5 shows the hydration of GCL 2 resting on three subsoils (clayey sand, SC; silty sand, SM; and sand, SP) at 10% gravimetric moisture content. For clayey sand it took significantly longer (close to 8 weeks) to reach 60% of the reference hydration, compared to 5 weeks for silty sand and 2 weeks for sand. The final equilibrium moisture content over clayey sand (80%) was less than that over sand (88%) and silty sand (85%). These differences can be attributed to the higher suction of the clayey sand soil at a given moisture content (Fig. 1b) than for the silty sand or sand subsoil. These higher suctions made it more difficult for the GCL to extract moisture from the clayey sand than for the silty sand or sand. Thus as the fine portion of the subsoil increases, the difference in the suction at the subsoil-GCL interface decreases, reducing the relative driving force for moisture movements form the subsoil to the GCL.

**Table 5**
GCL hydration from different subsoils.

| Subsoil type | Time to reach 60% degree of saturation ($w/w_{\mathrm{ref}}$ 0.6) | Time to reach final equilibrium moisture content | Final equilibrium moisture content ($w/w_{\mathrm{ref}}$) |
|---|---|---|---|
| Sand (SP) | 2 Weeks | 10 Weeks | 77% |
| Silty sand (SM) | 5 Weeks | 13 Weeks | 74% |
| Clayey sand (SC) | 8 Weeks | 13 Weeks | 69% |

## 5. Conclusions

The hydration of three GCL types from underlying clayey sand subsoil was studied under isothermal conditions at room temperature, as well as under daily thermal cycles over several months. The initial moisture content of the subsoil had a significant effect on the degree of hydration reached by the GCLs. The GCLs overlaying 5% moisture content soil only reached moisture contents of 21–24% (12–18% of the maxumim moisture content of the GCL at the same stress when there is plentiful water) and hence had a very low degree of saturation. In contrast, when the GCLs was overlaying the clayey sand at 20% initial moisture content (i.e., close to field capacity) GCL moisture contents reached 106–170% depending on the GCL which was 90–92% of the fully hydrated value at low (1 kPa) stress. Over the 5% subsoil moisture content, the GCLs reached equilibrium moisture content in 2–3weeks, while it took the full 13 weeks for the GCLs over 10–20% subsoil moisture content to reach equilibrium.

The hydration of GCL from a given subsoil was also found to be depended on the method of GCL manufacture. Over subsoil moisture content less than field capacity ($w_{\mathrm{fdn}}$ 5–15%), GCL2 reached the highest normalized hydration. Over subsoil close to field capacity (20%) all GCLs reached similar range of saturation (90–92%). GCL 2 showed the least swelling and highest saturation for a given subsoil. This suggests better hydration performance over the other two GCLs due to the lower the bulk void ratio at a given degree of saturation. The rate of hydration of the three GCLs in reaching equilibrium moisture content when resting on this clayey sand was very similar and proved not to be significant.

When subjected to thermal cycles with daily surface heat of 56 °C (representative of exposed geomembrane in the sun) and an evening temperature of 22 °C, the GCL hydration from the subsoil only reach about 30% of moisture content reached under isothermal conditions at room temperature. The effect of seasonal cycles was approximated by leaving the GCLs at room temperature for three weeks. While the GCLs were able to uptake significant moisture over this long period without heating, the moisture attained during this time was quickly lost once subjected again to the daily heat cycle. This suggests that timely soil covering over GCLs would results in a higher and more sustained saturation, which is beneficial to long-term performance.

Clayey sand subsoil (SC) affected the rate and degree of hydration of the GCLs in comparison with other subsoils (SP and SM). For GCLs over clayey sand subsoil it took 8 weeks to reach 60% of the reference moisture content, whereas it took only 2 and 5 weeks for GCLs overlaying sand (SP) and silty sand (SM) subsoils respectively. Additionally, the final equilibrium moisture content reached by the GCLs over clayey sand was less than that reached by the other subsoils. These differences can be explained by the higher suction of the clayey sand in comparison with the other subsoils at a given moisture content.

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