Hydration of Deconstructed Geosynthetic Clay Liners Under Daily Thermal Cycles

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ABSTRACT
Geosynthetic clay liners (GCLs) have been shown to achieve lower hydraulic conductivity and, hence, better performance as a barrier material than non-prehydrated specimens provided adequate hydration has occurred. However, there is evidence that exposure to daily thermal cycles could inhibit hydration of the bentonite which is significant in field applications with delayed installation. In this paper, two deconstructed GCLs (needle-punched fibres cut) with powdered and fine granular bentonite overlying a 450mm-thick silty sand foundation at 16% moisture content are subjected to laboratory simulated daily thermal cycles of 24-60 °C. Different configurations of the deconstructed GCLs allow the roles of the needle-punched fibres, bentonite granularity, and thermal treatment on hindering or facilitating the effects of thermal cycles to be investigated.

RÉSUMÉ
Les revêtements en argile géosynthétique (GCL) ont montré une conductivité hydraulique inférieure et, par conséquent, de meilleures performances en tant que matériau barrière que les spécimens non préhydratés à condition qu'une hydratation adéquate se soit produite. Cependant, il existe des preuves que l'exposition aux cycles thermiques quotidiens pourrait inhiber l'hydratation de la bentonite, ce qui est important dans les applications sur le terrain avec une faible couverture du sol ou une installation retardée. Dans cet article, deux GCL déconstruits (fibres aiguilletées coupées) avec de la bentonite granulaire en poudre et fine recouvrant une fondation de sable limoneux de 450 mm d'épaisseur à 16% d'humidité sont soumis à des cycles thermiques quotidiens simulés en laboratoire à 24-60 ° C. Différentes configurations des GCL déconstruits permettent d'étudier les rôles des fibres aiguilletées, la granularité de la bentonite et le traitement thermique pour entraver ou faciliter les effets des cycles thermiques.

1 BACKGROUND

Geosynthetic clay liners (GCLs) have been shown to achieve lower hydraulic conductivity and, hence, better performance as a barrier material, after adequate hydration has occurred compared to non-prehydrated specimens (Petrov and Rowe, 1997; Petrov et al., 1997; Jo et al., 2004).

In landfill liner applications where a GCL would typically be covered by a geomembrane, the source of moisture for the GCL is the underlying foundation soil or subgrade. The factors affecting moisture uptake and the degree of hydration under isothermal conditions for have been investigated by several researchers (Daniel et al., 1997; Rayhani et al., 2011; Anderson et al., 2012).

To better understand the performance of GCLs in the field when left exposed to the sun, the effects of thermal cycles on the hydration of GCLs have also been investigated (Rowe et al. 2011; Hosney et al., 2016). This is applicable to cases such as when the GCLs are not covered in a timely manner during installation and could potentially explain issues such as shrinkage (Brachman et al., 2007) and downslope bentonite erosion (Rowe et al., 2016) which have been observed in the field.

1.1 Granular GCL Under Thermal Cycles

Rowe et al. (2011) performed column hydration tests to study the moisture uptake of three GCLs with granular bentonite from a silty sand subgrade exhumed from the Queen's Experimental Liner Test Site (QUELTS) under laboratory-simulated daily thermal cycles. It was found that, at 16% subgrade water content (W_{FDN}), the GCL equilibrium water content (W_{GCL}) was suppressed to 30% or less than one-third of what was achieved under isothermal conditions (without thermal cycles).

Particularly, GCL 2 – a needle-punched and thermally treated GCL with granular bentonite, scrim-reinforced nonwoven carrier geotextile and woven cover geotextile – had an isothermal to cyclic water content ratio (W_{ISO} / W_{CYC}) of 0.31 at W_{FDN}=16%.

1.2 Downslope Bentonite Erosion

Take et al. (2015) and Rowe et al. (2016) observed significant downslope bentonite erosion in four GCLs with granular bentonite but no significant erosion in two GCLs with powdered bentonite that were covered with a high-density polyethylene geomembrane and exposed to field conditions for over two years at QUELTS.

Low ionic strength water that evaporated from the GCL during daytime heating and condensed on the underside of the geomembrane during nighttime cooling can flow downslope on the surface of the GCL and lead to bentonite loss. One possible reason that the powdered GCLs tested on site such as GCL 6 – needle-punched and thermally treated with woven carrier and nonwoven cover geotextiles – did not develop significant erosion features may be from greater moisture retention when subjected to thermal cycles. Field observations (Figure 1) suggest that GCL 6 had a greater degree of hydration than GCL 2 – the same GCL tested by Rowe et al. (2011) – with granular bentonite.

Figure 1. Photographs of GCL 2 (top) and GCL 6 (bottom) specimens cut from GCL panels at QUELTS after 3.5 months of field exposure when covered only by a black geomembrane. For scale, the specimens are 100 mm x 100 mm.

1.3 Powdered GCL Under Thermal Cycles

Hosney et al. (2016) performed column hydration tests on GCL 2 and GCL 6 placed on silty sand subgrade in the laboratory. The columns were left to hydrate isothermally at room temperature for four weeks before simulated daily thermal cycles were applied for another four weeks. The daily thermal cycles comprised 12 hours of heating (up to 60°C) and 12 hours of cooling.

Prior to thermal cycles, GCL 6 achieved almost twice the gravimetric water content of GCL 2 at equilibrium owing to the greater surface area of its finer-sized bentonite grains; GCL 6 reached W_{GCL}=139% and GCL 2 reached W_{GCL}=77% in four weeks. Upon thermal exposure, GCL 2 immediately started to lose moisture and reached an W_{GCL}=16% within five cycles whereas GCL 6 continued hydrating to an equilibrium W_{GCL}=150% for thirty cycles (**Error! Reference source not found.**). This is consistent with Rowe et al.'s (2016) findings in the field. However, the mechanisms and factors that lead to moisture retention as opposed to moisture loss remain unexplained.

1.4 Objectives

This paper will: (1) explore the index properties of GCL 2 and GCL 6, (2) assess their effects on moisture loss or retention, and (3) introduce a new set of hydration tests conducted on deconstructed GCLs (layers separated by cutting of needle-punched fibres) that allow the effects of each GCL component to be studied.

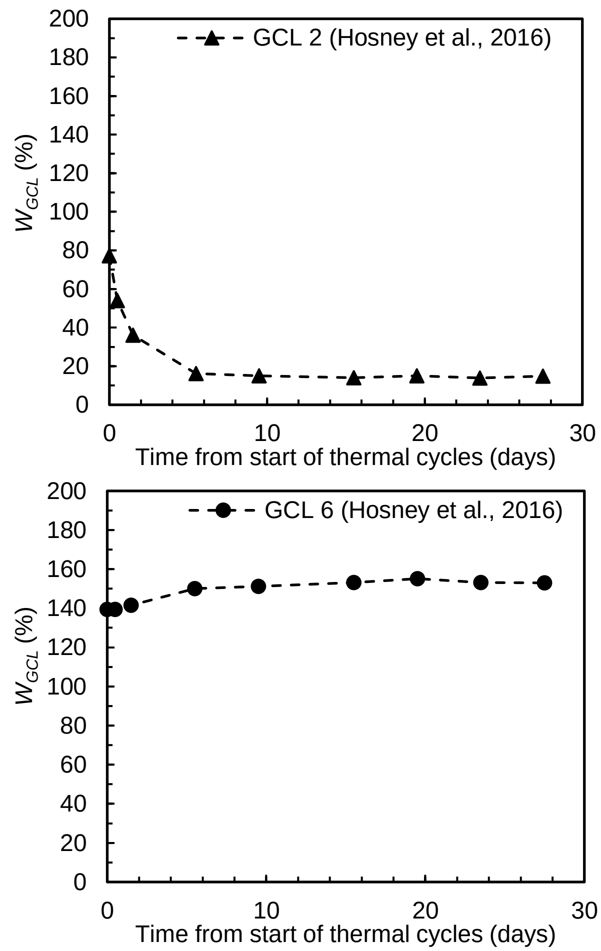

Figure 2. Water content versus time of GCL 2 (top) and GCL 6 (bottom) under daily thermal cycles on 16% subgrade water content and 2 kPa confining stress (adapted from Hosney et al., 2016).

2 METHOD

2.1 Geosynthetic Clay Liners

Two needle-punched and thermally-treated GCLs were investigated. These are listed in Table 1 and denoted as GCL 2 and GCL 6, following the nomenclature used at QUELTS (Brachman et al., 2007; Rowe et al., 2014; Rowe et al., 2016). GCL 2 contained fine granular bentonite encapsulated by a scrim-reinforced nonwoven carrier geotextile and a nonwoven cover geotextile. GCL 6 contained powdered bentonite encapsulated by a woven carrier geotextile and nonwoven cover geotextile.

2.2 Foundation Soil

The foundation or subgrade soil was silty sand that was exhumed from QUELTS in Godfrey, Ontario (Brachman et al., 2007). It had a standard Proctor maximum density of 18.3 kN/m^3 at an optimum water content of 11.4% (Rayhani et al., 2011). The average concentration of Ca^{2+} in the porewater was 230 mg/L (Hosney et al., 2016).

Table 1. Virgin properties of GCL 2 and GCL 6 at QUELTS.

Properties	GCL 2	GCL 6
Needle-punched	Yes	Yes
Thermally Treated	Yes	Yes
Carrier Geotextile[1]	NWSR	W
Cover Geotextile[2]	NW	NW
Bentonite Grain Size	Fine-grained	Powdered

[1]NWSR = nonwoven scrim-reinforced; W = woven
[2]NW = nonwoven

2.3 Procedure

2.3.1 Hydration Test

Following the procedure of Hosney et al. (2016), the test cell consisted of a PVC column with a diameter of 150 mm and a height of 500 mm (Figure 3). The subgrade was compacted to a thickness of 450 mm, in three lifts, and allowed to stand overnight. The 150 mm diameter GCL specimen was then placed on the subgrade and covered with an HDPE geomembrane and 2 kPa seating load. The GCL was allowed to hydrate isothermally at room temperature for a month before the start of heating cycles.

2.3.2 GCL Deconstruction

Some of the tests involved deconstructed GCL specimens. The purpose of deconstruction was to separate the three layers (cover geotextile, bentonite and carrier geotextile) and allow them to be interchanged. Changing one component at a time provides a way to study their individual effects on moisture uptake and loss. Working from one edge to another, the cover geotextile was lifted until the fibres were visible. A blade was inserted underneath the carrier geotextile to cut the fibres with very little disturbance to the bentonite (Figure 4). The GCL layers were kept flat at all times.

Figure 3. Each test consisted of a PVC column wrapped with glass fibre insulation (top) and placed in an insulated wooden box (bottom). (Photo: M. Hosney, Queen's University)

Figure 4. A deconstructed GCL specimen prepared by cutting the fibres between the geotextiles with a long blade.

2.3.3 Index Tests

Atterberg limits, swell index and cation exchange capacity tests were performed according to the following standards: ASTM D4318 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM D5890 Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners, ASTM D7503 Standard Test Method for Measuring the Exchange Complex and Cation Exchange Capacity of Inorganic Fine-Grained Soils.

2.3.4 X-Ray Diffraction (XRD)

Samples of bentonite were taken from the virgin GCL and sieved to passing 0.075 mm (U.S. Sieve No. 200). The samples were scanned with a Panalytical X'Pert Pro MPD Diffractometer with K-beta filtered Co radiation. The results were analyzed using PANAlytical Highscore Pro software. A semi-quantitative estimation of the percentage of minerals in the bentonite was performed using peak properties and reference intensity ratio factors in the International Centre of Diffraction Data (ICDD) PDF2+ database.

3 RESULTS & DISCUSSION

3.1 Atterberg Limits

The Atterberg limits of the bentonite component in GCL 2 and GCL 6 are provided in Table 2. GCL 6 bentonite has a higher plasticity index than GCL 2 bentonite. Both GCLs were well below their liquid limits at any point during the hydration test. At W_{GCL}=140% prior to thermal cycles, GCL 6 was above its plastic limit. At W_{GCL}=77% prior to thermal cycles, GCL 2 was below its plastic limit. This may be a factor in explaining why GCL 2 deformed differently upon drying when exposed to thermal cycles than GCL 6.

Table 2. Preliminary Atterberg limits for GCL 2 and GCL 6, tested as per ASTM D4318.

Atterberg Limits (%)	GCL 2	GCL 6
Plastic Limit	96	57
Liquid Limit	390	485
Plasticity Index	294	423

3.2 Swell Index & Cation Exchange Capacity

The swell index and cation exchange properties of GCL 2 and GCL 6 bentonite are provided in Table 3. GCL 2 had a swell index of 28 ml/2g and cation exchange capacity of 72 cmol/kg which were within typical range for a sodium bentonite. GCL 6 had an even higher swell index at 32 ml/2g and cation exchange capacity of 84cmol/kg, owing to a greater amount of sodium ions in the bentonite. More sodium ions allow for more initial swelling and hence lower hydraulic conductivity to water and greater self-healing capacity. However, the GCL hydraulic conductivity can also increase, over time, due to cation exchange between calcium and magnesium in the pore water and the sodium in the bentonite double layers.

Table 3. Initial swell index, cation exchange capacity and exchangeable cations of GCL 2 and GCL 6, tested as per ASTM D5890 and ASTM D7503.

Properties	GCL 2	GCL 6
Swell Index (ml/2g)	28	32
Cation Exchange Capacity (cmol/kg)	72	84
Exchangeable Cations (%):		
Na	66	83
Ca	25	11
Mg	7	3
K	2	3

3.3 Bentonite Mineralogy

As shown in Table 4, both GCLs contained greater than 90% smectite – the minerals responsible for swelling of the bentonite with hydration. Any slight differences in percentage can be attributed to sample variability and analytical uncertainty. However, the nature of the smectite minerals are still being investigated.

Table 4. Percentage of minerals found in the bentonite component of GCL 2 and GCL 6 via x-ray diffraction.

Mineralogy (%)	GCL 2	GCL 6
Smectite	96	93
Feldspar	2	-
Mica	-	7
Quartz	2	1

3.4 Normalized GCL water content, W / W_{ref}

Hosney et al. (2016) measured the steady-state water content or W_{ref} of GCL 2 and GCL 6 when submerged in DI water under 2 kPa for two months. These values indicate different hydration potentials of the GCLs and were reported to be 119% and 222%, respectively.
Figure 1 was replotted in Figure 5 on a scale of W/W_{ref} versus time. Both GCLs achieve a similar W/W_{ref} at the start of thermal cycles. However, GCL 2 still lost moisture within the first five thermal cycles whereas GCL 6 maintained a W/W_{ref} of 0.65±0.05 over the next thirty cycles. This implies that the hydration potential of the GCLs

did not play a significant role in their moisture retention capacity.

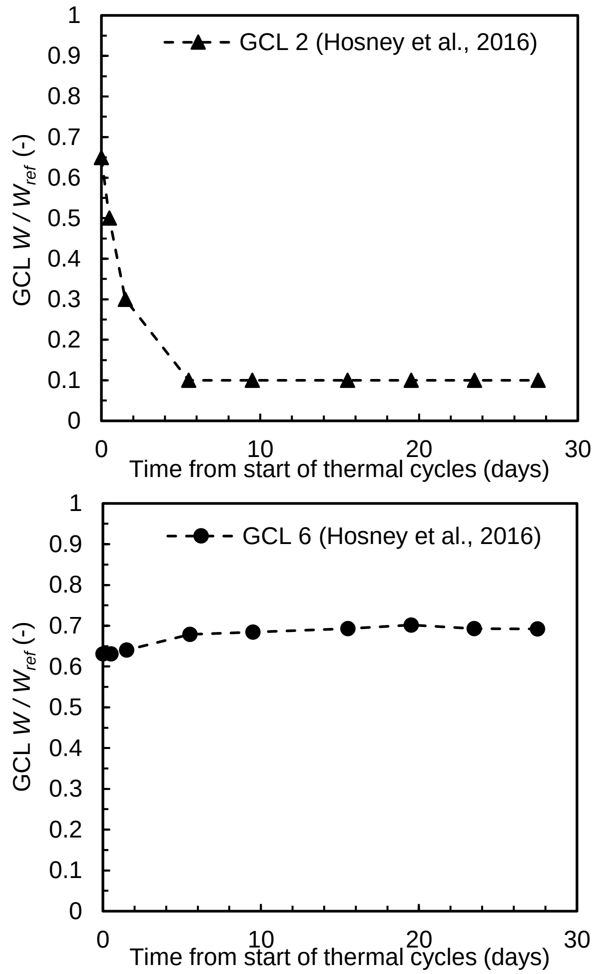

Figure 5. Normalized water content versus time from the start of thermal cycles for GCL 2 (top) and GCL 6 (bottom) (adapted from data in Hosney et al., 2016).

3.5 Effect of GCL Deconstruction

The thermal treatment and needle-punching was lost during the deconstruction process. This allowed the bentonite in GCL 6 to swell more freely and resulted in an increase in bulk thickness from 8.5 mm to 12 mm (measured at the end of isothermal hydration) thereby increasing bulk void ratio by 5% (2.55 to 2.67). GCL 2 did not exhibit a significant difference in thickness under these hydration conditions.

The deconstructed GCL 6 and deconstructed GCL 2 specimens both lost moisture during thermal cycles (Figure 6). Desiccation cracks in the bentonite were also observed in both tests (Figure 7). These tests were also repeated with virgin samples as a control measure and different results to those presented in Figure 2 and Figure 5 were achieved. More work is being done to investigate this.

The loss of moisture retention capacity of GCL 6 during deconstruction suggests that there are more factors at play than bentonite granularity alone. More tests are being performed to identify the roles of needle-punching and thermal treatment, the geotextiles, and the subgrade properties on moisture retention capacity.

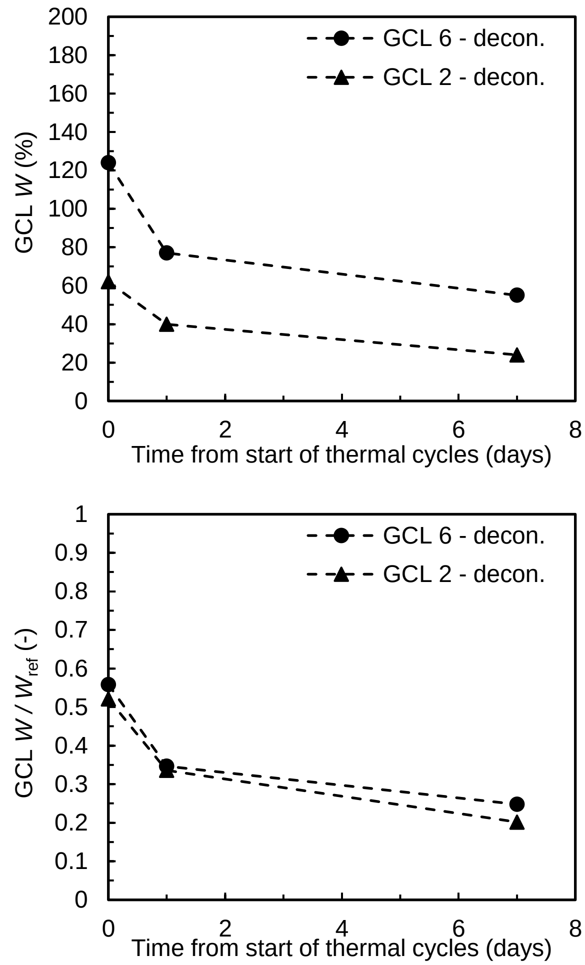

Figure 6. Comparison of gravimetric water content (top) and normalized water content (bottom) from the start of thermal cycles for deconstructed specimens of GCL 2 & 6.

3.6 Effect of Confining Stress on Deconstructed Specimens

Figure 8 presents a test on deconstructed GCL 6 with a 10 kPa confining stress in comparison to 2 kPa. Both tests lose moisture upon exposure to thermal cycles. Since there is no discernable difference in behaviour, this suggests that the confining stress imposed by the fibres has not yet been reached at 10 kPa. More tests are being performed at a higher confining stress. It is postulated that the moisture retention behaviour of the GCL will return at a high enough confining stress but less than 100 kPa.

Figure 7. Desiccation cracks observed in GCL 2 (top) and GCL 6 (bottom) deconstructed specimens after seven daily thermal cycles.

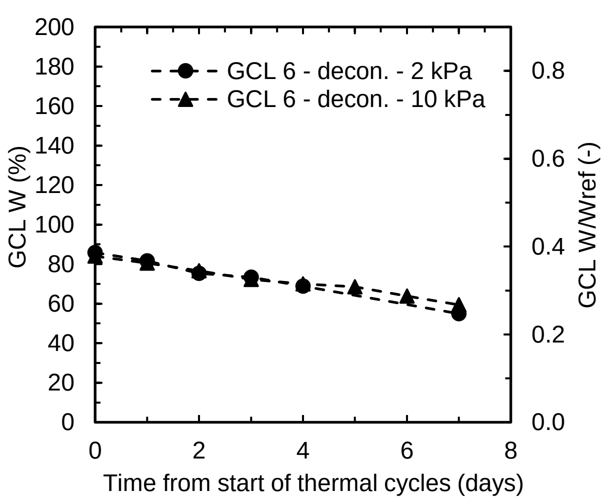

Figure 8. Effect of 10 kPa confining stress on deconstructed specimen of GCL 6.

4 CONCLUSIONS

Based on this preliminary study and for the conditions and materials examined, the following tentatively conclusions were reached.

1. Hosney et al. (2016) showed that virgin specimens of GCL 6 and GCL 2 exhibited different behaviours under thermal cycles: GCL 6 retained its moisture but GCL 2 lost over 50% of its moisture. However, when plotting the data in terms of normalized water content (W/W_{ref}), it can be inferred that both GCLs reached a similar degree of saturation at equilibrium before the start of daily thermal cycles. This suggests that a difference in hydration potential did not affect the observed difference in moisture retention and that other factors are at play.

2. It appears that the loss of the confinement due to needle-punching during the deconstruction process can lead to moisture loss from thermal cycles. Additional testing is required to fully explain the observations.

3. The effect of thermal treatment and needle-punching appears to be equivalent to a confining stress of greater than 10 kPa but smaller than 100 kPa.

5 ACKNOWLEDGEMENT

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