Factors affecting hydration of Geosynthetic Clay Liners in landfill applications

Facteurs influençant l'hydratation des géosynthétiques bentonitiques dans les applications d'enfouissement

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ABSTRACT: The progression of hydration of Geosynthetic Clay liner (GCL) from underlying subsoil was studied for three GCL products under simulated landfill conditions, before and after being covered by municipal solid waste. GCL hydration is shown to be highly dependent on the GCL manufacturing techniques, the grain size distribution and initial moisture content of the subsoil. The hydration behaviour of the GCL was also affected by the exposure conditions in the landfill. Prior to waste placement, the composite liner may be exposed to daily and seasonal thermal cycles for a period of time (weeks to months). These cycles significantly suppressed the hydration of the GCLs and kept the equilibrium moisture content of the GCLs far less than what expected under isothermal conditions at room temperature (22°C). After waste placement, the GCL may experience elevated temperatures that occur during waste decomposition in municipal solid waste landfills. Results indicated that as the temperature increased (from 22 to 55°C), the final equilibrium moisture content decreased, from about 96% at room temperature to about 14% at 55°C. Moreover, the normal stress of 2 to 5 kPa was shown to induce an adequately high rate of hydration and the maximum equilibrium moisture content.

RÉSUMÉ: La progression de l'hydratation de Géosynthétique Bentonique (GSB) du sol a été étudiée pour trois GSB produits dans des conditions simulées d'enfouissement, avant et après avoir été recouverts par des déchets solides municipaux. Hydratation est dépendante des techniques de fabrication GSB, la distribution de granulométrie et la teneur en humidité initiale du sol. Hydratation de GSB a également été affectée par les conditions d'exposition d'enfouissement. Avant déposer des déchets, le revêtement composite peut être exposé à des cycles journaliers et saisonniers thermiques pendant une période de temps (quelques semaines ou mois). Ces cycles ont supprimé l'hydratation des GSBs de manière sévère et ont gardé la teneur en humidité d'équilibre des GSB beaucoup moins ce que prévue dans des conditions isothermes à température ambiante (22°C). Après déposer des déchets, le GSB peut subir des températures élevées qui se produisent lors de la décomposition des déchets dans les sites d'enfouissement des déchets solides municipaux. Les résultats ont montré que lorsque la température a été augmentée (de 22 à 55 °C) le contenu d'humidité d'équilibre final a été diminué de manière sévère, de 96% à la température ambiante à environ 14% à 55 °C. En outre, la pression normale de 2 à 5 kPa a été montrée de causer un taux suffisamment élevé d'hydratation et de la teneur maximale en humidité d'équilibre.

KEYWORDS: Geosynthetic Clay Liners (GCL), hydration, thermal gradient, normal stress

1 INTRODUCTION

Geosynthetic Clay Liners (GCLs) are utilized as part of a barrier system while covered by a geomembrane liner to prevent the escape of contaminants form solid waste landfills (Rowe 2005, Benson et al. 2010, Gates and Bouazza 2010). The GCLs typically consist of a core of bentonite encapsulated by nonwoven or woven geotextiles. The hydraulic performance of the GCL depends on the degree of hydration from the pore water of the underlying soil prior to contact with leachate (Rowe 2005). Previous studies have shown that the hydraulic performance of the GCL is influenced by the GCL manufacturing techniques as well as the grain size distribution, and initial moisture content of the subsoil (e.g., Chevrier et al. 2012, Beddoe et al. 2010 and 2011, Rayhani et al. 2011). Beddoe et al. (2011) showed that the GCL manufacturing techniques affect the Water Retention Curve (WRC) of the GCL, indicating that the hydration of the GCL depends on the WRCs of both GCL and subsoil. Also, a reduction of approximately 12.5 % in the final moisture content of a needle-punched GCL with sand subsoil was observed as the initial normal stress of 7 KPa was increased to 28.2 KPa (Chevrier et al. 2012).

Composite liners in landfill applications might be left exposed to daily thermal cycles induced by solar radiation for a period of time prior to waste placement. Rowe et al. (2011) reported that the daily thermal cycles significantly suppressed the rate of hydration of GCLs placed on silty sand subsoil. Also, constant thermal gradients applied to the GCLs placed over subsoil have shown to induce loss of moisture and, hence, desiccation and cracking of the GCLs. The temperature at the base of bioreactor landfills and also the Municipal Solid Waste (MSW) landfills where the Leachate Collection System (LCS) has failed could increase up to 40-60ºC after placing the waste (Azad et al. 2011). Furthermore, the temperature within the aquifer is significantly lower which in turn causes temperature gradients. This induces downward flux of vapor (diffusion) from the GCL to the subsoil which causes the moisture loss of GCLs and the desiccation cracking of the GCLs (Barclay and Rayhani 2012, Azad et al. 2011, Southen and Rowe 2005). This paper summarizes the results of an extensive testing program which was initiated to evaluate the effect of field conditions such as the elevated temperatures and normal stresses on the GCL hydration from different underlying subsoils. Also, the effect of the GCL manufacturing techniques and the initial water content of the subsoil are investigated.

2 EXPERIMENTAL PROGRAM

This research analyzes the hydration behavior of the GCL from underlying soil under different field exposure conditions, including daily thermal cycles before waste placement, and constant temperatures induced by the waste decomposition after waste placement. Also, the effect of normal stresses provided by the overlying layers (e.g., Leachate Collection System (LCS), cover soil) is investigated. The hydration progression of three GCL products (GCL1, GCL2, and GCL3) which have significantly different manufacturing techniques has been evaluated in this study. Ontario Leda clay (CL in USCS classification system, ASTM D2487), clayey sand (SC), silty sand (SM), and ordinary construction sand (SP) were used to investigate the effect of the subsoil grain size distribution on GCL hydration. The hydration process was monitored by measuring the gravimetric moisture content (i.e. mass of water/mass of dry material) of the GCL up to 40 weeks.

2.1 *GCL properties*

GCL 1 and GCL2 contained fine granular sodium bentonite with D_{50} of 0.35 mm while GCL3 was coarse granular with D_{50} of 1 mm. All GCLs had NW cover geotextiles. The main difference of the GCLs was the connection layer and also the type of the carrier geotextile (Table 1). GCL1 and GCL2 had similar swell and plasticity indices of 24 ml/ 2g min. and 216% (ASTM D 4318), respectively. GCL3 had a swell index of 23 ml/ 2g min. and plasticity index of 262%. The water retention curves for these GCLs have been presented by Beddoe et al. (2011). The submerged moisture content, i.e., the maximum gravimetric moisture content which the GCL could attain while immersed in water is also given in Table 1.

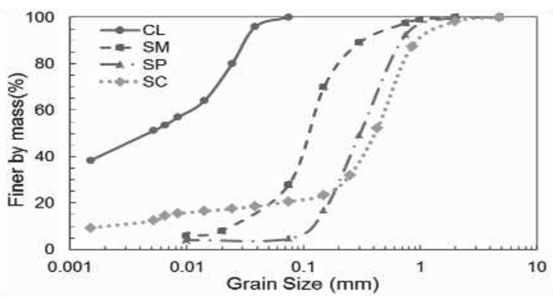
Table 1. GCL properties

GCL	Total dry mass/area (g/m^2)	Carrier/ Cover Geotextile	Connection Layer	Submerged Moisture Content
1	4555-4988	W/ NW	NPTT	150±10
2	3312-4006	SRNW/ NW	NPTT	118±5
3	4499-5295	W/ NW	NP	190±10

W = Woven, NW = Nonwoven, SRNW = Scrim reinforced nonwoven, NP = Needle punched, NPTT = Needle punched and thermally treated.

2.2 *Soil properties*

The basic geotechnical properties of the four subsoils were determined through laboratory testing (Figure 1). The sand (SP), silty sand (SM), and clayey sand (SC) contained 5%, 35%, and 21% fines passing through the 0.075 mm sieve, respectively. The plasticity indices of the clay and the fine portion of clayey sand were measured at 21.6%, and 4%, respectively (ASTM D 4318). The maximum dry densities of the sand, silty sand, clayey sand, and clay were measured at 1.68, 1.83, 1.96, and 1.43 Mg/m^3 with the corresponding optimum moisture contents of 10%, 11.4%, 11.3%, and 28.3%, respectively (ASTM D 698).



(a)

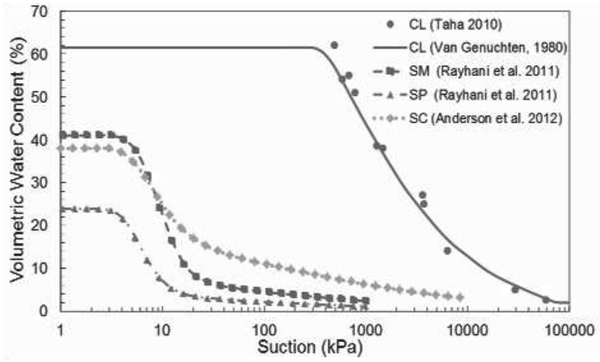


Figure 1. (a) Grain size distribution and (b) matric suction curves for the subsoils examined.

2.3 *Sample preparation*

Figure 2 demonstrates the diagram of instrumented test cells used for simulating GCL hydration from subsoil. To simulate the profile of a composite liner, the soil under examination was placed in cells having a diameter of 150 mm and a height of up to 500 mm. Tap water with an average calcium concentration of 40 mg/L was mixed with bulk samples of dried soils to the wet of optimum moisture content (w_{opt} + 2%). Some soil samples were watered to other gravimetric moisture content to evaluate the effect of the initial moisture content (10%). The soil samples were wrapped in airtight plastic bags to cure overnight. Afterwards, the soil was compacted into the PVC cylinders in five layers with a final height of 250 mm, and a dry density corresponding to approximately 90% of the maximum dry density. The GCL sample was placed over the subsoil and overlain by geomembrane. A steel seating block with a known weight corresponding to a specific level of normal stress (0-8 kPa) was placed on the liner. The test cells were closed and sealed to prevent any loss of moisture, and were opened weekly to determine the mass before returning them to the cells.

2.4 *Experimental procedure*

In order to investigate the effect of constant temperature on GCL hydration after waste deposition, heating blankets set to the temperatures of 35, 45, and 55°C were placed on top of a series of test cells. Some cells were left in room temperature (22°±2C) for isothermal and control experiments. Also, heat was applied for 8 hours to the top of some cells before they were subsequently left in room temperature (22°C) for 16 hours to simulate daily thermal (heating and cooling) cycles induced by solar radiation. The sides of all cells were surrounded by fibreglass insulation while their bottom was maintained at room temperature to simulate vertical thermal gradients developed in the field. Also, after 6 weeks of daily thermal cycles, the heating cycles were brought to a halt for a period of 6 weeks to simulate seasonal cooling periods before they were resumed.

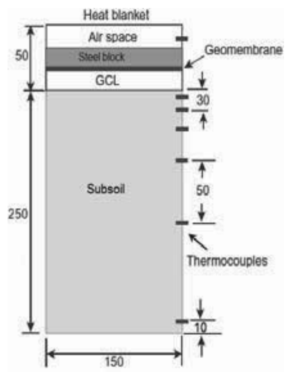


Figure 2. Diagram of instrumented test cells used for simulating GCL hydration from subsoil (numbers in mm)

Moreover, the normal stresses of 0, 0.5, 1, 2, 5, and 8 kPa were applied to some GCL specimens to evaluate the effect of the normal stress on the GCL hydration.

3 RESULTS AND DISCUSSION

The evolution of GCL hydration was monitored up to 40 weeks. In this paper, the effect of daily and seasonal thermal cycles, elevated constant temperatures, and external loading as well as the GCL manufacturing techniques and grain size distribution of subsoil on GCL hydration is discussed.

3.1 *Subsoil grain size distribution*

GCLs are placed over different subsoils depending on the availability of the type of the soil where a solid waste landfill is constructed. As mentioned earlier, the GCL hydration depends on the water retention curves of both subsoil and the GCL (Beddoe et al. 2011). In order to investigate this phenomenon, the isothermal hydration progressions of GCL2 from four different subsoils (SP, SM, SC, and CL) at 10% initial gravimetric moisture content were juxtaposed for comparison (Figure 3). GCL2 in close contact with clay subsoil stabilized with the equilibrium gravimetric moisture content of 48% while this value ranged between 79 to 88% for the other subsoils.

The rate of moisture uptake from the clay subsoil was also found to be lower compared to the other subsoils (SP, SC, and SM). As shown in Figure 3, the gravimetric moisture content after the first week for the GCL sample in close contact with clay (13%) subsoil was less than the other sandy subsoils which varied from 31% to 44%. This could be attributed to the fact that the difference between the suction of the GCL and the subsoil decreased as the portion of fine particles within the subsoil increased which in turn induced lower rate of hydration and equilibrium moisture content for the GCL.

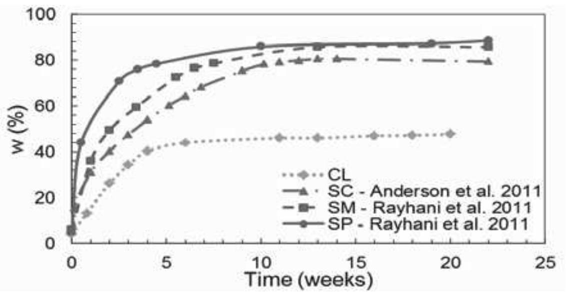


Figure 3. Hydration response of GCL2 from different subsoils at w_{fdn}=10% initial moisture content (CL: Clay, SC: clayey sand, SM: silty sand, SP: poorly graded sand)

3.2 *Daily and Seasonal Thermal Cycles*

Figure 4 compares the hydration progression of GCL2 from the clay subsoil at 30% initial gravimetric moisture content under the simulated daily thermal cycles with that of the isothermal condition (22°C). The GCL sample stabilized at the equilibrium gravimetric moisture content of 14% (week 6) while subjected to daily thermal cycles. Comparatively, the same GCL experienced the equilibrium moisture content of 61% under isothermal condition. Similarly, the results for GCL3 indicated that the equilibrium moisture content under thermal cycles was approximately 15% of the moisture content expected under isothermal conditions. As shown in Figure 4, a meager increase of 5% in moisture content was observed after cooling in each thermal cycle; however, the equilibrium moisture content under the daily thermal cycle was significantly suppressed and was much less than that attained under isothermal condition.

The daily thermal cycles were also stopped for a period of 6 weeks to simulate and evaluate the effect of seasonal cooling cycle on the GCL hydration. This led to an increase of the moisture content from 18% at the end of the daily thermal cycle period (week 6) to 44% at the termination of the cooling period (week 12). However, the moisture content of the GCL sample dropped to its initial level as the thermal cycles resumed. This shows that cooling periods followed by daily thermal cycles, which could normally occur during winter, may not guarantee the sustainable hydration of the GCL.

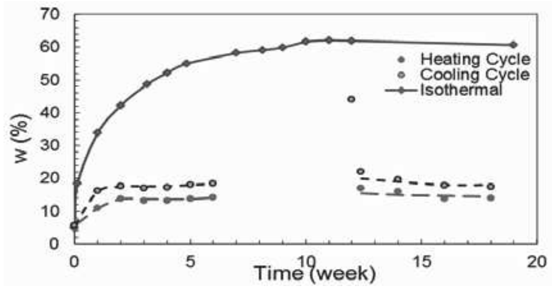


Figure 4. Effect of daily and seasonal thermal cycles on hydration of GCL2 (subsoil=CL, w_{fdn}=30%) (Sarabiam and Rayhani, 2012)

3.3 *GCL manufacturing techniques*

GCL manufacturing process was shown to affect the swelling of the bentonite upon hydration, and in turn the hydraulic conductivity of the GCL by controlling the level of constraint between the carrier and cover geotextiles (e.g. Lake and Rowe 2000, Beddoe et al. 2011). Particularly, Beddoe et al. 2011 reported that the type of the connection layer significantly influenced the WRC of GCLs in low ranges of suctions (i.e. high values of moisture content).

In order to compare the effect of GCL manufacturing techniques on the degree of hydration of GCL, the normalized equilibrium moisture content defined as the ratio of equilibrium moisture content of the GCL to its submerged moisture content (w/w_{ref}) was utilized. GCL3 demonstrated the least effective anchorage of geotextiles inducing the least normalized hydration values for all subsoil moisture contets. The normalized equilibrium moisture content of GCL1 which was thermally treated was 5-10% less than GCL2. GCL2 reached the highest normalized moisture content and in turn degree of hydration (Figure 5). The improved anchorage of the thermally treated scrim-reinforced GCL provided less swelling and final bulk void ratio which is expected to improve the hydraulic performance. Moreover, there was a positive correlation between the equilibrium moisture content of the GCL and the subsoil initial moisture content due to higher levels of suction at the GCL-subsoil interface in higher subsoil moisture contents (Figure 5).

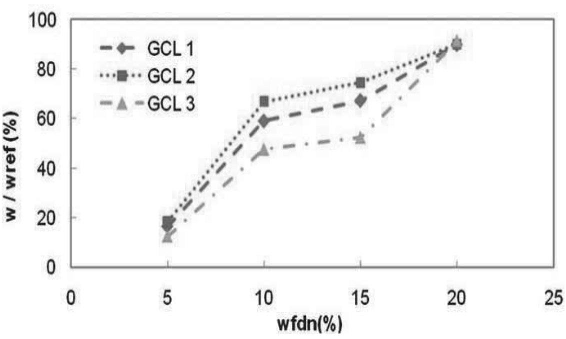


Figure 5. Normalized moisture uptake (w/wref) for all GCLs from clayey sand (SC) subsoil with different initial moisture contents (Barclay and Rayhani 2012) (w: equilibrium moisture content)

3.4 *Constant temperature*

In order to investigate the effect of the high constant temperatures induced by waste biodegradation, the hydration of GCL samples while subjected to the constant temperatures of

22, 25, 45, and 55°C were compared. The results demonstrated that the rate of hydration of both GCLs was significantly suppressed after 1 day of hydration while exposed to elevated temperatures, as opposed to continuous moisture uptake for months under the isothermal condition (22°C). Figure 6 demonstrates the hydration of GCL 2 and GCL3 from either sand or clay subsoil for all the aforementioned temperatures. The addition of 35°C heat source significantly decreased the average equilibrium moisture content (of all experiments) by 3/4, from an average value of 96 to 24%. Also, the GCL average equilibrium moisture content reduced from 24 to 14% as the applied constant temperature increased from 35 to 55°C. These results are notably similar to certain previous findings on GCL hydration under daily thermal cycles discussed above. The thermal gradients initiated by biodegradation of waste after depositing the waste or solar radiation before waste placement could induce severe loss of moisture in GCL and, hence, higher hydraulic conductivity.

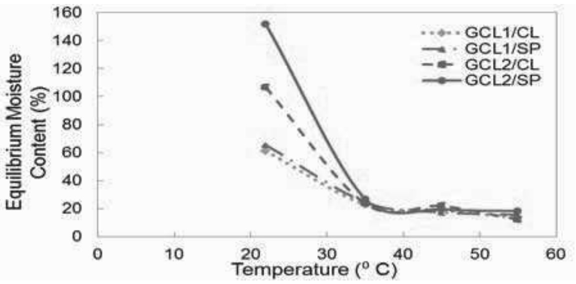


Figure 6. GCL moisture uptake vs. temperature (Barclay & Rayhani, 2012)

3.5 *External loading*

The level of normal stress provided by the leachate collection system or the cover soil could affect the swelling characteristics and hence the degree of hydration of the GCL. Figure 7 demonstrates the variation of equilibrium moisture content versus the normal stress for 4 different conditions. In general, the normal stress of 2-5 (for a typical leachate collection system) induced the highest equilibrium moisture uptake. The rate of moisture uptake also increased significantly as the level of the normal stress increased. GCL2 with sand subsoil (12% moisture content) achieved 62% gravimetric moisture content under 8 kPa normal stress after one week of hydration which was significantly more than that of the unconfined condition (36%). The normal stress enhanced the contact between the GCL and the subsoil leading to significantly higher rate of hydration as well as more equilibrium moisture content.

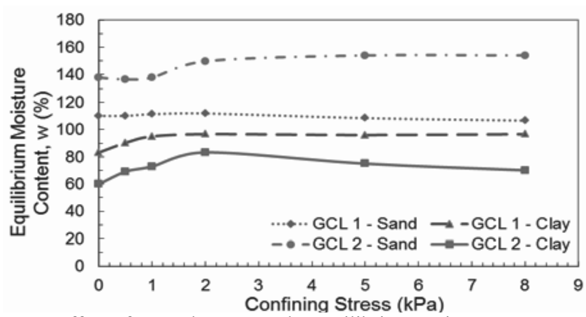


Figure 7. Effect of normal stress on the equilibrium moisture content

4 CONCLUSIONS

The hydration of three GCL different products from the subsoil pore water under simulated landfill conditions was studied. The following conclusion points could be extracted:

- The hydration potential of the GCL was found to be dependent on the difference between the suction of the GCL and the subsoil. The small grain size and high levels of matric suction associated with clay compared to other sandy soils was seen a limiting factor for the GCL hydration.
- The thermally treated, scrim-reinforced GCL (GCL2) demonstrated higher rate and degree of hydration compared to the other GCL product under similar conditions mainly due to the better anchorage of the connection layer against swelling of bentonite upon hydration.
- Thermal cycles severely suppressed the moisture uptake of the GCL to as low as 15% of the moisture content observed under isothermal conditions. Seasonal cooling was shown to not guarantee sustainable hydration of the GCL provided that the GCL is subsequently exposed to daily thermal cycles.
- Elevated constant temperatures at the bottom of landfills could significantly decrease the rate of hydration, the equilibrium moisture content of the GCL, and consequently the hydraulic performance of the GCLs.
- Employing the cover soil or the construction of leachate collection system could provide the sufficient normal stress (2-5 kPa) for an adequately high rate of hydration as well as degree of hydration.

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