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Effect of temperature on hydration of geosynthetic clay liners in landfills

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Abstract

Geosynthetic clay liners (GCLs) have gained popularity as a barrier system in modern landfill construction. As such, it is depended upon to provide a level of impermeability to prevent the escape of contaminants into the surrounding soil and groundwater. It has been proven that a GCL's hydraulic conductivity is closely related to its moisture content. GCLs are known to absorb moisture from the underlying soil after installation. In a landfill, temperatures near the liner can reach upwards of 55ºC. The effect of these elevated temperatures on the hydration process of the GCL was determined for two types of GCL over two types of subsoil: sand and clay. It was found that elevated temperatures prevented the GCL from reaching moisture content levels that would be acceptable in a real-life scenario. Temperatures in landfills could be expected to cause a GCL to reach a moisture equilibrium at roughly 16% gravimetric moisture content, where GCL at room temperature would reach higher than 100% gravimetric moisture content. The significant difference in moisture equilibrium of GCLs at different temperatures may suggest that the heat naturally produced in landfills could negatively affect the liner's hydraulic performance. The importance of allowing a GCL to properly hydrate before heat exposure must be better understood in order to minimize the potential negative effect of a landfill on our environment and our livelihood. This study also confirmed that the hydration potential of GCL depends on the method of GCL manufacture and the subsoil characteristics.

Keywords

Geosynthetic clay liners (GCL), hydration, temperature, landfill barrier system

Introduction

Modern municipal solid waste landfills are designed and regulated in order to minimize the landfill's environmental impact. One way landfills jeopardize the environment is the possibility of leachate escaping into the surrounding soil or groundwater. Precautions must be taken in designing and constructing these landfills to prevent this contamination. Thus, reliable landfill liners have become a necessity in today's society.

Geosynthetic clay liner (GCL) has been adopted recently by the industry as a component of a composite landfill liner. It is a composite fabric consisting of a fine layer of bentonite clay sandwiched between two geotextile fabrics. The GCL is laid directly on the underlying subsoil, where it will will absorb the soil's moisture. Once sufficiently hydrated, the bentonite layer is able to effectively prevent the flow of leachate from the landfill. Owing to its effectiveness and ease of installation, GCLs are often preferable to other liner materials. It is, however, a relatively new material and exhaustive testing has not yet been performed to assess the GCL's ability to perform under all possible site conditions.

Owing to heat-producing physical, biological and chemical processes that occur during waste decomposition in municipal solid waste landfills, the temperature of the waste is often elevated compared with the ambient temperature. For instance, it was reported that North American landfills have been found to reach temperatures higher than 55°C, with the highest heat being generated near the bottom of the landfill close to the liner (Hanson et al., 2010; Rowe et al., 2010; Yesiller et al., 2011). Investigations into the dangers of exposing GCLs to heat after hydration have also concluded that thermal gradients, along with a dry subsoil, could lead to desiccation cracking in the GCL and that this risk increased as the temperature gradient increased (Southen and Rowe, 2005). The diffusion coefficient and hydraulic conductivity in a liner at 35°C are shown to be 100% and 80% higher, respectively, than at 10°C (Rowe, 1998). Though temperature is a factor in the desiccation of a mineral landfill liner, it has been found that the relationship is complex and there are many other contributing factors, especially the moisture content and the matric suction potential of the GCL and the underlying subsoil (Doll, 1997).

The effects of temperature on the swelling behaviour of clay soils have been investigated by many researchers (e.g. Romero et al., 2005; Villar and Lloret, 2004). Reduction in swelling of compacted bentonite was reported by Romero et al. (2005) as the

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temperature increased from 30°C to 80°C. This reduction in water retention behavior was attributed to reduction in surface tension of water, as well as the alteration of clay fabric and intra-aggregate fluid chemistry. Increase in temperature reduces the amount of vapor (or water) adsorbed by the bentonite surface (Myers, 1991). This reduction in hydration was found to be more significant at lower suction (Romero et al., 2001; Villar et al., 2005) because of cumulative effects between the low capability of bentonite to absorb water at higher temperature (or decrease in hydration force) and the effect of surface tension of water (Grant and Salehzadeh, 1996). Similarly, an increase in permeability of compacted soil was observed with the increase in temperature due to decrease in water viscosity (Villar and Lloret, 2004).

Upon investigation of the effects that daily thermal cycles may have on the hydration of GCL it was determined that exposure to simulated daily thermal cycles along with adverse subsoil conditions can limit the equilibrium moisture content of GCL to as little as 15% of that under isothermal conditions at room temperature (Rowe et al., 2011). It has also been reported that the range of subsoil moisture content that will allow sufficient hydration is relatively narrow. When placed on subsoil with moisture contents near field capacity, GCL absorbed roughly four times more moisture than when placed on subsoil with residual moisture content (near the wilting point). Other factors that have been shown to affect GCL hydration include the GCL design and manufacturing processes, subsoil grain size distribution and the presence of an overburden stress (Rayhani et al., 2011).

Clay mineralogy plays a major role in hydraulic and strength behaviour of clay soils. Bentonite clay possesses low hydraulic conductivity and a high adsorption capacity (Sivapullaiah et al., 2000). However, sodium-dominated smectite in bentonite is shown to be more sensitive to temperature changes than kaolinite-dominated soil (Jefferson and Rogers, 1998). For smectitic clay the liquid limit increases with temperature, whereas a slight reduction occurs with kaolinite dominant clay. A similar increase in liquid limit of high plastic clay (CH) clay with temperature was reported by Hamutcu et al. (2008).

Upon consideration of these previous findings the possibility becomes clear that constant heat generated in MSW landfills could adversely affect the hydration potential of GCL. This concern warrants an investigation into the effects of constant heat exposure to GCL in typical landfill settings. Therefore, the goal of the research presented in this article is to better understand the effects of this heat on the hydration process of the GCL.

Materials and Methods

This research analyzes the hydration behaviour of GCL from underlying soil at different temperatures. Two types of GCL products (GCL1 and GCL2) were analyzed on two types of soil. Ontario Leda clay (CL) and ordinary construction sand (SP) were used in this research to compare the effect that the subsoil properties have on the GCL hydration process. This process was monitored by measurement of the GCL's gravimetric moisture content (i.e. mass of water/mass of dry material). The experimental research consists of four experiments performed at different elevated temperatures ranging from 22–55ºC. In each experiment, four specimens with different GCL–soil combinations were analyzed: GCL1/sand, GCL1/clay, GCL2/sand and GCL2/clay.

GCL types and properties

Table 1 outlines some of the properties of GCL1 and GCL2 used in this study. Both GCLs consisted of an air dry sodium bentonite with similar swelling index (23–24 ml/2g). GCL1 contained fine-grained bentonite with a D_{50} of about 0.35 mm, while GCL2 contained coarse, granular bentonite with a D_{50} of 1.0 mm. The plasticity index of bentonite was measured at about 216% for GCL1 and about 262% for GCL2 (ASTM D 4318, 2005). The average mass per unit area of GCL1 was less (4280 g/m^2) than that of GCL2 (5250 g/m^2).

Soil properties

The basic geotechnical properties of the two underlying soils in this study have been determined through laboratory testing. Of specific importance is grain size distribution, matric suction potential and the optimum water content (Figure 1). The sand (SP in in Unified Soil Classification System (USCS) classification system; ASTM D2487, 2005) contained approximately 5% non-plastic fines passing through the 0.075-mm sieve. The plasticity index of the clay (CL) was found to be 21.6% (ASTM D4318, 2005). It was found that the sand and clay had an optimum moisture content of 10% and 28% respectively. The maximum dry

Table 1. Geosynthetic clay liner (GCL) properties.

Material	Property	GCL1	GCL2
Bentonite	Average size (D_{50})	0.35 mm	1.0 mm
	Plasticity index	216%	262%
	Swell index	24 ml/2g min	23 ml/2g min
GCL	Method of manufacture	Needle-punched, nonwoven geotextiles with thermally-fused scrim reinforcement	Needle-punched, woven and nonwoven geotextiles
	Average mass per unit area	4280	5250
	Average peel strength	260 ± 17 (N)	204 ± 35 (N)
	Submerged moisture content	118 ± 5%	190 ± 10%

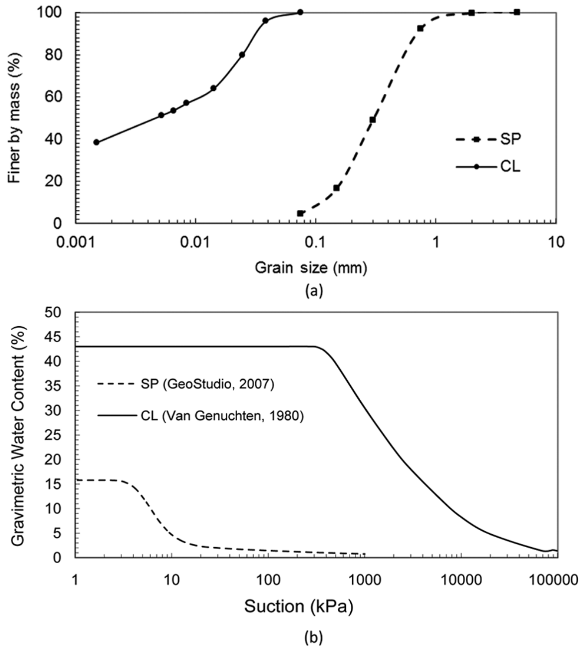

Figure 1. (a) Grain size distribution and (b) estimated matric suction curves for sand and clay subvsoils (CL: low plastic clay, SP: poorly graded sand).

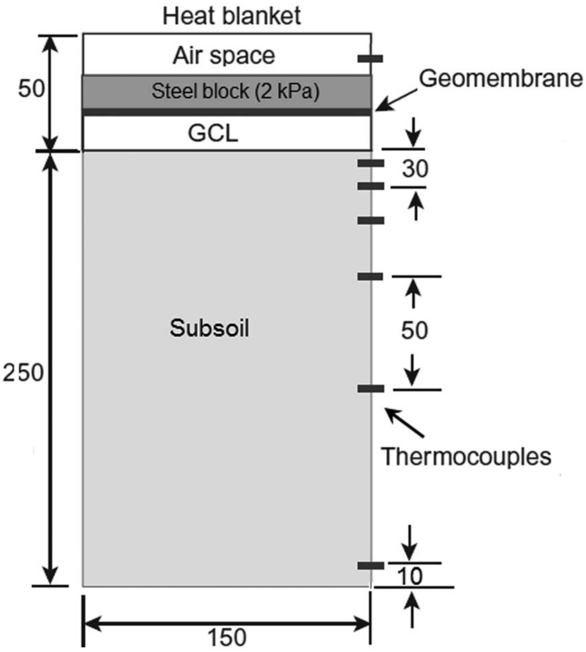

Figure 2. Diagram of instrumented test cells used for simulating geosynthetic clay liner (GCL) hydration from subsoil (numbers in mm).

densities of the sand and clay were determined at 1.68 mg/m^3 and 1.43 mg/m^3 respectively (ASTM D698, 2005). The matric suction of the soils at optimum moisture content was found to be roughly 6 kPa for sand and 1200 kPa for clay (Figure 1b). The water retention curves (WRC) were estimated using the grain size distribution and saturated water content of the soil.

Experiment cells

In order to simulate a real composite liner profile, the GCL and soil under examination were contained in a polyvinyl chloride (PVC) cell. These cells were cylindrical and roughly 300 mm tall with a 150 mm radius. The bottom of each cell was sealed with a PVC disk and epoxy or rubber cement. After the cells were assembled they were sealed with a metal lid using silicone caulking to provide a thermally permissive, but watertight, closed system. Each cell contained approximately 250 mm of compacted soil under a GCL specimen and a plastic membrane. In order to ensure contact between the soil and the GCL, a confining pressure of about 2 kPa was applied by placing a static weight on top of the simulated composite liner. For each experiment one cell was instrumented with thermocouples placed at different depths in the column to enable measurement of the temperature profile of the system (see Figure 2).

Sample preparation

To prepare the experiment cells, tap water with an average calcium concentration of 40 mg/l was added to the relatively dry soil until the soil reached wet of optimum (w_{opt} + 2%). Then, the soil was allowed to cure in airtight plastic bags overnight to ensure uniform moisture distribution. The soil was then compacted in five layers into the cells (90% of the maximum dry density). At each compaction layer a specimen of soil was obtained to measure the moisture content of the soil throughout the cell.

Using a template, circular specimens of GCL were cut from uniform areas in a roll of unused GCL and weighed for consistency. These specimens were placed on top of the soil under a membrane and a small confining pressure (2 kPa). This small stress was applied on top of the GCL specimens to ensure contact between the subsoil and the GCL, and to encourage GCL hydration through pore-to-pore water transfer (liquid phase). The 2 kPa of stress was selected as it is a large enough value of stress to be effective at maintaining contact between the GCL and the subsoil during hydration (Rayhani et al., 2011).

Experimental procedure

The cells were left exposed to the ambient air at 22±2 °C for the control experiment. For experiments 2, 3 and 4 the cells were placed in an insulated box; the sides of the cells were surrounded by fiberglass insulation leaving only the metal lids exposed to provide one dimensional thermal transfer conditions. An electric heating blanket was placed on top of the cells and connected to a controller, which was set to the experiment temperature; experiment 2 at 35°C, experiment 3 at 45°C and experiment 4 at 55°C. Thermocouples were used to measure temperature at six elevations in the soil and one in the headspace above the steel block

Over several weeks, different data were gathered periodically. First, the temperature profile was measured using the thermocouples in the instrumented cell; then, all of the cells were opened and the mass and thickness of each GCL specimen was recorded. The mass of the GCL was used in conjunction with the initial GCL moisture content to determine the moisture content of the

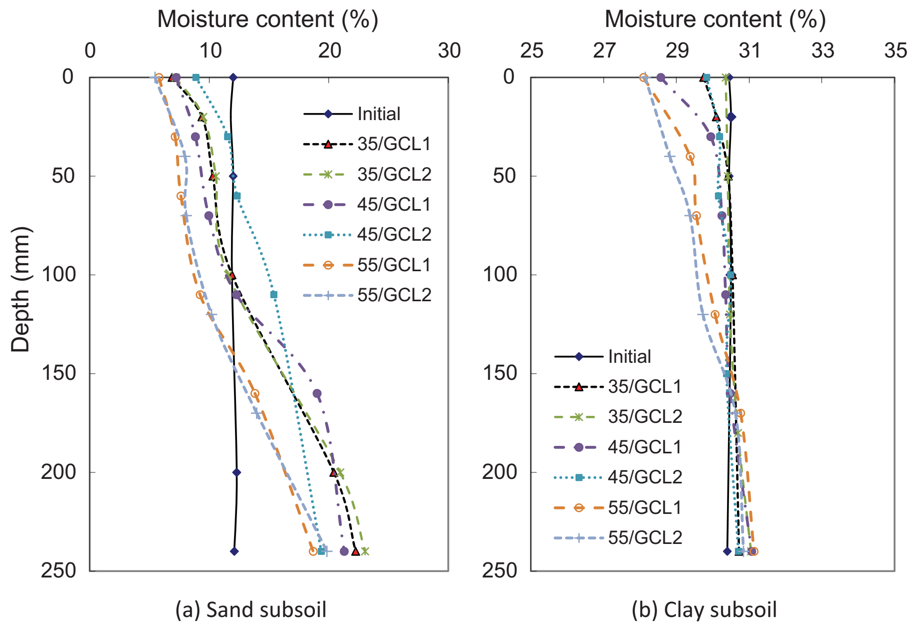

Figure 3. Moisture profile of sand and clay subsoils after termination of experiment cells.

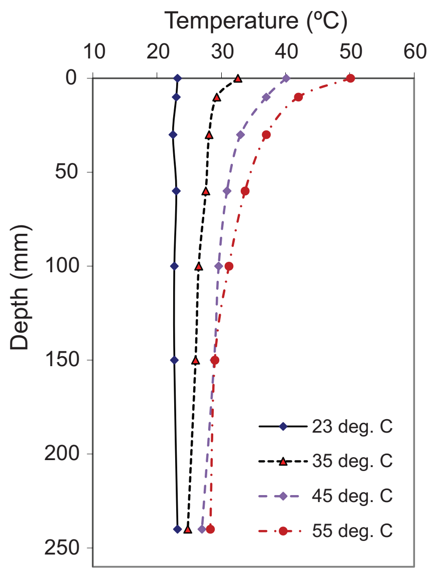

Figure 4. Equilibrium temperature profile of the test cells.

specimens. The cells were then resealed and replaced in the box, having been removed from their environmental conditions for less than 10 mins. The experiment for each cell was terminated when the equilibrium moisture content between the GCL and the subsoil was achieved. Upon termination of an experiment each GCL specimen mass and thickness was measured for a final time. As the soil was removed from the cell, soil specimens were taken for soil moisture content measurement at increasing depths to determine the moisture profile of the soil.

Results

Subsoil moisture content profile

Upon assembly of the cells, the soil was found to have a relatively constant initial moisture content within a range of ± 2% (i.e. 12% for sand and 30% for clay). However, this was expected to change after settling and heat exposure. Upon termination of the experiments, it was found that the sand was much drier at the surface than deeper in the soil (Figure 3a). The moisture was seen to migrate downwards through the sand leaving the soil with a moisture gradient that increased with depth. This effect was not demonstrated in the clay, which, upon termination, was seen to have a relatively constant moisture profile (Figure 3b). The difference between the responses of the two soils is likely due to their differing field capacity moisture content. Because the field capacity of clay is higher, moisture propagates less freely through the soil. It is also apparent that temperature differences in the range of 35°C to 55°C had little-to-no effect on the terminal soil moisture profile. It is also apparent that the soil responded independently of the GCL type.

Temperature profile

Using the thermocouples installed in the instrumented cell, the temperature of the GCL and soil was recorded at different depths. It was noted that the temperature was greatest at the GCL level, where temperatures approached those of the heating blanket, and is plotted in the temperature profile of Figure 4 at depth of 0 mm. The temperature measured in the soil decreased as depth increased (Figure 4). The thermal change within the subsoil was shown to be a factor of the applied temperature boundary conditions. For the case in which cells were exposed to a temperature of 35°C, the majority of the thermal change occurred in the upper 20 mm of the soil, while variation in the thermal profile was observed at levels deeper than 100 mm for the 55°C experiment.

GCL moisture content

Figure 5 shows the evolution of GCL moisture content over time for all experiments. For the control experiment at ambient

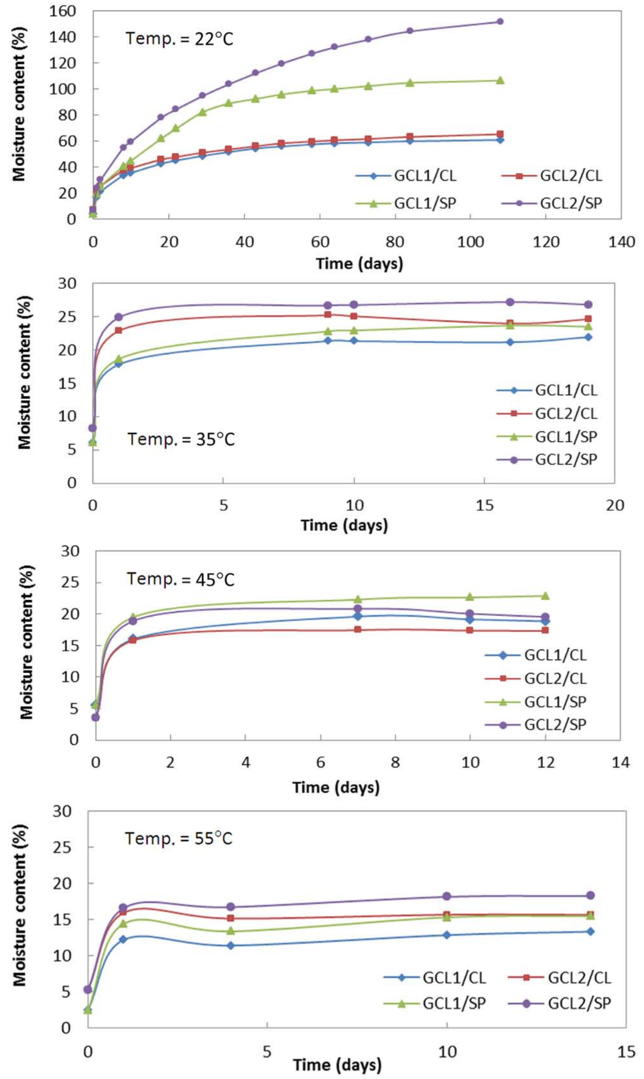

Figure 5. Evolution of geosynthetic clay liner moisture content from subsoil for all experiments.

temperature of 22°C, both GCL1 and GCL2, reached around 65% gravimetric moisture content when placed on clay, and reached around 35% gravimetric moisture content within the first week of hydration. When placed on sand the difference between GCL1 and GCL2 is more significant. These specimens both achieved more than 100% gravimetric moisture content, with GCL1 reaching 106% and GCL2 reaching 152%. Within the first week of the experiment GCL1 and GCL2 reached 40% and 55% gravimetric moisture content respectively (Table 2).

The test cells in experiment 2 were exposed to a temperature of 35°C for 19 days before being terminated. The initial moisture content of GCL1 and GCL2 was 6% and 8% respectively. For all cells the final GCL moisture content was between 23% and 27%, and a moisture content of between 18% and 25% was reached within 1 day of hydration (Figure 5b). Differences between specimens were minimal; however, it was noted that on both soils GCL2 reached slightly higher moisture content and that both GCL specimens on sand performed better than those on clay.

For the case in which cells were exposed to a temperature of 45°C (experiment 3), the initial moisture content of the GCLs was determined to be roughly 6% and 4% for GCL1 and GCL2 respectively. Over 12 days the GCLs reached final equilibrium moisture content at 17–23% moisture content, and reached between 16% and 19% moisture content within the first day of hydration (Figure 5c). For cells subjected to a temperature of 55°C, the GCLs reached between 13% and 18% gravimetric moisture content within the first day of hydration, and, beyond this, were not seen to increase significantly (Figure 5d). Similarly, it was observed that the specimens performed better on sand than on clay and that the moisture content of GCL2 was, again, slightly higher than GCL1, possibly because of the higher suction of granular bentonite in GCL2 (Beddoe et al., 2011).

GCL swelling

As the mass and moisture contents of the GCLs increased, the GCL specimens tended to increase in thickness owing to swelling of the bentonite layer. The amount of swelling demonstrated by the GCL was proportional to the amount of moisture absorbed from the subsoil. Hence, while significant swelling was seen throughout the control experiment (Figure 6), all other experiments demonstrated very little swelling, especially beyond the first day (Table 2).

Discussion

Effect of temperature on equilibrium moisture content

GCL specimens absorbed moisture from underlying subsoil pore water until they reached an equilibrium moisture content. The average equilibrium moisture content at each temperature is one indicator of the heat's effect on the GCL hydration potential. It should be noted, however, that the range of equilibrium moisture content is quite broad in the absence of a heat source. This could be attributed to the effects of the GCL manufacturing techniques and the type of subsoil on the rate of hydration, as discussed later. At higher temperatures, heat evidently becomes a limiting factor because other factors have a much less exaggerated effect. With the addition of a 35°C heat source, the average equilibrium moisture content was reduced by three quarters, from an average value of 96% to 24%. The magnitude of the external heat applied also had an effect on the degree of hydration. When the heat source was increased from 35°C to 55°C the GCL average equilibrium moisture content was reduced from 24% to 14% (Figure 7). This could be explained by the water retention curves (WRC) of the GCL and the subsoil, as well as the nature of moisture migration (Figure 1). As the temperature increases, the degree of saturation of the subsoil decreases and pore air replaces pore water within the soil's void space. This desaturation zone extends until the WRC reaches the residual degree of saturation (Figure 1), in which no further liquid-phase drainage occurs and the hydration mostly relies on the vapor phase (Barbour, 1998). The process of hydration through the vapor phase is much slower than that of the

Table 2. Summary of results.

GCL	Subsoil	Temperature (°C)	Dry mass/area (g/m²)	Initial thickness (mm)	Final thickness (mm)	GCL moisture content, w (%)			
						Initial	1 day	10 day	Final eq.
1	Sand	22	3705	5.4	6.6	3.1	20.0	45.0	106.6
		35	3550	5.5	5.5	6.0	18.7	22.9	23.5
		45	4048	6.3	6.4	5.6	19.5	22.6	22.9
		55	3515	5.3	5.5	2.5	14.4	15.3	15.5
	Clay	22	3787	5.5	6.4	3.1	17.3	35.8	61.1
		35	3783	5.7	6.0	6.0	17.8	21.3	22.9
		45	4113	6.2	6.2	5.6	16.0	19.2	18.9
		55	3541	5.4	5.5	2.5	12.2	12.9	13.3
2	Sand	22	4308	6.2	9.3	7.3	24.4	60.0	151.7
		35	4729	7.2	7.5	8.2	24.9	26.8	26.8
		45	4400	7.0	7.0	3.6	18.9	20.1	19.5
		55	4792	6.9	6.9	5.3	18.2	18.2	18.3
	Clay	22	4371	6.0	7.8	7.3	22.3	39.5	65.4
		35	4918	7.5	7.5	8.2	22.9	25.1	24.6
		45	4493	6.8	6.8	3.6	15.8	17.4	17.3
		55	4584	6.6	6.6	5.3	15.7	15.7	15.7

Eq.: equilibrium; GCL: geosynthetic clay liner.

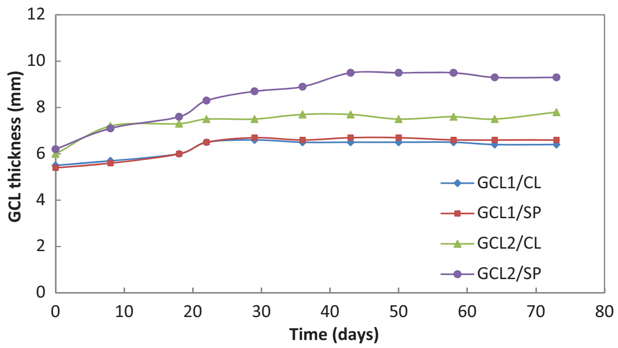

Figure 6. Geosynthetic clay liner swelling in control experiment (22°C).

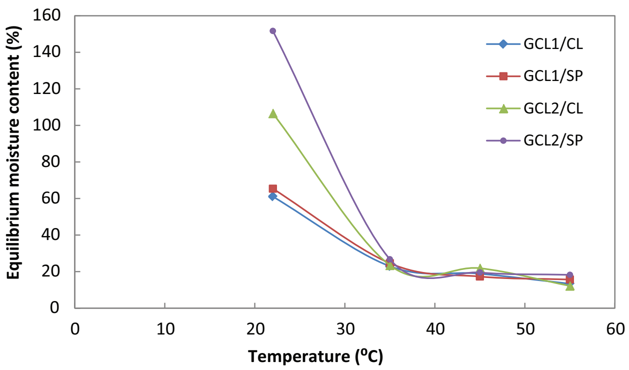

Figure 7. Equilibrium moisture content versus temperature for all experiments

liquid phase (Beddoe et al., 2011), leading to much lower equilibrium moisture contents at high temperatures. These results are notably similar to certain previous findings. It has been concluded that similar to the continuously applied heat in this study, simulated daily thermal cycles can cause a drastic reduction in the moisture content of a GCL (Anderson et al., 2011; Rowe et al., 2011).

Effect of temperature on rate of hydration

The rate of hydration of both GCLs was affected dramatically by exposure to different temperatures. When exposed to elevated temperatures it was seen that the GCL stopped absorbing moisture after the first day of hydration as opposed to continuously absorbing moisture for months when not heated. For the purpose of this discussion, only specimens that were placed on sand (SP) are considered. When left unexposed to heat GCL1 was observed to absorb moisture continuously for many weeks, but when exposed to a heat source absorption was seen to stagnate after 1 day (Figure 8a). GCL1 achieved an equilibrium gravimetric moisture content of 15–25% when exposed to a continuous temperature of 35–55°C. Without thermal exposure, at room temperature, the equilibrium moisture content for similar conditions was more than 70%.

The results for the specimens of GCL2 were very similar to those of GCL1. All specimens absorbed much more moisture during the first day than in subsequent days. After 10 days GCL2 had reached 60% moisture content with no heat source exposure, and had reached 27%, 20% and 18% when exposed to 35°C, 45°C and 55°C respectively (Figure 8b). The higher temperatures decreased the GCL's ability to absorb moisture from the underlying soil, especially beyond the first day of hydration. As discussed above, this reduction in rate of hydration after the first day of hydration could be related to the change in moisture

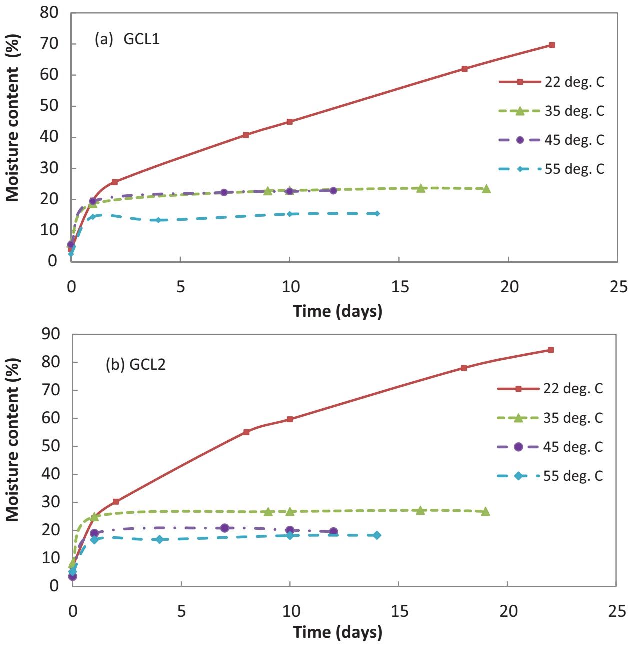

Figure 8. Effect of temperature on rate of hydration for GCL1 (a) and GCL2 (b) on sand subsoil.

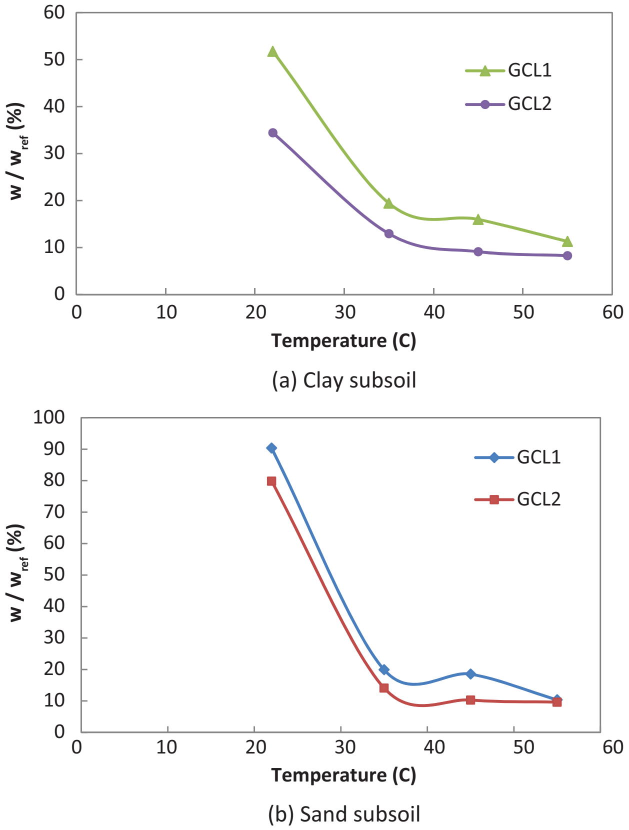

Figure 9. Effect of geosynthetic clay liner (GCL) type on hydration of GCL from subsoil.

migration phase from a faster liquid pore migration to much slower vapor phase at the residual zone of WRC under higher temperatures.

Effect of subsoil type on GCL hydration at different temperatures

As heat exposure limited the hydration potential of GCL, exposed specimens were rendered relatively insensitive to differences in the subsoil. In both soils (SP and CL) the hydration of the GCLs was suppressed by thermal exposure, and the final equilibrium moisture content under the action of thermal exposure was 25% or less than that expected from the control experiment at ambient room temperature (Figure 7). However, analysis of GCL hydration throughout the control experiment reveals that soil type does, in fact, play a significant role in GCL hydration. When placed on clay with a relatively low hydraulic conductivity and a high matric suction, the GCL did not reach more than 65% moisture uptake, while when placed on sand both types of GCL reached more than 100% moisture content. As expected, the difference in moisture uptake from the two subsoils is due to the difference between the water retention curves of the GCL and the soils at the GCL–soil interface. The lower suction supplied by the sand provides a higher difference in suction between the GCL and the sand, which is reflected in the higher equilibrium moisture content. The fact that GCL1 and GCL2 performed very similarly when placed on clay suggests that the soil properties of the clay are acting as a limiting factor in GCL hydration.

Effect of GCL type on GCL hydration at different temperatures

The effect of thermal exposures on GCL hydration was dependent on the GCL type, as shown in Figure 9 for GCLs placed on sand at an initial moisture content of 12%. For the case with no heat exposure, GCL1 and GCL2 reach very different moisture contents, suggesting that the GCL manufacturing techniques influences equilibrium moisture content. In order to compare how well each GCL performs, consideration of the best case scenario was taken. The best case scenario for maximum GCL hydration would be to completely submerge the GCL in water. Upon doing this, it was found that GCL1 could reach a maximum moisture content of 118% when submerged, and GCL2 could reach 190%. By dividing the observed moisture contents (w) by their respective GCL's maximum moisture content (w_{ref}), the values are normalized and may be interpreted as an indication of how well the GCL is performing. This method of analysis revealed that although GCL2 had a consistently higher moisture content, GCL1 consistently hydrated closer to its maximum value. The differences between GCLs are related to the difference in the level of interlock of the needle-punched fibers within them and hence the resistance to swelling of the bentonite which affects the water retention curves for these GCLs (Beddoe et al., 2011). Thus, to the extent that hydration is a function of thermal exposures, GCL1 would perform slightly better under the conditions examined here.

Geotextiles in GCL1 are connected to each other through a scrim reinforcement needle-punched system that provides stronger anchorage and leads to better GCL hydration performance. Similar findings were reported by Petrov et al. (1997), Lake and Rowe (2000) and Rayhani et al. (2011) where improved anchorage of the needle-punching fibers provided by scrim reinforced elements restricted the GCL swell and, consequently, lowered hydraulic conductivity and diffusion coefficient, while other factors kept equal. This highlights the importance of manufacturing process and changes that can improve the hydraulic performance of the GCL.

Conclusions

Several experiments were conducted to determine the effects that different factors, such as the presence and magnitude of heat exposure, the characteristics of the subsoil and the method of GCL manufacture, have on the hydration process of GCL. When adverse conditions were most severe, GCL moisture content was limited to 12–21% of that achieved under optimal conditions, with subsoil and GCL type remaining constant. This difference in moisture content highlights the dangers of heat exposure to GCL during hydration.

The presence of a 35°C heat source reduced the average final moisture content by three quarters, from 96% without heat exposure to 24%. Moreover, an increase in temperature from 35°C to 55°C caused a reduction in the average GCL moisture content from 24% to 14%. With all other factors remaining unchanged it is apparent that constant heat exposure can limit a GCL's absorption ability and that an increase in temperature can lead to a decrease in equilibrium moisture content. The rate of hydration of the GCL was also affected by the presence of a heat source. The type of subsoil was also found to play a crucial role in the hydration of GCL. It was observed that a sand subsoil with a larger grain size and lower matric suction offered a preferable medium for GCL absorption. The undesirable properties of clay, namely the high matric suction and small grain size, were seen to be a limiting factor in the hydration of GCL. Evidently the hydration potential of GCL is dependent on the subsoil characteristics among other factors. The GCL manufacturing process was also shown to play a major role in hydration performance of GCL composite liners.

These observations underscore the importance of careful design of composite landfill liners. Though things like temperature, subsoil and GCL manufacture were found to have fairly predictable effects on GCL hydration it must be understood that this is merely an illustration of some factors that must be considered when designing and choosing a GCL composite landfill liner.

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