INFLUENCE OF NORMAL STRESS ON HYDRATION OF GCLS FROM SUBSOIL

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ABSTRACT

Geosynthetic Clay Liners (GCLs) are often used as part of a barrier system in modern landfills to prevent the escape of leachate into the surrounding environment. The hydraulic performance of GCLs depends on the degree of hydration from the underlying subsoil. The hydration behaviour of two GCL products from different underlying subsoils was examined under various normal stresses (0 to 8 kPa). The rate of hydration of GCLs significantly increased as the normal stress, provided by the waste or leachate collection system, increased from 0 to 8 kPa. For instance, the final equilibrium moisture content of the GCL was achieved in approximately 8 weeks when placed on sand subsoil under 8 kPa normal stress, while it took about 24 weeks for the same GCL under no normal stress. However, the effect of the normal stress on the final equilibrium moisture content of GCLs was not so significant. A normal stress of 2 kPa was shown to induce slightly higher equilibrium moisture uptake for most GCLs. Nevertheless, results indicated a meagre variation of the equilibrium moisture content as the normal stress increased from 2 to 8 kPa. The GCL manufacturing processes and the grain size distribution of the subsoil were shown to affect both the rate of hydration and the final equilibrium moisture content attained.

Keywords: Geosynthetic Clay Liners (GCL), hydration, normal stress, landfill barrier system

INTRODUCTION

Geosynthetic Clay Liners (GCLs) are often used in modern solid waste landfills as part of a composite liner system to prevent the escape of contaminants from the landfill. GCLs basically consist of a layer of bentonite bonded by nonwoven or woven geotextiles which have been needle-punched together. Implicitly, the hydraulic performance of the GCLs depends on the rate of hydration which occurs due to absorption of pore moisture from the underlying subsoil. Previous studies have shown that the rate of hydration of a GCL is influenced by the GCL manufacturing properties (Beddoe et al., 2011; Rayhani et al., 2011). A thermally treated scrim-reinforced GCL was shown to have a higher rate of hydration when placed in contact with sand subsoil (Rayhani et al., 2011), and lower susceptibility to shrinkage under simulated daily thermal cycles between 20 and 60 ºC (Rowe et al., 2011).

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The initial moisture content and the type (grain size distribution) of subsoil were also shown to affect the rate of hydration of the GCL (Chevrier et al., 2010; Rayhani et al., 2011; Rowe et al. 2011). Chevrier et al., (2010) demonstrated that the bentonite moisture content of a needle-punched GCL increased from an initial value of 39 to 160% as the initial water content of the sand subsoil increased from 3 to 17 %, after 24 days of hydration. A similar trend was shown by Rayhani et al. (2011) indicating that the rate of hydration for a GCL placed over sand subsoil was much higher than that placed in contact with silty sand subsoil. This was attributed to the high hydraulic conductivity and lower suction of the sand, which led to higher rate of hydration. Also, Eberle and von Maubeuge (1997) reported that an initially dry GCL in contact with well graded sand (90% passing 4.75 mm sieve) with an initial moisture content of 8-10%, reached a moisture content of 100% in less than 24 hours.

Composite liners in landfill applications might be left exposed to daily thermal cycles for a period of time prior to being covered by the waste. Rowe et al. (2011) investigated the effect of daily thermal cycles on the rate of hydration of GCLs and reported that the thermal cycles significantly suppressed the rate of hydration of GCLs placed on silty sand subsoil at initial moisture contents of 5%, 10% and 16%. Nevertheless, the equilibrium moisture content of GCL in contact with a subsoil at an initial moisture content of 21% (close to field capacity) proliferated as high as 113-127 %.

The moisture uptake data noted above provides information as to the likely hydrated moisture content for the GCLs under small normal stresses (mostly under 2 kPa). However, the composite liner may experience much higher normal stresses when covered by waste. To date, there is limited data in the literature assessing the effect of normal stress on the rate of hydration of GCLs. Rayhani et al. (2011) evaluated the rate of hydration for two GCL samples under unconfined conditions and a normal stress of 2 kPa. The confined GCL showed a higher rate of hydration due to better contact with the subsoil. Chevrier et al. (2010) demonstrated a reduction of approximately 12.5 % in the equilibrium moisture content of a needle-punched GCL placed over sand subsoil as the initial normal stress of 7 KPa was increased to 28.2 KPa. Also, Petrov et al., (1997) showed that an increase in the normal stress prior to hydration contributed to lower final bulk void ratios, less time required for complete hydration, and a reduction in GCL hydraulic conductivity from 3.7×10^{-11} to 6.4×10^{-11} m/s for low normal stress (σ= 3-4 kPa), to 7.1×10^{-12} to 7.9×10^{-12} m/s for high normal stress (σ= 109-117 kPa). However, there are still continued uncertainties regarding the effect of normal stress in other ranges. Furthermore, the optimum normal stress which contributes to the highest final equilibrium moisture uptake as well as the rate of hydration of GCLs has not been documented in the literature. Thus, the objective of this paper is to investigate the rate of hydration of two different GCL products using different subsoils under a wide range of normal stresses, and to find the optimum normal stress which results in the highest equilibrium moisture uptake and rate of hydration. In addition, the effects of the GCL manufacturing techniques and the grain size distribution of the subsoil on the GCL hydration behaviour are investigated.

MATERIAL PROPERTIES

Geosynthetic Clay Liners

Two different types of GCLs from North American manufacturers, including Bentofix NWL (GCL1) and Bentomat ST (GCL2) were examined in this study. The index properties of these GCLs, including carrier and cover geotextiles, layer connection, and average peel strength are given in Table 1. Both GCLs contained granular sodium bentonite with similar smectite contents of 50 to 58%. GCL1 and GCL2 had swell indexes of 24 and 23 ml/2g, respectively. The former GCL contained fine grained bentonite with D_{50} of about 0.35 mm, while the latter contained coarse granular bentonite with D_{50} of approximately 1.0 mm. The plasticity index of bentonite was measured at approximately 216% for GCL1 and 262 % for GCL2 (ASTM D 4318). The cation exchange capacities of the bentonite were 78 and 103meq/100g for GCLs 1 and 2, respectively.

TABLE 1
Properties of GCLs Examined

GCL	Total dry mass/area (g/m^2)	Carrier GT		Cover GT		Layer Connection	Average peel strength
		Type	*Mass (g/m^2)*	*Type*	*Mass (g/m^2)*		*(N)**
1	3312-4006	SRNW	230-253	NW	200-224	NPTT	260 ± 17
2	4499-5295	W	120-130	NW	260-280	NP	204± 35

W = Woven, NW = Nonwoven, SRNW = Scrim reinforced nonwoven, NP = Needle punched
*NPTT = Needle punched & thermally treated; *Tests performed by M. Hosney, Queen's University*

Soil Properties

Hydration rates for the two GCL specimens were examined using two different subsoils: ordinary construction sand (SP in USCS classification system, ASTM D2487), and Ontario Leda clay (CL) from the Navan landfill near Ottawa, Ontario, Canada. The particle size distributions of both soils are shown in Figure 1 (ASTM D 422). The sand (SP) contained approximately 5% fines passing through the 0.075 mm sieve. The fines were non-plastic. The plasticity index of the clay (CL) was found to be 21.6% (ASTM D4318). The Standard Procter compaction tests (ASTM D 698) indicated maximum dry densities of 1.68 and 1.43 Mg/m^3 at optimum moisture contents of 10% and 28.3% for the sand (SP) and clay (CL), respectively. GeoStudio (2007) was implemented to estimate the water retention curve (WRC) of the sand, based on the grain size distribution and the saturated moisture content of the soil. Also, Van Genuchten (1980) model was used to derive the water retention curve of the clay (CL) based on the experimental data points reported by Taha (2010) (Figure 2). The initial suction in the clay is much higher than that of the sand subsoil.

EXPERIMENTAL PROCEDURE

This paper investigates the effect of normal stress on the hydration behaviour of GCLs from the underlying subsoil. Typical composite liner profiles were re-created in Polyvinyl Chloride (PVC) cells having a diameter of 150 mm and a height of up to 500 mm. The experimental testing consisted of 24 cells, with tests performed at ambient room temperature (22°C). Each cell consisted of 250 mm of subsoil, a GCL, a geomembrane, and a steel seating block with a known weight

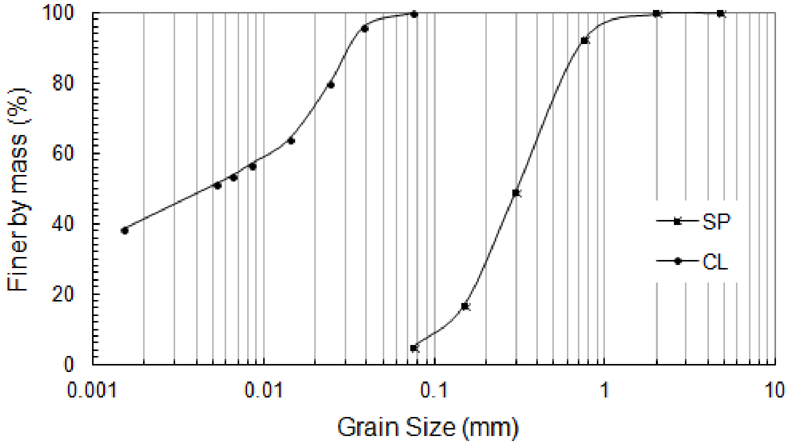

FIGURE 1
Grain size distributions for the subsoils examined

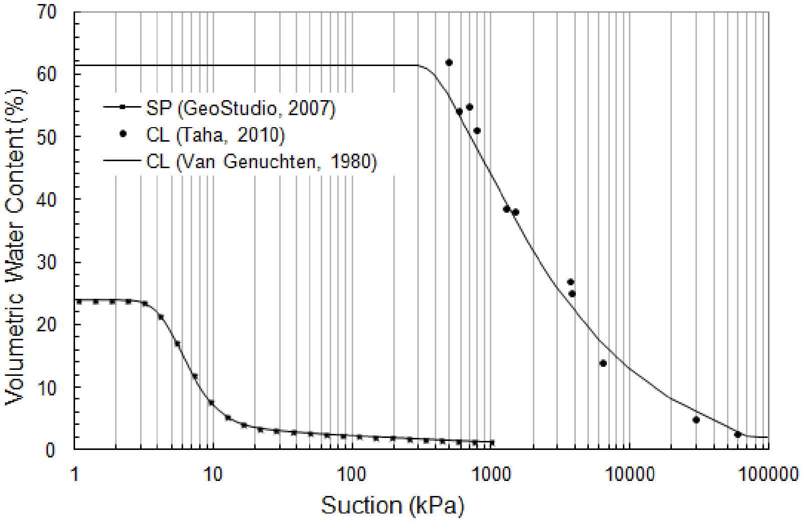

FIGURE 2
Estimated Water Retention Curves (WRCs) for the subsoils examined

to provide specific normal stresses on the GCL (Figure 3).

Bulk samples of dry sand (SP) were mixed with tap water having an average calcium concentration of 40 mg/L in order to bring its moisture content to 12%, i.e. a moisture content which is 2% higher than the Standard Proctor optimum moisture content (w_{opt} + 2%), to represent the moisture content used in the construction of barrier systems in most modern solid waste landfills. The sand was then compacted into the PVC cylinders (12 cells) in three layers with a final height of 250 mm, and a dry density of 1.51 Mg/m^3, corresponding to approximately 90% of the maximum dry density ($\rho_{d(max)}$). Similarly, 12 cells were filled with clay (CL) subsoil at a moisture content of 30% (w_{opt} + 2%) and compacted to a dry density of 1.29 Mg/m^3 ($0.9\times\rho_{d(max)}$). Each cell was closed, sealed, and left for 24 hours to cure before the GCL sample was placed on top of the soil. GCL samples with a diameter of 150 mm were cut from the roll, placed over the subsoil, and overlain by a geomembrane. Afterwards, a steel seating block was placed on the geomembrane to apply normal stress over the GCL, except for the samples which were not to be subjected to normal stress. Details of the initial moisture content of the GCLs as well as the normal stresses applied to the GCLs are outlined in Table 2.

The hydration process of the GCLs was monitored by measuring the GCL's gravimetric moisture content for up to 40 weeks in order to evaluate the hydration of GCLs under different normal stresses. The test cells were opened at specific times (weekly) in order to measure the mass and the thickness of the GCL, before returning it to the cell. The cells were closed and sealed again to prevent any loss of moisture. A schematic of a typical test cell is demonstrated in Figure 3.

RESULTS

Typical Hydration Results

In general, the gravimetric moisture content of the GCL increases from its initial moisture content as it attains equilibrium with the subsoil. The rate of hydration was significantly higher during the first 10 weeks, but it gradually decreased, and the moisture content of the GCLs finally levelled out and reached a steady-state value. The corresponding gravimetric moisture content is reported as the equilibrium moisture content. Also, the normalized moisture contents of GCLs have been calculated so that it would be possible to compare the rate of hydration of GCLs which are different in manufacturing properties. The normalized moisture content was defined as the ratio of moisture content of the GCL to the hydration potential (w_{ref}), i.e. the maximum moisture content of the GCL when there is no limitation on the moisture content available. To obtain the w_{ref}, the GCL specimens were immersed in water while applying the same normal stresses to which the GCLs were subjected during the hydration from subsoil experiments. Geotextiles were placed between the GCL samples and the seating block so as to provide sufficient space for water to reach the GCL sample.

The equilibrium moisture content, normalized moisture content, and also the time required to reach equilibrium for GCL1 and GCL2 while placed over sand (SP) and clay (CL) subsoils are reported in Table 2. The time required to reach equilibrium moisture for GCLs placed over sand (SP) subsoil was typically lower than that of clay (CL) subsoil. Also, it took a longer time for GCL2 to attain the equilibrium moisture content in comparison to GCL1 at the same normal stresses in contact with the same subsoil. Moreover, the results for initial thickness and final thickness of the GCL samples are indicated in Table 2. The thickness of the GCLs was measured at three specific points using a caliper, and finally averaged to obtain a value which represents the mean thickness of the GCL. Based on the derived data, the effect of the normal stress on GCL swelling was also evaluated and will be further described. In the remainder of this paper, the factors which influence the hydration of GCLs, including normal stress, the GCL manufacturing process, and subsoil grain size distribution are analyzed and discussed in detail. Meanwhile, the results of the present study are compared with those of

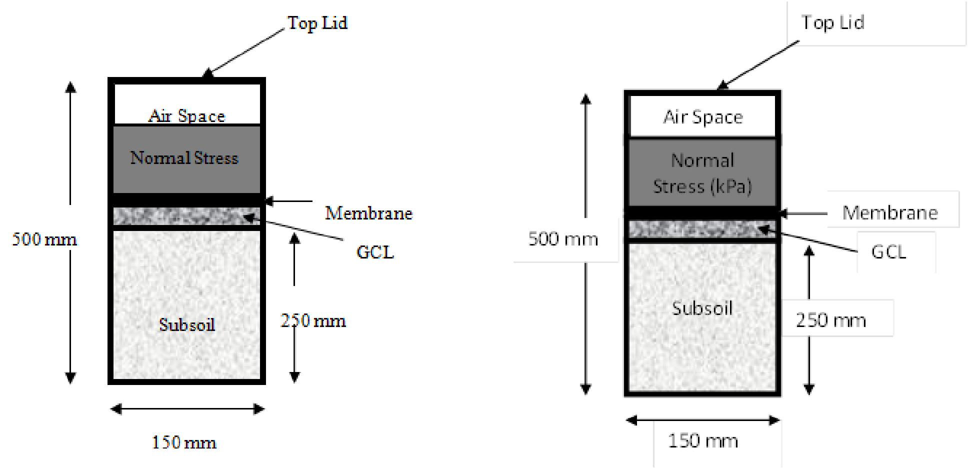

FIGURE 3

Geometry of the apparatus used for evaluation of hydration under isothermal condition

TABLE 2

Details of experiments conducted under isothermal condition

GCL	*Subsoil*	*Conf. Stress (kPa)*	*Dry mass/area* (g/m^2)	*Initial Thick. (mm)*	*Final Thick. (mm)*	*Moisture Content, w (%)*			*Normalized MC.* ($w/{}^*w_{ref}$) *(%)*		*Time to Reach Eq. (week)*
						Initial	*1 week*	*Eq. MC*	*1 week*	*Eq. MC*	
1	Sand	0	3648	6.55	7.15	6.49	35.8	110	25.6	78.7	24
		0.5	3780	6.73	7.4	6.56	43	110	32.2	82.3	18
		1	3515	6.58	7.08	6.58	45.2	111.3	34.1	84	14
		2	3582	6.53	7.1	6.46	50.6	111.8	37.7	81.8	12
		5	3984	6.3	7.05	6.46	56	108.4	42	81.2	8
		8	3701	5.82	6.57	6.46	62.6	106.6	46.7	79.5	8
	Clay	0	3846	6.9	7.5	6.44	33.1	83.1	23.6	59.5	26
		0.5	3664	6.63	6.93	6.47	36.3	90.3	27.2	67.5	22
		1	4006	6.93	7.42	6.46	39.1	95.1	29.5	71.7	16
		2	3312	6.4	6.72	6.49	42.2	96.6	31.5	72	16
		5	3595	5.92	6.43	6.47	43.3	95.9	32.4	71.9	16
		8	3426	5.58	6.08	6.46	44.6	96.6	33.3	72	8
2	Sand	0	4499	7.75	9.67	8.02	35.3	137.7	15.4	60.1	32
		0.5	4535	7.58	9.33	8.02	38.4	136.4	17.2	61.1	32
		1	5295	7.88	11.01	8.01	42.4	137.7	19.4	63	32
		2	4998	7.32	10.1	8.05	48.4	149.7	22	68	28
		5	4811	7.23	9.68	8.03	58.7	154.1	26	68.3	20
		8	4795	6.95	9.33	8.02	55.8	154	24.8	68.5	12
	Clay	0	4985	7.33	7.77	8.01	30.5	60	13.3	26.2	32
		0.5	4924	7.87	8.47	8	35	69.1	15.7	31	28
		1	4664	7.68	8.11	7.99	37.1	72.9	17	33.3	28
		2	5174	7.82	8.45	8.01	38	83.2	17.3	37.8	28
		5	4986	7.6	8.13	8.01	42.3	75	18.7	33.2	16
		8	4791	6.73	7. 53	8.02	42.7	70	19	31.2	8

** Results for* w_{ref} *are shown in Figure 7*

previous investigations.

Moisture Content Profile in Subsoil

The initial and final profiles of gravimetric moisture content for sand (SP) and clay (CL) subsoils are demonstrated in Figure 4. The initial moisture content of the sand (SP) subsoil was approximately 12%. As could be expected, the moisture content of the soil in contact with the GCL decreased due to the absorption of water by the GCL. In contrast, the moisture content increased at the bottom of the sand (SP) subsoil since the water moved downward due to gravimetric force. The moisture reduction (6.4-9.8%) on top of the subsoil was more than the increase observed (2.6-5.6%) at the bottom of the subsoil. This could be related to the absorption of moisture content by the GCL on top of the sand subsoil. The results reported for the clay (CL) subsoil also indicated a decrease of moisture content on top of the subsoil due to the absorption of moisture by the GCL. Nevertheless, the variation of final moisture content in the profile of the clay was less than that of the sand profile. This could be related to the grain size distribution and hence higher field capacity of clay compared

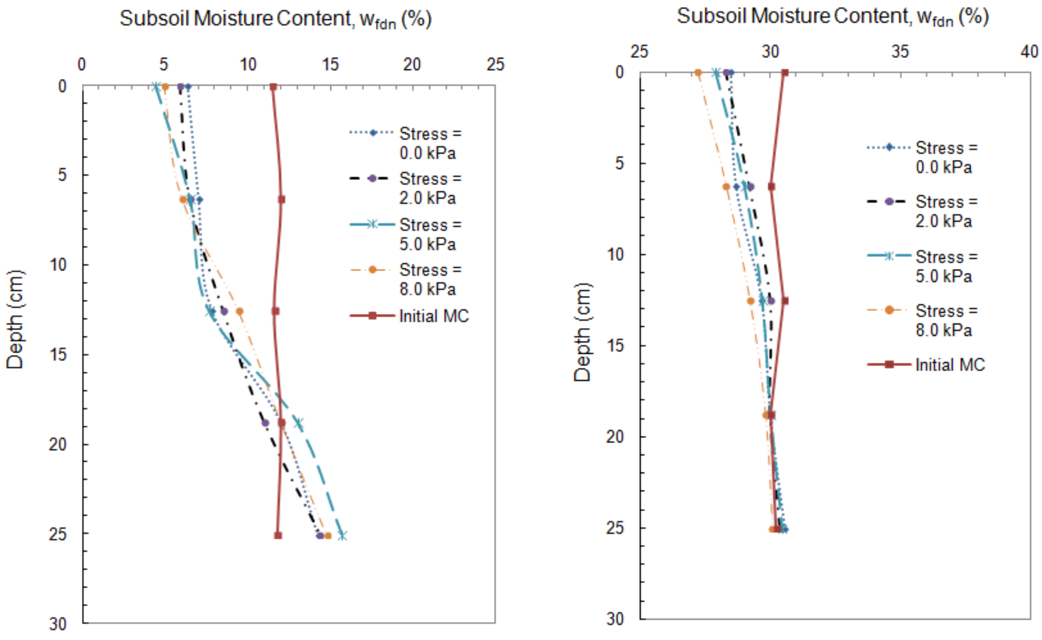

FIGURE 4

Moisture content profile in the subsoil before and after the test

to sand.

ANALYSIS AND DISCUSSION

Effect of Normal Stress on GCL Hydration

The hydraulic performance of a GCL in a barrier system depends on the degree of hydration of the bentonite in the GCL. The level of normal stress provided by the leachate collection system or the waste could affect the swelling characteristics and hence the degree of hydration of the GCL. Figure 5 shows the evolution of hydration for GCL1 from a sand subsoil at an initial moisture content of 12%. The rate of moisture uptake increased significantly as the normal stress increased from 0 to 8 kPa. GCL1 achieved more than 62%

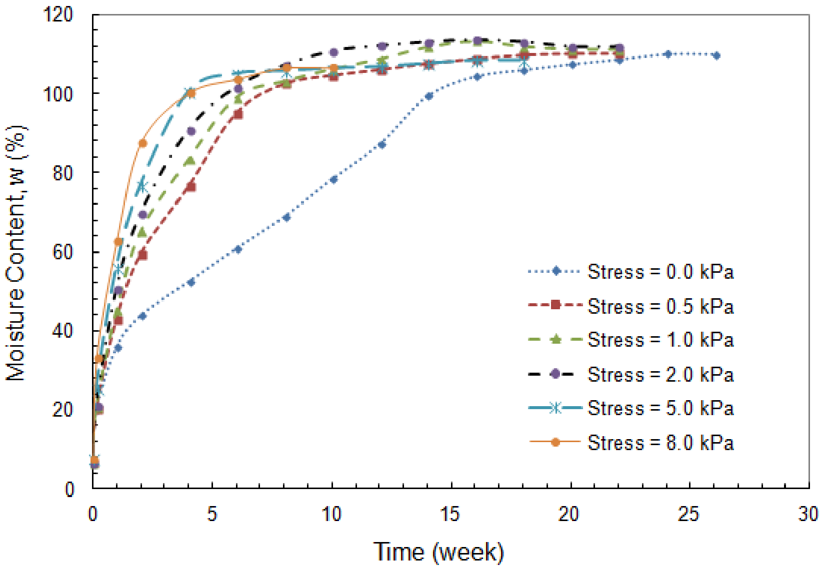

FIGURE 5

Hydration of GCL 1 from sand subsoil subjected to different normal stresses gravimetric moisture content after one week when subjected to a normal stress of 8 kPa (Table 2). Under similar conditions but with no normal stress, this GCL reached only a 36% moisture content after one week of hydration. The time to reach final equilibrium hydration, also, varied significantly for GCLs subjected to different normal stresses. Under no normal stress, the rate of moisture uptake from the subsoil was much slower and it took more than 24 weeks for GCL1 to reach its final equilibrium moisture content. Under similar conditions but with a normal stress of 8 kPa, GCL1 approached its final equilibrium moisture content in 8 weeks. The normal stress enhanced the contact intimacy between the GCL and subsoil which induced a higher rate of moisture uptake. The magnitude of the final equilibrium moisture content of GCLs, however, was not significantly affected by the normal stress. There was no significant variation in the values of the equilibrium moisture contents for GCL1 subjected to the normal stresses of 0 kPa to 2 kPa (Figure 5). However, the equilibrium moisture content decreased from 111.8 % to 106.6 % as the normal stress increased from 2 to 8 kPa. Although higher normal stress generally reduces the potential for zones of poor contact between the GCL and the subsoil, there will be more of a restriction on the swelling of the bentonite as the normal stress increases. Therefore, a meagre decrease of equilibrium moisture content was expected after a specific stress due to the much higher limitation for absorption of water. The results indicated that the normal stress which results in the optimum equilibrium moisture uptake for GCL1, while placed over a sand subsoil, was 2 kPa (Figure 5).

Figure 6 demonstrates the variation of equilibrium moisture content versus the normal stress for 4 different conditions, including either GCL1 or GCL2 placed over sand and clay subsoils. In general, the final equilibrium moisture uptake slightly increased as the normal stress increased from 0 to 2 kPa. This small normal stress enhanced the contact between the GCL and the subsoil leading to faster and slightly higher moisture uptake. The normal stress of 2 kPa led to the highest value of equilibrium moisture content for all conditions except for GCL2 placed over a sand subsoil. To elaborate, the equilibrium moisture content for GCL2 over sand increased from 149.7 % to 154 % as the normal stress increased from 2 to 5 kPa, which is not significant. Under the other conditions, a negligible reduction in moisture uptake was observed as the normal stress increased from 2 to 8 kPa. However, the results did not indicate a significant variation with normal stress as it increased from 2 to 8 kPa. This is mainly considered to be related to the fact that the swelling stress of the GCLs controlled the normal stress applied to them. As a result, increasing the normal stress from 2 to 8 kPa did not induce a significant decrease of the equilibrium moisture content.

These results could be also explained in terms of the maximum moisture content (w_{ref}) attained by the GCL when immersed in water. As shown in Figure 7, there was no significant variation in the maximum moisture content of GCLs while subjected to normal stresses ranging from 0 to 8 kPa. The results for maximum moisture content (w_{ref}) substantiated that the swelling stress of GCLs was much higher in comparison to the normal stress applied to them. Immersion of GCLs in water represents the conditions under which there is no limitation on the amount of water available to the GCL for absorption.

Effect of Normal Stress on GCL Swelling (Thickness)

To evaluate the effect of normal stress on GCL swelling, the ratio of the final thickness of GCL specimens after hydration to their corresponding initial thickness were plotted (Figure 8). There was little variation observed for GCL1 placed over either sand (SP) or clay (CL) subsoil with the values ranging from 108 % to 113 % and 104.5% to 110.5 %, re-

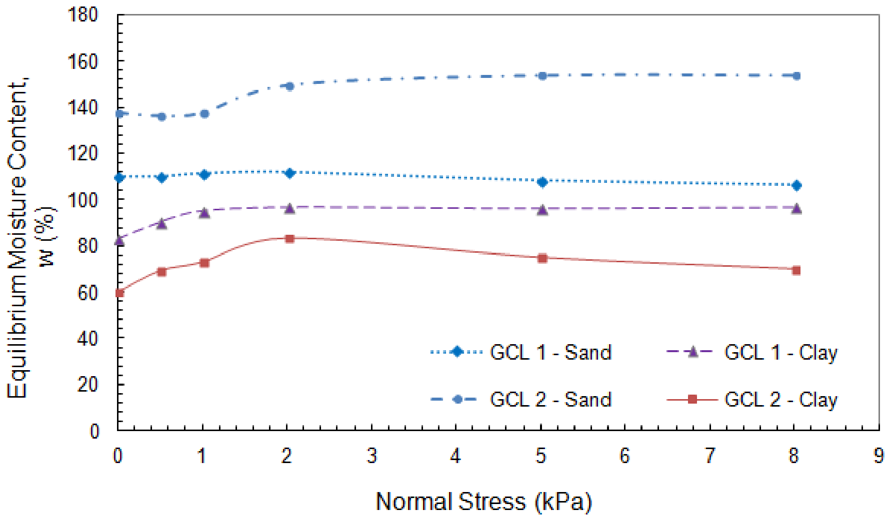

FIGURE 6
Effect of normal stress on the equilibrium moisture content of GCLs

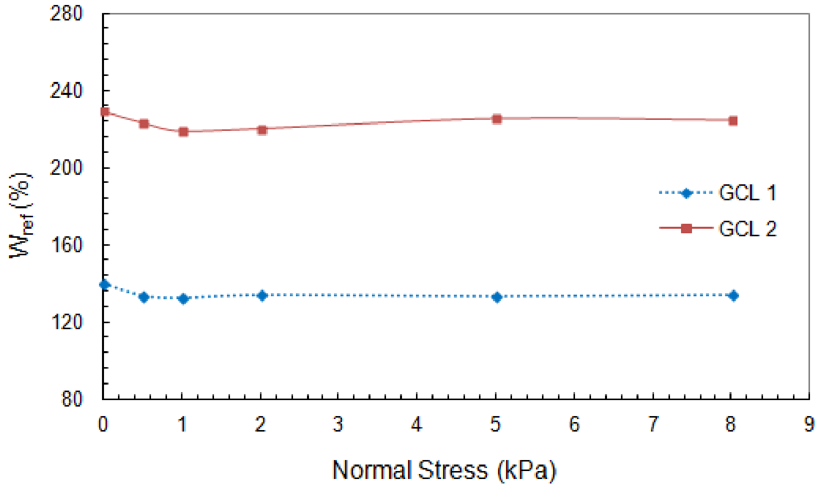

FIGURE 7

Effect of normal stress on maximum moisture content, immersed in water (w_{ref})

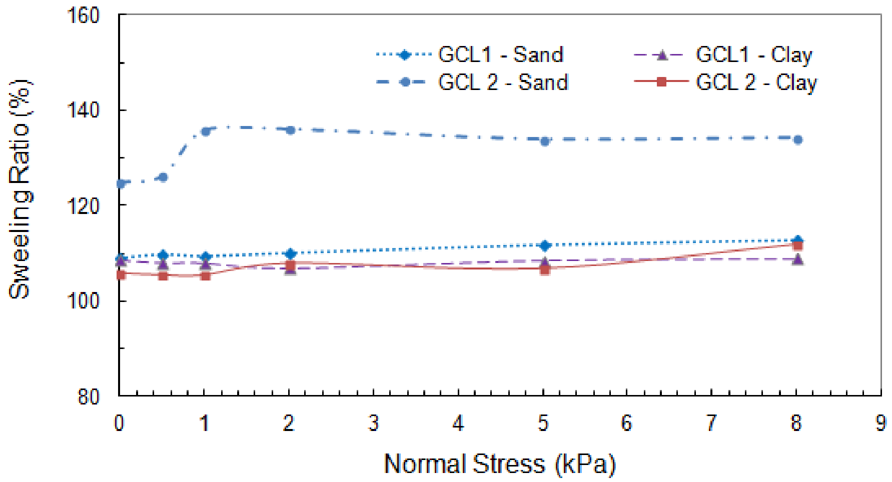

FIGURE 8

Effect of normal stress on the final thickness of GCLs

spectively. As shown in Figure 9, the ratio of swelling for GCL1 placed over sand (SP) subsoil was up to 5% more than that of the clay (CL) subsoil due to increased absorption of water by the GCL. In contrast, the results for GCL 2 indicated much more swelling for sand (SP) subsoil in comparison to clay subsoil. The former exhibited a swelling ratio of up to 135% while the latter swelled to 112% under the same normal stress of 8 kPa. There was a significant increase in the swelling ratio from 124 to 135% for GCL 2 on sand (SP) subsoil as the normal stress increased from 0 to 1 kPa (Figure 8). It might be concluded that the increase of normal stress induced much better contact between the GCL and the sand subsoil, which resulted in higher moisture uptake and swelling. Nonetheless, the swelling ratio almost stabilized and there was little fluctuation observed for normal stresses ranging from 1 to 8 kPa. The meagre variations pertaining to GCL1 could be attributed to the sufficient anchorage induced by the scrim-reinforced needle-punching and thermally treated layer connection of GCL1, which will be further discussed below.

Effect of GCL Manufacture on Hydration

The hydration of the GCL is dependent on the method of GCL manufacture, and different GCL products exhibit different hydration and swelling behaviours. The maximum moisture uptake for GCLs immersed in water varied significantly for the two GCL products examined. Hence the degree of saturation for GCL1 at a moisture content of e.g., w=100% (w/w_{ref}=71%) would be different than that for

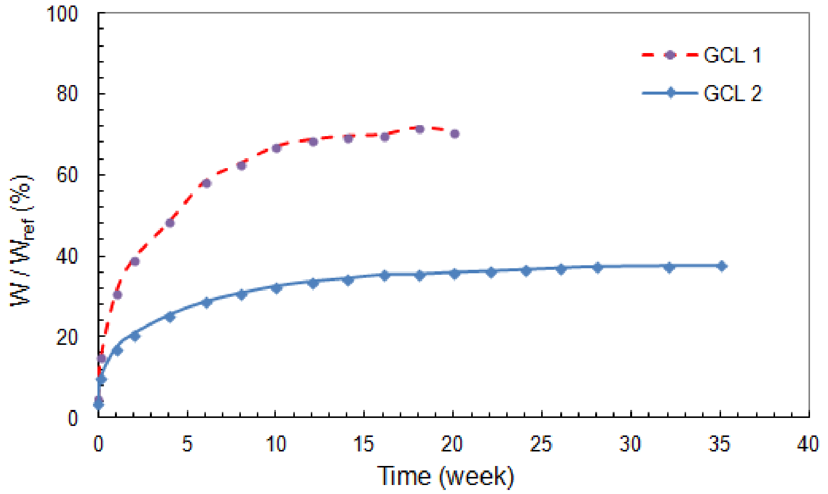

FIGURE 9
Effect of GCL type on rate of hydration from clay subsoil

GCL2 at the same gravimetric moisture content (w/w_{ref}=45%). Therefore both the absolute gravimetric moisture content (w) and the moisture content normalized with respect to the maximum moisture uptake when immersed in water (w/w_{ref}) are used to compare the performance of different GCLs subjected to various normal stresses (Table 2).

Figure 9 demonstrates the normalized moisture contents (w/w_{ref}) of GCL1 and GCL2 placed over a clay subsoil while subjected to a 2 kPa stress. GCL1 demonstrated a much higher rate of hydration compared to GCL2. As shown in Table 2, the former GCL reached a plateau by the 16th week with a normalized moisture content of 72%, while the latter stabilized at the normalized moisture content of about 38% by the 28th week. Figure 10 shows the normalized equilibrium moisture contents of both GCLs placed over a clay subsoil for normal stresses from 0 to 8kPa. The normalized equilibrium moisture content of GCL1 was approximately twice that of GCL2 for all normal stresses. This could be related to the difference in interlocking of the GCLs examined. GCL1 has a scrim-reinforced non-woven carrier geotextile with a needle punched and thermally treated layer connection that provides a sufficient anchorage (Table 1) resulting in less swelling during the hydration process, in contrast to GCL2. This contributed to its higher normalized equilibrium moisture content and lower hydraulic conductivity. In addition, the results showed that a normal stress of 2 kPa induced the maximum normalized equilibrium moisture content for both GCL 1 and

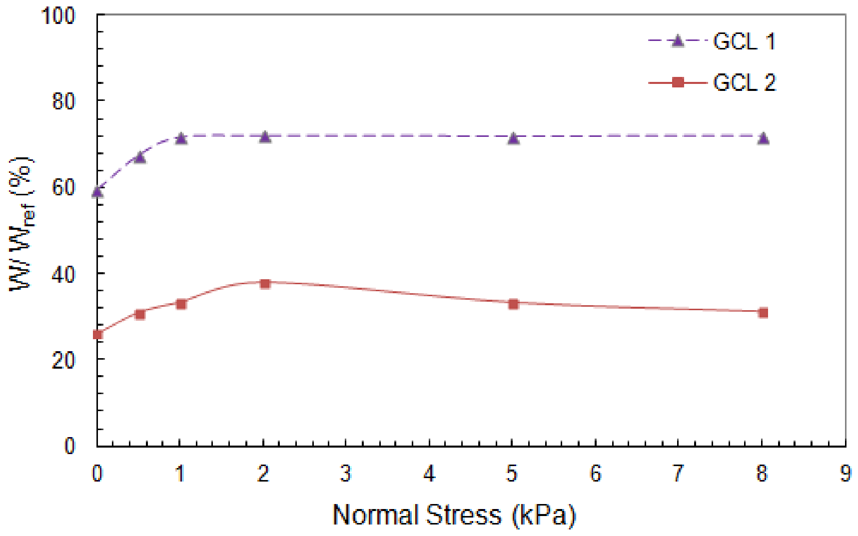

FIGURE 10
Normalized equilibrium moisture content from clay subsoil for different normal stresses

GCL 2. For normal stresses greater than 2 kPa, there was no significant change observed in the normalized equilibrium moisture content for either GCLs.

The results noted above are consistent with those reported in the literature in terms of GCL hydration behaviour. Rowe et al. (2011) indicated a lower daily variation in moisture content and furthermore less potential susceptibility to shrinkage for GCL1. Petrov et al. (1997), Lake and Rowe (2000), and Beddoe et al. (2011) reported that the limitation of swelling could be induced by much more sufficient anchorage of a GCL.

Effect of Subsoil Grain Size Distribution on GCL Hydration

The effect of normal stress on GCL hydration was highly dependent on the grain size distribution and associated matric suction of the subsoil (Figure 2). For sand with an initial moisture content close to the optimum moisture content, there is a significant uptake of moisture by both the GCLs under all normal stresses (Table 2). Figure 11 compares the equilibrium moisture uptake of GCL2 from both sand and clay subsoils for all normal stresses. GCL2 reached 140-145% (depending on the normal stress) moisture content when placed on the sand subsoil. Under similar conditions with clay subsoil, GCL2 achieved only 60-80% moisture content, approximately half that achieved on sand. Similarly, higher equilibrium moisture contents were observed for GCL1 with sand subsoil compared to clay subsoil (Table 2). The rate of hydration was also different for the two subsoils examined. After 1 week of hydration, GCL2 achieved 48% moisture uptake from the sand subsoil, while it was about 38% from the clay subsoil under similar conditions (Figure 12). This

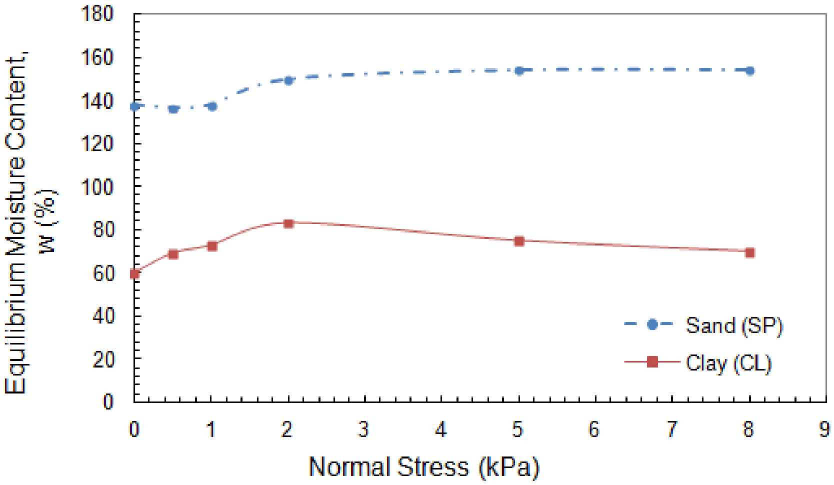

FIGURE 11
Effect of subsoil grain size distribution on the equilibrium moisture content of GCL2 for different normal stresses

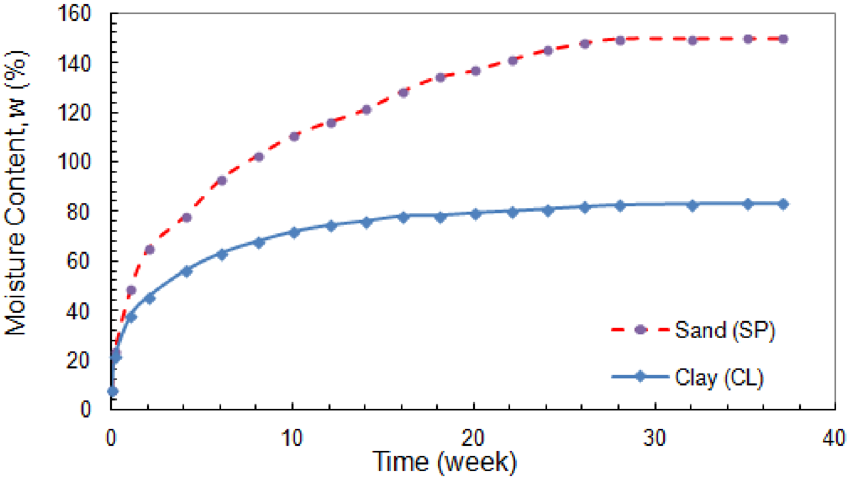

FIGURE 12
Hydration of GCL2 from two different subsoils

observation shows the importance of the subsoil on GCL hydration. The difference in hydration behaviour of GCL from different subsoils is related to the difference in suction levels of the soil and the GCL (Figure 2). The initial suction in the sand is much lower than that in the clay. This lower suction supplied by the sand subsoil results in a higher difference between the suction of the GCL and the subsoil, which leads to the higher moisture uptake by the GCL.

Comparison with results of previous studies

Chevrier et al., (2010) evaluated the rate of hydration of GCL specimens placed over sand subsoil with an initial moisture content of 12.5%. The specimens were subjected to normal stresses of 7.0, 9.9, 14.1, 21.2 and 28.2 kPa under isothermal conditions (T=20±2°C). Figure 13 compares the data derived in the present study with those of Chevrier et al., (2010). As previously noted, results from the present study complement those reported by Chevrier et al., (2010) indicating that there is little variation observed as the normal stress increases in the range of relatively high normal stresses. However, a meagre decrease of equilibrium moisture content occurs due to the restriction on swelling of the GCL because of the applied normal stress. Combining results from the two studies indicates that the equilibrium moisture content decreased by approximately 12.5% as the normal stress increased from 2 to 28.2 kPa. Rayhani et al. (2011) reported a higher rate of hydration for GCL specimens subjected to 2 kPa normal stress compared to those hydrated under unconfined conditions. These studies substantiate the results of the present study indicating that increasing the normal stress results in much better contact between the GCL and the subsoil, and consequently higher rates of hydration.

CONCLUSIONS

The hydration of two different GCL products from subsoil pore water at room temperature (i.e. 22°C) was examined under normal stresses ranging from 0 to 8 kPa. The results indicate a positive correlation between the rate of hydration and the normal stresses tested, which could be attributed to the better contact between the GCL and subsoil at the GCL-soil interface. GCL1 placed over sand subsoil while subjected to 8 kPa normal stress stabilized and attained equilibrium moisture content 16 weeks earlier compared to the condition without normal stress. The equilibrium moisture uptake was slightly increased for all experiments as the normal stress increased from 0 to 2 kPa. A meagre decrease was observed as the normal stress increased from 2 to 8 kPa. For instance, the equilibrium moisture content for GCL1 in contact with sand subsoil decreased from about 112 % to 106.5%. This is attributed to the restriction imposed on the swelling of the GCL because of the normal stress. Nevertheless, the equilibrium moisture content of GCL 2 with sand subsoil had an insignificant increase from 149.7% to 154% as the normal stress increased from 2 to 5 kPa. Hence, it might be concluded that the optimum normal stress would be between 2 to 5kPa, resulting in the maximum equilibrium moisture content and an adequate rate of hydration. This level of stress can easily be provided by a typical Leachate Collection System (LCS) of solid waste landfills. Therefore, it is proposed that the LCS be constructed right after placement of the GCL to provide the sufficient normal stress for hydration. The LCS will also prevent the thermal exposure which could suppress the GCL hydration from the underlying subsoil.

In order to validate the data, the results for the maximum water content (w_{ref}) which GCLs could absorb while immersed in water were determined under similar normal stresses (0-8 kPa). The normal stress applied to the GCLs is

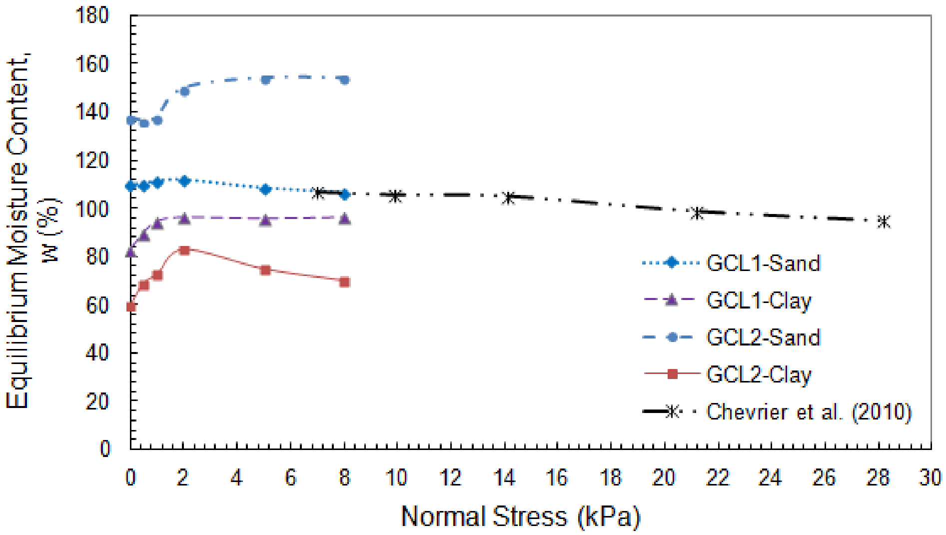

FIGURE 13
Comparison of GCL hydration data with results of previous studies

shown to have no significant influence on the maximum moisture which GCLs could absorb. This is mainly related to the fact that the swelling stress of GCLs controlled the normal stresses applied to them.

The method of manufacturing was also found to affect the rate of hydration. GCL1 and GCL2 attained normalized moisture contents of 72% and 38%, respectively, while placed over clay subsoil (σ=2 kPa). Hence, it might be concluded that the needle-punched and thermally treated layer connection and scrim-reinforced non-woven carrier geotextile of GCL1 provided sufficient anchorage and much better hydration compared to GCL2.

The grain size distribution of the subsoil was also shown to affect both the rate of hydration and the equilibrium moisture content attained. Both GCLs placed in contact with the sand subsoil achieved much higher equilibrium moisture uptakes in much shorter times in comparison to the clay subsoil. This was attributed to the differing levels of suction provided by the sand and the clay. Since sand has a lower suction in comparison to clay in unsaturated condition at similar moisture contents, there is a much higher difference between the suction of sand and the GCL at their interface. As a result, more water at a much higher rate is absorbed by the GCL placed over sand subsoil in comparison to the clay subsoil.

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