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Factors affecting GCL hydration under isothermal conditions

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ABSTRACT

The hydration of different GCLs from the pore water of the underlying foundation soil is investigated for isothermal conditions at room temperature. Results are reported for three different reinforced (needle punched) GCL products. Both a silty sand (SM) and sand (SP) foundation soil are examined. GCL hydration is shown to be highly dependant on the initial moisture content of the foundation soil. GCLs on a foundation soil with a moisture content close to field capacity hydrated to a moisture content essentially the same as if immersed in water while those on soil at an initial moisture content close to residual only hydrated to a gravimetric moisture content of 30–35%. The method of GCL manufacture is shown to have an effect on the rate of hydration and the final moisture content. The presence or absence of a small (2 kPa) seating pressure is shown to affect the rate of hydration but not the final moisture content. The GCL hydration did not change significantly irrespective of whether a nonwoven cover or woven carrier GCL rested on the foundation soil.

1. Introduction

Geosynthetic clay liners (GCLs) are often used as part of composite liners with a geomembrane liner placed over the GCL (e.g., Rowe et al., 2004; Guyonnet et al., 2009). GCLs have been found to be highly effective for preventing groundwater contamination provided that: (a) they are adequately hydrated (Petrov and Rowe, 1997), (b) the overlap between the panels is maintained (Rowe, 2005), (c) they are not subjected to excessive desiccation combined with cation exchange (Benson et al., 2010), or (d) internal erosion of the bentonite (Rowe and Orsini, 2003; Dickinson and Brachman, 2010). After placement, the GCL takes up water from the underlying soil and provided that it hydrates before contact with leachate, it is usually a very good barrier to advective transport of contaminants (Rowe, 2007). However while the performance of these GCLs as liners is known to depend, at least in part, on the degree of hydration that has occurred before it comes into contact with the contaminants to be contained (Petrov and Rowe, 1997), the rate of hydration of a GCL placed on an underlying subsoil has received very little attention and it is largely an article of faith that they will be adequately hydrated by the time they need to perform their containment function. Daniel et al. (1993) and Eberle and von Maubeuge (1997) have reported limited data for GCLs placed on sand. The former paper showed that, when placed on sand at 3% gravimetric moisture content, an initially air dry GCL reached 88% moisture content after 40–45 days. The latter paper showed that when placed over sand with a moisture content of 8–10%, an initially air dry GCL reached a moisture content of 100% in less than 24 h and 140% after 60 days. However these tests were on different foundation soils with water retention curves, different moisture contents and different GCLs and it is not clear to what extent the properties of the specific foundation soil and GCL affected the rate of hydration.

It is known that both the method of GCL manufacture (Rowe, 2007; Beddoe et al., 2011) and type of bentonite used (Bouazza et al., 2006) can both influence the performance of a GCL. For example, Beddoe et al. (2011) demonstrated that the water retention curve for a GCL was a function of how it was manufactured. Also, Bouazza et al. (2006) showed large differences in transport of liquids or gas between granular and powdered bentonite during the initial hydration of a GCL. Gates et al. (2009) reported that GCLs with fine grained (powdered) bentonite took up water faster and formed an effective seal sooner than coarse granular bentonite due to larger surface area of the bentonite particles.

The speed of hydration is important in terms of both assessing how fast the composite liner system must be covered with soil/waste if one aims to minimize damage due to shrinkage and wetting and drying cycles (e.g., Thiel et al., 2006; Gassner, 2009; Rowe et al., 2010, 2011; Bostwick et al., 2010), to minimize the

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potential for desiccation cracking due to heat generated by the waste (Rowe, 2005), or to be confident that the GCL is adequately hydrated before coming into contact with the contaminant to be contained in applications such as leachate ponds or landfills. Thus, the objective of this paper is to investigate the effect of the subgrade moisture content and GCL manufacture on the rate of moisture uptake of GCLs from an underlying soil.

2. Material properties

2.1. Geosynthetic clay liners

Three different types of GCLs from two different manufacturers were examined in this study. They included Bentofix NSL (GCL1 in this paper) and NWL (GCL2) and Bentomat DN (GCL3). The basic characteristics of the GCLs are summarized in Table 1. The GCLs differed in the type of carrier geotextiles, the size of bentonite granules, and the manufacturing treatment. All GCLs contained granular sodium bentonite with similar smectite content and swell index but GCL3 had a higher cation exchange capacity than GCLs1 and 2 (Table 2). GCL3 contained coarse grained bentonite with D_{60} of 1.1 mm, while other GCLs contained fine grain bentonite with D_{60} of about 0.35 mm.

2.2. Soil characteristics

Silty sand (SM) from the Queen's composite geosynthetic liner experimental field site in Godfrey Ontario (Brachman et al., 2007) was used as primary foundation soil examined. The particle size distribution of the soil obtained using ASTM D 422 is given in Fig. 1. This data indicates that the soil is silty sand with 35% passing the 0.075 mm sieve. The fines were non-plastic. Standard Proctor compaction tests (ASTM D 698) gave a maximum dry density of about 1.83 Mg/m^3 at an optimum moisture content of 11.4% (Fig. 2).

A series of tests also were performed on a poorly graded sand (SP, ASTM D 2487) with 5% fines to investigate the influence of soil type on GCL hydration. Its Standard Proctor maximum dry density (ASTM D 698) was 1.89 Mg/m^3 at an optimum moisture content of 10.3%. The grain size distribution of the sand as well as its compaction parameters are shown in Figs. 1 and 2. Fig. 3 shows the estimated soil water retention curves (based on the data point function in GeoStudio, 2007) for the silty sand and sand.

3. Method

Polyvinyl chloride (PVC) cells 150 mm in diameter and 500 mm high were constructed to investigate the closed-system (i.e., constant mass of moisture) hydration of various GCLs from foundation soil pore water. Each cell was filled with a foundation soil, with height of about 450 mm, at a known void ratio and moisture content as described below, sealed, and allowed to come to moisture equilibrium. Then a GCL sample (initial thickness of 6–9 mm) was placed on top of the soil, and the system was sealed again (with just enough headspace to allow swelling as the GCL hydrated) (Fig. 4). The test cells were opened weekly and the GCL was removed, thickness measured, weighed, and returned to the column to track the evolution of hydration with time (several months). A laser measurement technique was used to track the change in GCL thickness due to swelling of the bentonite during hydration.

Bulk samples of Godfrey silty sand were mixed with water to bring its moisture content (w_{fdn}) to 10%, 16% and 21%, which correspond to the lower, average, and higher moisture content observed during GCL installation at the Godfrey field site (Brachman et al. 2007).The moisture content of 21% is approximately field capacity for the silty sand. A series of tests with subsoil samples at a much drier initial moisture content of 5% were also conducted to study GCL hydration at moisture contents corresponding to the residual degree of saturation.

Experiments on sand foundations were performed at moisture contents of 10% and 2%, to investigate hydration behavior at the standard Proctor optimum and the residual degree of saturation, respectively for this soil.

At the beginning of the test, GCL samples were taken from the roll at its initial moisture content, cut to a diameter of 150 mm, and placed on the foundation soil. Full details of the initial moisture contents of each GCL specimen and foundation soil investigated in this study are presented in Table 3. After installation, a geomembrane was placed on top of the GCL to minimize potential evaporation into the headspace above the GCL. A steel seating block of 25 mm thickness was then placed over the geomembrane to apply a 2 kPa stress to encourage contact between the GCL and the foundation soil. To investigate the effect of contact on the time rate of hydration of the GCL, one test (PM-1, Table 3) was conducted without this surcharge being applied. The experiments were conducted under isothermal conditions at 22 °C.

Tap water with an average calcium concentration of 30–40 mg/L was used as the pore fluid in the foundation soil.

4. Results and discussion

4.1. Typical results

The measured GCL moisture contents (w) for all tests are reported in Table 4 for regular time periods up to 30 weeks. In this

Table 2
Properties of bentonite in GCLs tested.

GCL	Grain Size Distribution (mm)				Smectite Content (%)[a]	Swell Index (ml/2g)[b]	Cation Exchange capacity (meq/100g)[b]
	D_{10}	D_{30}	D_{60}	D_{90}			
GCL1	0.1	0.28	0.35	0.65	50–55	26	80
GCL2	0.15	0.3	0.35	0.7	50–55	24	80
GCL3	0.4	0.65	1.1	1.7	53–58	23	100

[a] Data from Bostwick L,E, (2009).
[b] Tests performed by M. Hosney, Queen's University.

Table 1
Properties of the reinforced GCLs examined.

GCL	Total dry mass/area (g/m^2)	Initial moisture content, w (%)	Carrier GT		Cover GT		Layer Connection	Average peel strength (N)	Designation in this paper
			Type	Mass (g/m^2)	Type	Mass (g/m^2)			
NSL	4628–5650	7	W	120–126	NW	216–258	NPTT	94 ± 16	GCL1
NWL	3486–5068	7	SRNW	230–253	NW	200–224	NPTT	260 ± 17	GCL2
DN	4307–5145	8–10	NW	200–283	NW	226–263	NP	219 ± 30	GCL3

W = Woven, NW = Nonwoven, SRNW = Scrim reinforced nonwoven, NP = Needle punched, NPTT = Needle punched and thermally treated; The Geotextile masses were measured by D.N. Arnepalli, Queen's University. Peel strength tests performed by M. Hosney, Queen's University.

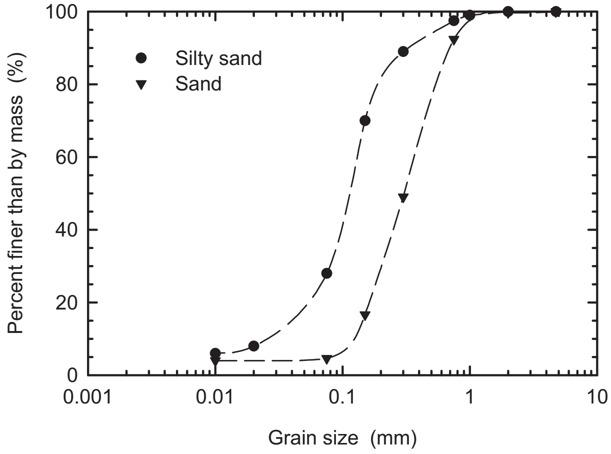

Fig. 1. Grain size distributions for the foundation soils examined.

paper, all moisture contents reported are gravimetric moisture contents (i.e., mass of water/mass of solids). Typical results for three tests conducted on GCL1, GCL2 and GCL3 are shown in Fig. 5. These were all obtained with the silty sand foundation soil at an initial moisture content of $w_{fdn} = 16\%$. All three showed a rapid increase in moisture content over the first 10 weeks, reaching gravimetric moisture contents of between about 80 and 100%. After 10 weeks, the rate of moisture uptake decreased and the GCLs reached essentially steady-state conditions with the foundation soil after 30 weeks, beyond which there was no significant (less than 4%) further increase in moisture content when allowed to hydrate for up to 70 weeks.

Recognizing that the hydration of GCLs may be expected to be different for different products (e.g., GCL3 is different to GCL1 and GCL2 in Fig. 5), the measured moisture contents (w) are normalized in this paper by their hydration potential, w_{ref}, under specified conditions, which is defined here to be the moisture content to which a GCL will hydrate when immersed in water while being subjected to a 2 kPa confining stress. This is a reference moisture content that represents the maximum moisture content to which the GCL is likely to hydrate at a nominal stress of 2 kPa. These were measured (based on five replicates) to be 140% (±4%), 115% (±3%) and 150% (±5%) for GCLs1–3, respectively. Fig. 6 shows the results from Fig. 5 when normalized by w_{ref} for each GCL. In the remainder of this paper, GCL hydration results are presented in terms of w/w_{ref}.

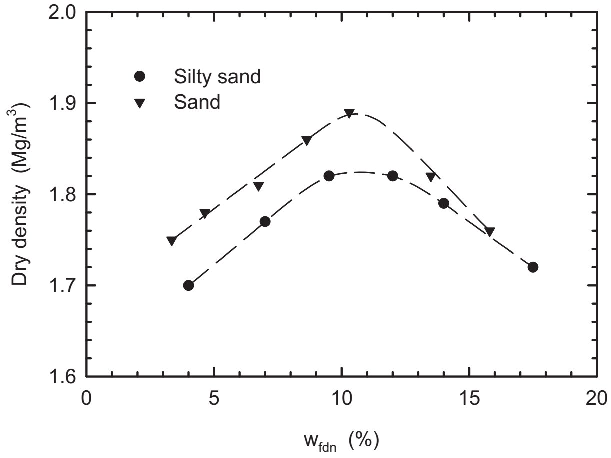

Fig. 2. Standard Proctor compaction results for the foundation soils examined.

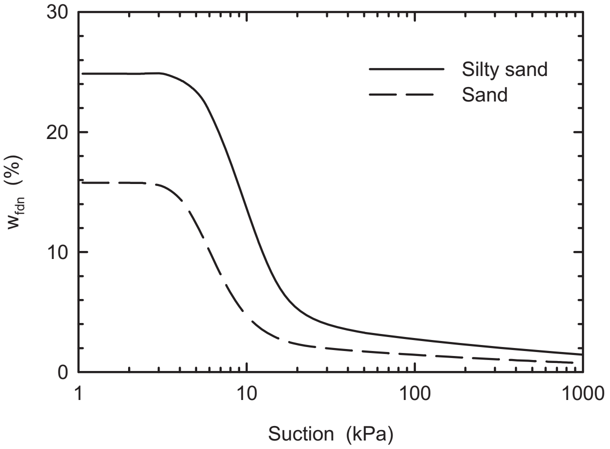

Fig. 3. Estimated water retention curves for the foundation soils examined.

4.2. Effect of foundation soil moisture content on GCL hydration

Normalized moisture content results from tests conducted with the silty sand soil prepared at four different moisture contents (5%, 10%, 16% and 21%) are presented in Fig. 7. These four moisture contents ranged from near field capacity to the residual moisture content (i.e., near the wilting point). In each case the moisture content of the GCL increases from its initial moisture content as it comes into equilibrium with the foundation soil. As expected the rate of hydration increases with increasing foundation soil moisture content. Interestingly, about half of the ultimate moisture uptake occurs in the first week and typically more than 70% of the uptake occurred in the first 5 weeks. The time to reach the final equilibrium moisture content depended on both the product and subsoil moisture content. The quickest water uptake occurred in GCL2 placed on the silty sand at 21% moisture content; in this case the GCL achieved 97% of its final equilibrium moisture content in 5 weeks. GCLs1 and 3 placed on silty sand at 21% moisture content

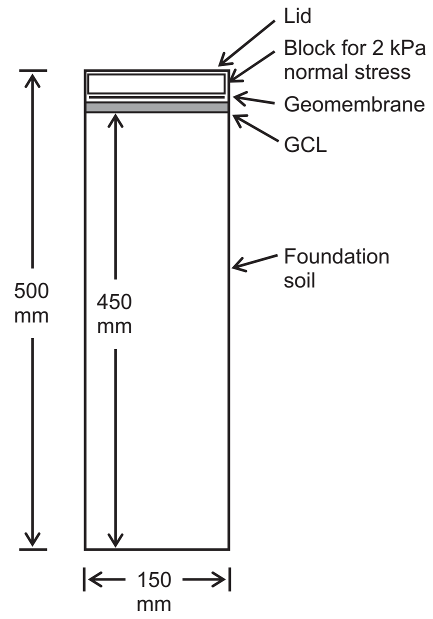

Fig. 4. Schematic of apparatus used for isothermal hydration.

Table 3
Experimental details: Subgrade dry density was 1.65 Mg/m^3 for all cases. Subgrade was Godfrey silty sand (SM) and seating load was 2 kPa unless otherwise noted.

GCL type	GCL		Initial Subgrade w (%)	GT component of GCL in contact with underlying soil	Test
	w (%)	Total Dry mass/area (g/m^2)			
GCL1	7.5	4752	5	W	PM14
GCL1	7.5	4771	10	W	PM15
GCL1	7.0	4709	16	W	PM5
GCL1	7.0	4628	16	NW cover	PM6
GCL1	6.0	5650	21	W	PM12
GCL2	5.8	4437	5	SRNW	PM16
GCL2	5.8	5068	10	SRNW	PM17
GCL2	2.6	3486	16	SRNW	PM7
GCL2	8.8	4877	16	SRNW	PM9
GCL2	6.6	4585	16	NW cover	PM3
GCL2	8.1	4627	21	SRNW	PM13
GCL2	6.3	4771	2[a]	SRNW	PM18
GCL2	6.3	4409	10[a]	SRNW	PM19
GCL3	5.0	4846	5	NW carrier	PM4
GCL3	8.3	5063	10	NW carrier	PM10
GCL3	9.0	5044	16	NW carrier	PM2
GCL3	6.4	4974	16	NW cover	PM8
GCL3	8.3	5145	21	NW carrier	PM11
GCL3[b]	8.4	4307	16	NW carrier	PM1

[a] Sand (SP) subgrade.
[b] No seating load.

achieved about 90% in of their final equilibrium moisture content in 5 weeks.

The ultimate moisture content attained by the GCL is a function of the moisture available in the foundation soil. As shown in Table 4, increasing the moisture content of the foundation soil results in an increase in the equilibrium moisture content of the GCL. The equilibrium moisture content of GCLs placed on foundation soil at 5% ranges between 24% and 55% of the reference moisture content (Fig. 8 and Table 4). GCLs placed on the silty sand at 21% moisture content attained 100% of the reference water content.

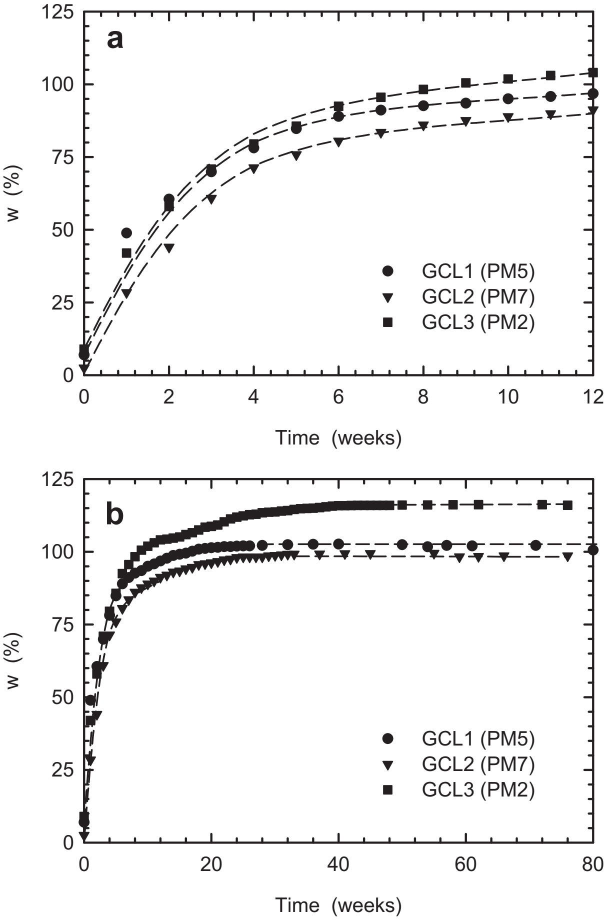

Fig. 5. Effect of GCL type on GCL hydration. Silty sand subgrade, w_{fdn} = 16%. (a) hydration in first 12 weeks, and (b) hydration for more than a year.

Table 4
Moisture content of GCLs after different elapsed times. All test on Godfrey silty sand (SM) with carrier geotextile on subgrade and 2 kPa seating pressure unless noted otherwise.

GCL	Initial subgrade w (%)	GCL Moisture Content, w (%)							w/w_{ref} after week				Test
		Initial (%)	1 day(%)	1 week (%)	5 weeks (%)	10 weeks (%)	20 weeks (%)	30 weeks (%)	5 (%)	10 (%)	20 (%)	30 (%)	
GCL1	5	7.5	12	23	35	35	34	34	25	25	24	24	PM14
GCL1	10	7.5	18	38	73	80	86	86	52	57	62	62	PM15
GCL1	16	7	22	45	84	95	101	102	60	68	72	73	PM5
GCL1	16	7	22	42	73	90	102	105	52	64	73	75	PM6[a]
GCL1	21	6	30	80	128	141	141	141	91	100	100	100	PM12
GCL2	5	5.8	12	22	37	38	39	40	32	33	34	34	PM16
GCL2	10	5.8	15	36	72	79	85	85	63	69	74	74	PM17
GCL2	16	2.6	21	44	80	89	97	99	68	76	83	85	PM7[b]
GCL2	16	8.8	24	45	76	81	86	88	66	70	75	77	PM9
GCL2	16	6.6	20	45	77	85	87	89	67	74	76	77	PM3[a]
GCL2	21	8.1	30	63	112	116	116	116	97	100	100	100	PM13
GCL2	2	6.3	11	22	30	31	31	31	26	27	27	27	PM18[c]
GCL2	10	6.3	19	51	79	86	87	90	68	75	76	78	PM19[c]
GCL3	5	5	13	31	48	62	76	83	32	41	50	55	PM4
GCL3	10	8.3	22	36	75	91	99	102	50	61	66	68	PM10
GCL3	16	9	20	42	86	102	109	114	57	68	73	76	PM2
GCL3	16	6.4	19	38	79	103	115	120	53	68	77	80	PM8[a]
GCL3	21	8.3	35	91	134	141	149	149	89	94	99	99	PM11
GCL3	16	8.4	19	33	53	83	93	119	33	52	58	74	PM1[d]

w_{ref} = 140% for GCL1, w_{ref} = 115% for GCL2 and w_{ref} = 150% for GCL3.
[a] Cover geotextile in contact with subgrade for these tests.
[b] Very low mass per unit area for this case.
[c] Sand (SP) for PM18 and 19.
[d] No seating load.

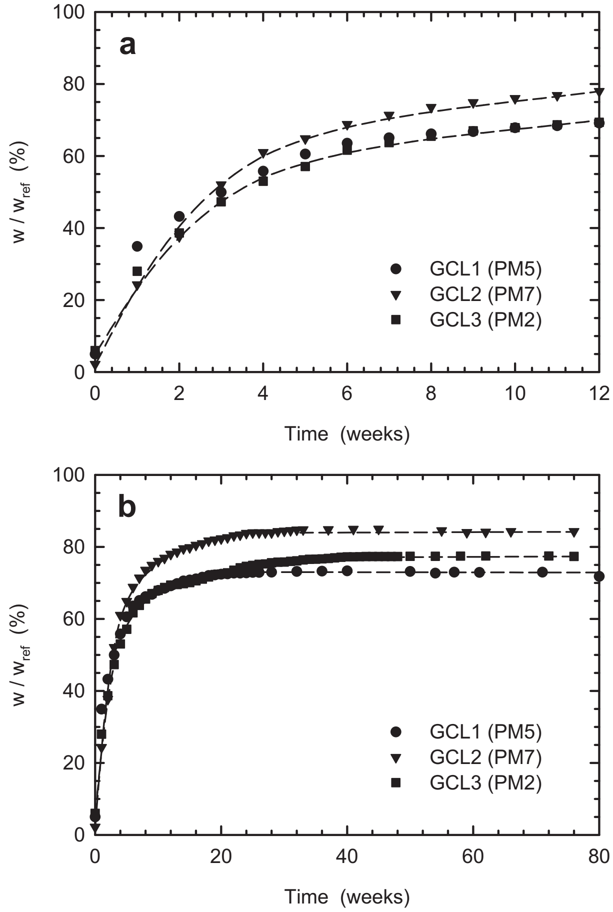

Fig. 6. Effect of GCL type on normalized hydration (w/w_{ref}). Silty sand subgrade, $w_{fdn} = 16\%$. (a) hydration in first 12 weeks, and (b) hydration for more than a year.

4.3. Effect of GCL manufacture on hydration

The method of GCL manufacture affected the moisture uptake by the GCLs both when immersed in water and resting on the silty sand foundation soil. All GCL contained Wyoming bentonite with swell indices between 23 and 26 mL/2 g, similar smectite content but cation exchange capacity of 80 meq/100 g for GCLs1 and 2 and 100 meq/100 g for GCL3 (Table 2). When immersed in water with a 2 kPa seating pressure, the constraint imposed by the good anchorage of the needle punched fibers by the scrim-reinforcement and thermal treatment of the carrier geotextile for GCL2 (peel strength 260 N, Table 1) limited the swelling and the moisture content stabilized at about 115% (with a slight variation). Even though it was thermally treated, the woven carrier in GCL1 (peel strength 94 N, Table 1) provided much less effective anchorage and hence was less effective at constraining swelling and the moisture content stabilized at 140%. The least effective anchorage of fibers was for GCL3 (peel strength 219 N, Table 1) which stabilized at moisture content of about 150%. Despite the much higher peel strength, GCL3 hydrated to slightly higher moisture content (w_{ref}) than GCL1.

This finding is similar to that of Petrov et al. (1997), Lake and Rowe (2000a,b) and Beddoe et al. (2011) who reported that improved anchorage of the needle-punching restricted the GCL swell, lowered bulk GCL void ratios and consequently gave (other factors being equal): (a) lower hydraulic conductivity, (b) lower diffusion coefficients, and (c) less difference between the wetting and drying water retention curves. This is especially true for GCL2;

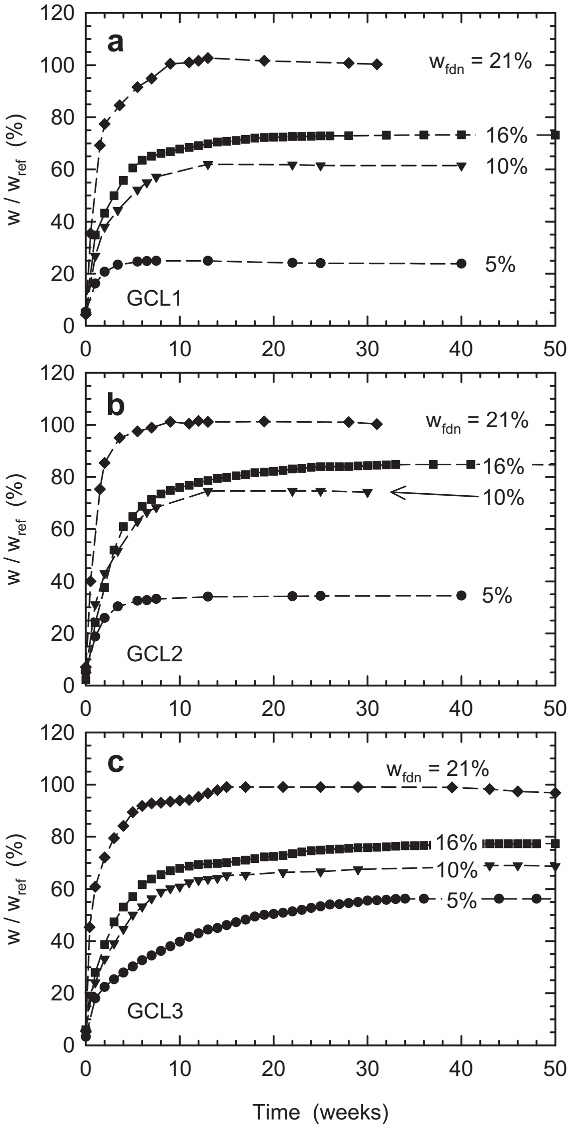

Fig. 7. Effect of initial subgrade moisture content (w_{fdn}) on normalized GCL hydration (w/w_{ref}). Silty sand subgrade.

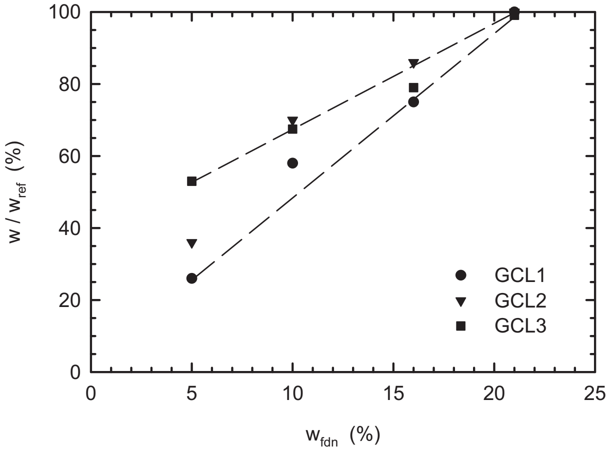

Fig. 8. Effect of initial subgrade moisture content (w_{fdn}) on GCL normalized hydration (w/w_{ref}). Silty sand subgrade after 30 weeks.

in this study and that by Beddoe et al. (2011) the performance of GCL1 was closer to that of GCL3 than GCL2 and this is attributed to the better anchorage achieved with the scrim reinforce nonwoven in GCL2 than for either GCL1 and GCL3.

When placed on the silty sand foundation soil at essentially field capacity (21%), all three GCLs hydrated to equilibrium moisture contents in excess of 99% of the reference value (Table 4). The time taken to reach about 95% of the reference values was about 3.5 weeks for GCL2, 7 weeks for GCL1 and about 10 weeks for GCL3. Of particular note in terms of the effect of method of GCL manufacture is the change in thickness of the GCL as it hydrates (Table 5). On this foundation soil with ample water to fully hydrate the GCL, the final hydrated thickness was 10.4, 8.2 and 10.9 mm and this represents an increase from the initially air dry state of 22%, 6% and 18% for GCL1–GCL3 respectively. This difference is manifest by a lower bulk void ratio for the hydrated GCL2 than the other two GCLs (Table 5) which can be expected to result in improved performance as noted above for the water hydrated samples. This is the result of the much better anchorage of the needle punched fibers afforded by the thermal treatment of the nonwoven carrier of GCL2 than was evident for either the other two GCLs. The improved bulk void ratio of GCL2 compared to GCL3 is consistent with the earlier findings of Petrov et al. (1997) and Lake and Rowe (2000a,b). However in their tests the GCL with a thermally treated woven carrier (product NS) provided much better anchorage of the thermally treated woven carrier in the presently tested product (NSL). The NSL product was manufatured to be a “lighter” (hence the “L”) version of the NS with less material so that it would be more competitive in markets where GCLs are primarily selected based on price. What is apparent here is that the changes made to achieve a reduction in cost has also resulted in some reduction in hydration performance relative to the former NS product and its current companion product (GCL2). The improved hydration performance of GCL2 to GCL1 from the same manufacturer as well as compared to GCL3 from a different manufacturer is consistent with other studies (e.g. Beddoe et al., 2011). This highlights the importance of manufacture and changes that can occur over time even with the same manufacturer.

4.4. Effect of small confining stress on GCL hydration

All but one of the tests reported in this paper were conducted with a 2 kPa confining stress on top of the GCL. The small confining stress was applied to improve experimental repeatability by reducing the potential for zones of poor contact between the GCL and foundation soil. Fig. 9 shows results from the one test conducted with zero confining stress. These values were normalized by a reference moisture content of 160%, obtained when immersed in water with no confining stress. Without the small confining stress, the rate of moisture uptake from the foundation soil was slower and it took 30–35 weeks before reaching a similar moisture content as when the 2 kPa pressure was used.

4.5. Effect of GCL mass per unit area on hydration

Although GCLs have a minimum average roll value certified by the manufacturer, there can be considerable variability in the mass per unit area of samples taken from the same roll as is evident from the range given in Table 1. To investigate the influence of GCL mass per unit area on the rate of hydration, two samples of GCL2 with mass per unit area of 3490 g/m^2 (PM7) and 4880 g/m^2 (PM9) were examined under otherwise similar conditions. There was a small difference in the moisture uptake between the two tests (Table 4 and Fig. 10) with the higher mass per unit area sample initially taking up moisture faster but then coming to a final equilibrium moisture content slightly lower than that for the lower mass per unit area sample. The ratio of equilibrium moisture content to the reference value (w/w_{ref}) was about 86% for the specimen with the lower mass per unit area and about 77% for that with the higher mass of bentonite per unit area. Thus the mass per unit area appears to have some small effect on hydration but further testing would be required to investigate the mechanism by which this is achieved.

4.6. Effect of GCL placement on hydration

GCLs are commonly placed with the carrier geotextile in contact with the foundation soil and this was the normal case considered in

Table 5
GCL thickness (mm) with time of hydration and 30 week bulk void ratio.

GCL type	Initial sub grade w (%)	Initial thickness (mm)	1 week	5 weeks	10 weeks	20 weeks	30 weeks	Bulk void ratio at 30 weeks	Tests
GCL1	5	6.2	6.2	6.4	7.0	7.3	7.7	2.70	PM14
GCL1	10	7.0	7.0	7.4	7.7	8.0	8.2	2.93	PM15
GCL1	16	6.2	6.9	7.5	8.0	8.1	8.2	2.95	PM5
GCL1	16	6.2	6.4	6.5	6.7	7.4	8.0	2.92	PM6[a]
GCL1	21	8.5	8.9	9.4	9.6	10.4	10.4	3.28	PM12
GCL2	5	6.0	6.0	6.1	6.4	6.9	6.9	2.30	PM16
GCL2	10	6.8	6.8	7.0	7.2	7.9	7.9	2.41	PM17
GCL2	16	6.0	6.1	6.4	6.8	6.8	6.8	2.81	PM7[b]
GCL2	16	7.0	7.2	7.8	7.9	8.0	8.0	2.63	PM9
GCL2	16	7.0	7.2	7.5	7.8	7.8	8.0	2.75	PM3[a]
GCL2	21	7.7	7.8	8.0	8.2	8.5	8.5	3.00	PM13
GCL2	2	6.1	6.1	6.2	6.4	6.6	6.6	1.99	PM18[c]
GCL2	10	6.1	6.2	6.5	7.0	7.6	7.6	2.66	PM19[c]
GCL3	5	7.9	8.0	8.4	8.5	8.6	8.6	2.74	PM4
GCL3	10	9	9.2	9.3	9.3	9.4	9.4	3.05	PM10
GCL3	16	7.8	8.0	8.1	8.6	8.8	9.2	3.00	PM2
GCL3	16	9	9.2	9.6	10.4	10.5	10.5	3.53	PM8[a]
GCL3	21	9.2	9.8	10.4	10.5	10.8	10.9	3.64	PM11
GCL3	16	7.8	7.9	8.0	8.1	8.5	8.7	3.24	PM1[d]

[a] Cover geotextile in contact with subgrade for these test.

[b] Very low mass per unit area for this case.

[c] Concrete sand (PM18 and 19).

[d] No seating load.

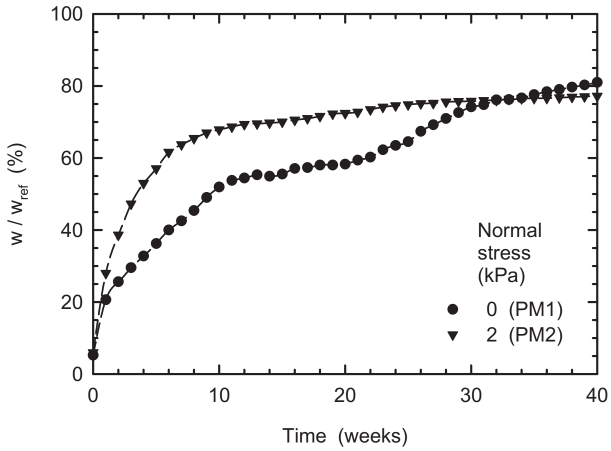

Fig. 9. Effect of normal stress on normalized hydration (w / w_{ref}) for GCL 3. Silty sand subgrade, $w_{fdn} = 16\%$.

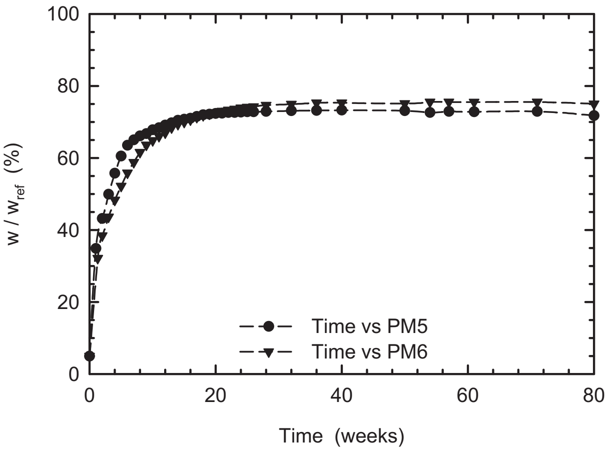

Fig. 11. Effect of geotextile in contact with subgrade on normalizesd hydration (w/w_{ref}) for GCL1. Silty sand subgrade, $w_{fdn} = 16\%$.

this study. To assess what, if any, effect this may have on the hydration of the GCL, three tests (PM6, PM3 and PM8 in Tables 3 and 4) were conducted with the cover geotextile directly on the foundation soil. The results for GCL1 (Table 4 and Fig. 11) show that little difference in the equilibrium water content and rate of hydration can be observed despite the differences in geotextile type (W versus NW) in contact with the subsoil. Similar results were observed for GCL2 (PM5 and PM6) and GCL3 (PM2 and PM8). This suggests that the mode of hydration is not dependent on the type of geotextile which is placed in contact with the foundation soil.

4.7. Influence of soil type on GCL hydration

To examine the effect of foundation soil type (and hence the water retention curve), one test was conducted for GCL2 placed on sand for comparison with silty sand. Fig. 12 shows the moisture uptake for the two soils at initial 10% moisture content. The rate of hydration was slightly higher for the sand than for the silty sand. The GCL moisture uptake of about 60% of the reference value (w/w_{ref}) occurred in the first 2 weeks on sand, while it took about 5 weeks on the silty sand. However, the time to reach the final equilibrium moisture content was similar for both foundation soils. The difference in rate of hydration of the GCL is attributed to the complex unsaturated behavior of the foundation soil-GCL interaction. At lower suctions the sand will have a higher unsaturated conductivity and will allow initial passage of water to the GCL faster than the silty sand. As the GCL extracts water from the soil and the soil suction increases the unsaturated conductivity of the sand dips below that of the silty sand which allows the GCL on the silty sand to catch up. From the water retention curves, the sand has

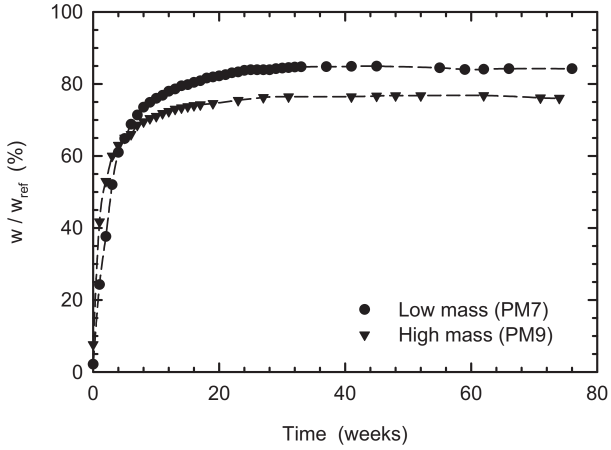

Fig. 10. Effect of mass per unit area on normalized hydration (w/w_{ref}) for GCL2. Silty sand subgrade, $w_{fdn} = 16\%$.

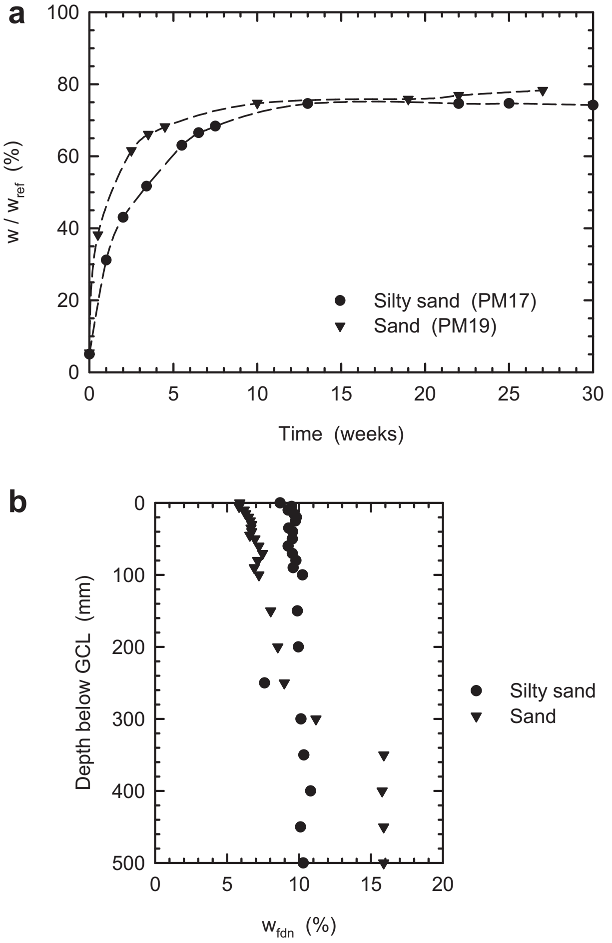

Fig. 12. Effect of subgrade soil type on GCL2 hydration $w_{dfn} = 10\%$. (a) (w/w_{ref}) with time and (b) equilibrium subgrade water content.

a lower suction compared with the silty sand at similar water contents, however the sand is a free-draining material. Therefore although the average moisture content was 10%, downward moisture migration occurred during the period before placement of the GCL and subsequently. As a consequence, the final moisture at the soil-GCL interface was closer to 6% for the sand compared with about 9% in the silty sand. Comparing the water retention curves in Fig. 3 this in turn should still lead to a slightly higher equilibrium moisture content for the GCL placed on top of sand. However GCL2 has a very flat water retention curve (Beddoe et al., 2011) in the low suction region and therefore the changes in suction did not result in any significant changes in moisture content.

4.8. *Comparison with findings from previous studies*

Daniel et al. (1993) investigated the hydration of an adhesive bonded GCL consisting of 3.5-mm-thick layer of sodium bentonite mixed with an adhesive and attached to a geomembrane (Gundseal) placed on a foundation sand ($D_{10} = 0.2$ mm, $D_{60} = 0.5$ mm, $D_{85} = 0.7$ mm) at initial sand moisture contents between 1% and 17%. These adhesive bonded GCLs were observed to hydrate to GCL moisture contents of approximately 75% and 155% when on sand at 2% and 10% moisture content, respectively (after 6 weeks). The sand used in the experiments of Daniel et al. (1993) is similar to the one used in the present study ($D_{10} = 0.15$ mm, $D_{60} = 0.38$ mm, $D_{85} = 0.6$ mm) in which needle punched GCL2 was observed to hydrate to moisture contents of 30% and 79% after 5 weeks of equilibration with sand foundations at 2% and 10% moisture contents (PM18 & PM19, Table 4). This large difference in moisture content between the adhesive bonded GCL and the needle punched GCL illustrates the higher degree of confinement (and resistance to large increases in void ratio) provided by needle punched GCL.

Eberle and von Maubeuge (1997) reported that a needle punched GCL placed with a well graded sand (90% passing 4.75 mm sieve and at an initial moisture content of 8–10%) both above and below it, achieved a moisture content of 100% in less than 24 h and 140% after 60 days under isothermal conditions (23 °C). These results indicate that the rate of hydration in these experiments were significantly higher than the present study (e.g. PM10, 15, 17, 19 in Table 4). This significant difference in GCL moisture uptake is probably due to a combination of factors but in particular (a) the presence of powdered bentonite in their GCL compared with granular bentonite in the present study, and (b) hydration from two sides in their experiment compared with from only one side in the current study (which simulates a GCL in a composite liner).

5. Conclusions

The hydration of different GCLs from the pore water of the underlying foundation soil in a closed-system was investigated for isothermal conditions at room temperature 22 °C. Three different reinforced (needle punched) GCL products were tested for hydration from both an underlying silty sand (SM) and sand (SP) foundation soil for time periods up to 70 weeks.

Of the factors examined, the initial water content of the silty sand foundation layer had the greatest impact on the rate of GCL hydration and the steady-state GCL moisture content. GCLs placed on a foundation soil with an initial moisture content close to field capacity hydrated to moisture contents that were essentially the same as if the GCL was immersed in water. In contrast, GCLs on soil at initial moisture content close to their residual moisture content (5% for the silty sand and 2% for the sand considered) only hydrated to a gravimetric moisture content of 30–35%, which is only about a quarter of the value achieved immersed in water.

The method of GCL manufacture was also found to have a significant effect on the rate of GCL hydration and the steady-state GCL moisture content at low foundation moisture contents because of the difference in confinement of the bentonite afforded by the combination of different carrier geotextiles and the presence/absence of thermal treatment of the needle punched fibers.

It was also found that the presence or absence of a small (2 kPa) seating pressure (which affects the intimacy of contact between the GCL and foundation soil) affected the rate of hydration but not the final moisture content. Due to the differences in the water retention curves of the different foundation soil, a GCL placed on a sand (SP) demonstrated faster hydration and slightly higher final moisture content than when on a silty sand (SM) with same initial moisture content. For the particular GCLs tested, hydration did not change significantly irrespective of whether the cover or carrier GCL rested on the foundation soil, suggesting that the water retention characteristics of the GCL are not affected by placement orientation.

The results are for the specific materials and conditions tested and should not be directly used for significantly different conditions without independent verification.

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