

Geosynthetic clay liners: Perceptions and misconceptions

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ABSTRACT: The behaviour of geosynthetic clay liners (GCLs) as part of a physical-environmental system is examined. Consideration is given to: (a) both the physical and hydraulic interactions with the materials, and the chemical interactions with the fluids, above and below the liner, (b) time dependent changes in the materials, (c) heat generated from the material to be contained, as well as (d) the climatic conditions both during construction and during service. This paper explores some common perceptions about GCL behaviour and then examines the misconceptions that can arise and their implications. It demonstrates how what may first appear obvious is not always as one expects and that more is not always better. It discusses: (i) the pore structure of a GCL, (ii) the dependency of the water retention curve of the GCL on its structure, bentonite particle sizes and applied stress, (iii) the effect of the subgrade pore water chemistry, (iv) the mineralogy of the subgrade, and (v) thermal effects. The desirability of a GCL being reasonably well-hydrated before being permeated is examined. The critical size of needle-punch bundles at which preferential flow can increase hydraulic conductivity by orders of magnitude is illustrated. The dependency of self-healing of holes on the interaction between GCL and subgrade is discussed. Finally, the transmissivity of the geomembrane/GCL interface is shown to be a function of GCL and geomembrane characteristics and to be poorly correlated with GCL hydraulic conductivity.

Keywords: Geosynthetic clay liner, Hydration, Hydraulic conductivity, Interface transmissivity

1 INTRODUCTION

For the past few decades, geosynthetics have been successfully containing fluids (be they liquids or gases) and protecting the environment. Their use grew out of geotechnical engineering but has now evolved considerably with the development of new materials and new variations on the original basic geosynthetics. The focus of this paper and the related presentation is on geosynthetic clay liners (GCLs): how they interact with the surrounding environment and how this can affect their performance.

GCLs may be used as a sole liner (e.g., for potable water ponds, some covers) or as part of a composite liner (e.g., for landfill bottom liners, heap leach pads, some covers). The primary resistance for fluid flow through a GCL is provided by the bentonite. Bentonite (typically sodium bentonite) is known for its low permeability to liquids and gases when well-hydrated; this low permeability being especially critical for gases. It is often assumed that the GCL will hydrate sufficiently from the adjacent soil and, indeed, it often does. However, there are many factors affecting the hydration, and dehydration, of a GCL that have not been well understood. In particular, the interaction between the GCL and its surrounding environment (including the climatic conditions) need very careful consideration in critical designs. This is true for GCLs used both as a sole liner and as part of a composite liner.

There has been great progress in the development of geosynthetic liners and in understanding the factors affecting their field performance that should be considered in design and construction. However, there is still a very prevalent assumption that a liner system with a geomembrane (GMB) and/or GCL will work despite ignorance or lack of care. There is too much emphasis on 20th Century folk law and not enough sound engineering based on 21st century knowledge. In particular, while good emphasis is often placed on ensuring adequate components when viewed in isolation, in the writer's opinion (based on fo-

rensic cases), too little attention is still being paid to liners as part of a physical-environmental system. This involves both the physical and hydraulic interactions of the liner with the materials above and below the liner, the chemical interactions with the fluids above and below the liner, the time dependent changes in the materials, the effect of heat generated by the material to be contained, as well as the climatic conditions both during construction and during service. As part of a physical-environmental system, a liner may be subjected to time-varying temperature, chemistry, and stresses/strains as the system ages (e.g., settlements below the liner, degradation and settlement of waste above the liner).

The objective of this paper is to summarize some recent findings regarding GCLs when used alone or in a composite liner and to direct the reader to other useful sources of more information on the issues touched upon herein. Dealing with GCL performance as an advective barrier in a physical-environmental system, this paper may be loosely thought of as the first in a three-part series. The second part (Rowe 2018a) deals with the geomembrane alone or in a composite liner as an advective barrier in a physical-environmental system. The third part (Rowe 2018b) deals with the barrier system including leachate collection system and liners and both advective and diffusive transport in containment and remediation applications.

2 PERCEPTIONS AND MISCONCEPTIONS

There are many perceptions commonly held by engineers and owners. Common perceptions relevant to this paper are that:

1. a GCL will be sufficiently hydrated from the subgrade to have the hydraulic conductivity, k , no higher than that given in the product specifications sheet (e.g., $k \leq 5 \times 10^{-11}$ m/s),
2. the form of the bentonite (coarse granular, fine granular, powder; Figure 1) does not matter since they will all have the same k when hydrated and permeated at the same stress with the same permeant,
3. how a GCL is manufactured will not affect performance since it is the hydrated bentonite that controls k ,
4. needle-punching only affects peel and shear strength (i.e., does not affect k),
5. leakage through a composite liner is controlled by the head on the liner, the number and size of holes in the geomembrane, and the permittivity (i.e., hydraulic conductivity divided by the thickness) of the underlying clay liner,
6. leaving a composite liner exposed for a protracted period of time has no effect on its hydraulic performance.

These perceptions may indeed be valid under certain circumstances, but this paper will seek to demonstrate that there are many important practical situations where these are misconceptions and designs need to take a more sophisticated view of GCL performance for important projects.



Figure 1. Deconstructed GCLs with coarse granular, fine granular, and powdered bentonite. Scale in cm.

3 GEOSYNTHETIC CLAY LINERS (GCLs): THE IMPORTANCE OF HYDRATION

Typically comprised of a layer of sodium bentonite sandwiched between two geotextiles and needle-punched together, GCLs have the capacity to be excellent barriers to the advective movement of both liquids and gases. When used alone, the resistance to fluid flow (advection) is controlled by the permeability of the GCL with respect to that fluid. To achieve a low permeability, a GCL will need to be adequately hydrated. This hydration is often assumed to occur due to moisture uptake (suction) from the adjacent soil (Figure 2). In some cases, it may occur from the liquid to be contained (e.g., when used as a pond liner or

locally in the area surrounding a hole, or wrinkle with a hole, in the GMB in a composite liner; Figure 3). In rare cases (e.g., for the GCL in a primary composite liner underlain by a drainage layer and secondary composite liner; Figure 4), by fluid accidentally (e.g., accumulated rainfall in the drainage layer during construction) or intentionally added through the drainage layer. This moisture uptake is important because, inter alia, it influences:

- the ability of GCL to contain hydrocarbons from both advective and diffusive transport (due to the high diffusion coefficient of volatile organic hydrocarbons through traditional GMBs; Rowe 2018b);
- the ability of the GCL to contain gases;
- the effect of cation exchange from surrounding soil on GCL hydraulic performance;
- the effect of leachate interaction on GCL hydraulic performance;
- GCL panel shrinkage and down-slope bentonite erosion for exposed liners; and
- the self-healing capacity of a GCL with a hole.

Despite its importance, frequently little thought is given to hydration. Very few specifications say anything about the conditions needed to ensure sufficient hydration for a particular application. Commonly GCL installation specifications (e.g., ASTM 6102) say very little about the foundation layer below the GCL other than that it should be firm and unyielding with no abrupt changes in grade and with a maximum protrusion size (e.g., 12 mm) and, in some cases, with maximum allowable rut depth of 25 mm (ASTM 6102). Occasionally the foundations will be required to be compacted within 1-2% of standard Proctor optimum water content (e.g., $w_{opt} \pm 2\%$). In some cases, compaction at $w_{opt} \pm 2\%$ may be sufficient to ensure reasonable hydration. For example, Daniel et al. (1993) reported hydration to 155% gravimetric moisture content for a GCL with sodium bentonite mixed with an adhesive and glued to a geomembrane on a sand foundation ($D_{10}=0.2$ mm, $D_{60}=0.5$ mm, $D_{85}=0.7$ mm) at an initial moisture content, $w_{fdn} = 10\%$. Also, Eberle and von Maubeuge (1997) reported GCL hydration to 140% for a needle-punched GCL with powdered bentonite placed on a well graded sand ($D_{90} = 4.75$ mm) at an initial moisture content, w_{fdn} , of 8-10%. Perhaps because of these examples, it has become part of GCL-mythology that a GCL will generally hydrate to $w \geq 100\%$ gravimetric moisture content and that $w = 100\%$ will provide adequate performance. For example, the French Committee for Geosynthetics (Fascicule No. 12, 1998) indicated that the GCL should be hydrated to at least 100% (Chevrier et al. 2012). There are situations where this is indeed valid – but generalities like this assume: (a) that the desired moisture content will be achieved, and (b) that 100% gravimetric will be adequate. This begs the question as to whether these two assumptions will generally be met. Furthermore, the focus on gravimetric water content loses sight of the fact that for many applications the required gravimetric water content will depend on how the GCL is constructed and in particular on the grain size of the bentonite. Similarly, the required apparent degree of saturation ($S_r \approx w / w_{ref}$, defined as the water content of the GCL, w , divided by the maximum water content to which the GCL would hydrate, w_{ref} , if sufficient water were available at the applied stress being considered) required for good performance will depend on GCL structure and bentonite grain size as will be demonstrated.

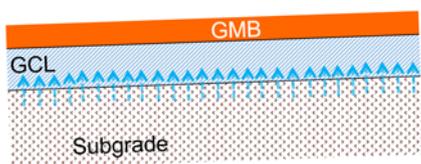


Figure 2. Hydration of GCL from subgrade

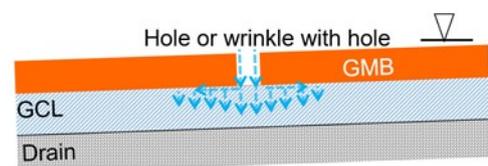


Figure 3. Local hydration of GCL from a hole in GMB

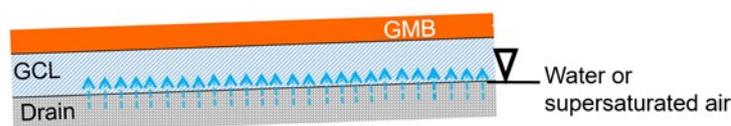


Figure 4. Hydration of GCL from underlying drain in a double composite liner

3.1 GCLs as barriers to hydrocarbons

GCLs are often used in secondary hydrocarbon containment applications to limit the migration of hydrocarbon spills including in remote and extreme locations like the Arctic (e.g., Bathurst et al. 2006, Rowe et al. 2007) and Antarctica (e.g., McWatters et al. 2016). Table 1 summarizes the water content of needle-punched GCLs with powdered bentonite exhumed from a composite liner below different biopiles (BP1-BP7) containing hydrocarbon contaminated soil after 1-3 years in service. The difference in hydration of the GCLs at different locations is notable – ranging from 22% to 66% to 154-182% gravimetric water contents, w , and apparent degrees of saturation (S_r) of about 12%, 36% and 85-100%, respectively. The difference in hydration was mostly related to different subgrade conditions at the different locations; the effect of subgrade on hydration will be discussed in a later section.

Rowe et al. (2005) examined the effect of water content and degree of saturation on GCL permeability to Arctic diesel (Table 2) of a scrim-reinforced needle-punched GCL with fine granular bentonite (denoted as GCL2). For $S_r \leq 70\%$, the permeability was very high and the GCL provided very limited resistance to permeation by Arctic diesel. For $S_r > 80\%$, relatively low permeability was achieved and, for the gradient examined, the permeability to Arctic diesel decreased to about 3×10^{-11} m/s. However, at $S_r > 80\%$, the permeability of a GCL to hydrocarbons is very dependent on the applied gradient as will now be demonstrated.

Table 1. Water content of GCLs exhumed from biopiles in Antarctica (modified from McWatters et al. 2016).

| GCL | Location | Year Exhumed | w (%) | S_r (%) |
|-------|----------|--------------|---------------|-----------|
| GCLA1 | BP1 | 3 | 162 (6, n=4) | 89 |
| | BP2 | 3 | 22 (1, n=4) | 12 |
| | BP4 | 3 | 66 (37, n=4) | 36 |
| | BP5 | 3 | 157 (11, n=4) | 86 |
| GCLA2 | BP3 | 3 | 154 (23, n=4) | 85 |
| GCLA3 | BP6 | 2 | 22 (2, n=4) | 12 |
| GCLA4 | BP7 | 1 | 182 (39, n=4) | 100 |

w : mean (standard deviations, %, n= number of specimens tested)

Table 2. Hydraulic conductivity of GCL2 permeated with Arctic diesel at 14kPa (adapted from Rowe et al. 2005)

| Degree of saturation, S_r (%) | Gravimetric water content, w (%) | Hydraulic conductivity, k (m/s) |
|---------------------------------|------------------------------------|--|
| ~ 7 | $\cong 8$ | 2×10^{-6} |
| ≤ 70 | 60-80 | $> 10^{-8}$ |
| ≥ 77 | 80 | $\leq 3 \times 10^{-10}$ |
| ~ 100 | 120 | 3.4×10^{-11} * (SD** 1.1×10^{-11} m/s) |

*Mean of 8 samples; ** Standard deviation

Mukunoki et al. (2004) demonstrated the dependence of the hydrocarbon permeability on hydraulic gradient (Figure 5). When a GCL was hydrated and permeated with water, the hydraulic conductivity was 2×10^{-11} m/s $< k < 4 \times 10^{-11}$ m/s. Once the water was replaced by the hydrocarbon, then for a pressure differential across the GCL of 7 kPa (equivalent to about 0.9m of hydrocarbon ponded on top of the GCL) the flow stopped. This is because when the bentonite pores are (mostly) saturated with water, the hydrocarbons do not displace the water until a threshold pressure is reached at which the hydraulic gradient is sufficient to overcome the interfacial tension between water and hydrocarbon. At this threshold, the water in the largest pores of the bentonite is displaced by hydrocarbon and flow begins. In these tests, the pressure head was increased in steps (and the cumulative volume monitored) until flow was measurable (Figure 5). The threshold pressure was between 14 and 21 kPa (depending on the specimen).

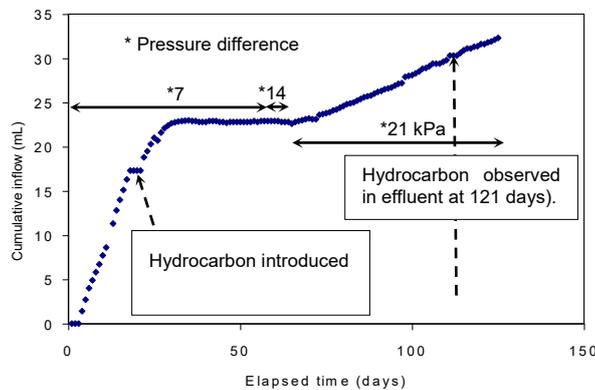


Figure 5. Cumulative inflow through water saturated GCL in FWP test (modified from Mukunoki et al. 2004)

3.2 GCLs as barriers to gas

GCLs are used as, or as part of, a barrier to greenhouse gas escaping from landfills (Didier et al. 2000a; Bouazza 2002, Hornsey et al. 2010, Bouazza et al. 2013, 2017b, Rowe 2005, 2014) and oxygen entering into covered piles of sulfidic mine tailings (Aubertin et al. 2000, Renken et al. 2005, Bouazza and Rahman 2004, 2007; Fourie et al. 2010), and to the movement of volatile hydrocarbons in hydrocarbon containment (McWatters et al. 2016). For relatively small differential pressures encountered in most practical applications, the resistance to gas flow (advection) can be expressed in terms of a gas permeability coefficient, k_g , (Bouazza and Vangpaisal 2003, Vangpaisal and Bouazza 2004, Rouf et al. 2016a,b) while the resistance to gas diffusion can be expressed in terms of a gas diffusion coefficient. This use of GCLs as gas barriers presumes that they will offer high resistance to both the advective flow (due to differential pressure) and diffusive transport (due to differential concentrations) between the two sides of the GCL. But under what circumstances will that be the case?

Rouf et al. (2016b) developed a “unified measurement system” to obtain both the gas permeability and gas diffusion coefficient from the same sample at different degrees of saturations and applied stress. Bouazza et al. (2017c) used this unified measurement system to obtain the gas permeability and gas diffusion coefficient for needle-punched GCLs with both powdered and coarse granular bentonite over a range of gravimetric water contents and apparent degrees of saturation at vertical stresses of 2 and 20 kPa. In this section, attention will be restricted to gas permeability although similar conclusions can be reached with respect to the gas diffusion coefficient.

For gravimetric water contents $w < 60\%$, the gas permeability was very high ($k_g > 1 \times 10^{-7}$ m/s) for GCLs with both powdered and coarse granular bentonite (Figure 6; Bouazza et al. 2017c) but for GCLs with powdered bentonite at $w > 60\%$ the values of k_g decreased rapidly. For the GCL with coarse granular bentonite the rapid decrease in k_g did not begin until $w > 100\%$. Thus at $w = 100\%$, k_g was about 1×10^{-7} m/s for the GCL with coarse granular bentonite but about 300-fold smaller at 3×10^{-10} m/s for the GCL with powdered bentonite. It was not until $w \geq 160\%$ that both GCLs were sufficiently hydrated to give a similar low value of $k_g \approx 2 \times 10^{-13}$ m/s. In terms of apparent degree of saturation, both had very high ($k_g > 1 \times 10^{-7}$ m/s) gas permeability for $S_r < 20-25\%$, after which k_g decreased and for both GCLs was low for $S_r > 78-80\%$ (Bouazza et al. 2017c). Given the sensitivity of k_g to water content, this raises the questions as to what water content can be expected in field situations and how does the nature of the GCL and sub-grade affect the hydration of the GCL?

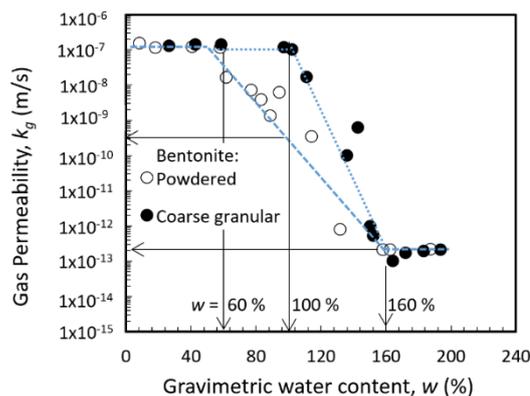


Figure 6. Gas permeability versus gravimetric water content under 20 kPa (modified from Bouazza et al. 2017c)

4 GEOSYNTHETIC CLAY LINER HYDRATION FROM ADJACENT SOIL

4.1 Basic concepts

The need for the uptake of moisture to provide adequate performance has been illustrated for the containment of hydrocarbons and gases in the previous two sections and the implications for other applications will be illustrated in subsequent sections. However, it is first important to discuss the mechanism for hydration of a GCL from the adjacent soil and the factors affecting the level of hydration.

The basic concepts behind GCL hydration are based on classical unsaturated soil mechanics and have been elaborated by numerous authors. To illustrate the basic concept, Figure 7 shows the water retention curves for a GCL and silt subgrade where it is assumed that when the two come into contact they have the “initial” water contents and suctions shown. The GCL (e.g., GCL4 in Figure 7) typically starts at a very low moisture content (relative to its final gravimetric, w_{ref} , or volumetric hydrated value) and a very high suction. For hydration to occur the subsoil must start at a lower suction (e.g., for the silt in Figure 7) and when the GCL and soil are in contact, the GCL uptakes moisture from the subgrade (e.g., the silt in Figure 7) and its suction is reduced while the subgrade loses moisture and the subgrade suction is increased. Depending on the GCL and subgrade moisture content, the GCL moisture uptake can be due to transport of water vapour (e.g., Rouf et al. 2016c) and/or subgrade pore water. The rate of change in moisture will be dictated by the diffusion coefficient for water vapor and the hydraulic conductivity of the soils; both of which will be dependent on the time-varying moisture content of the soils. Based on unsaturated soil mechanics, the hydration of the GCL is complete at a water content for both the GCL and subgrade dictated by the final equilibrium suction and will depend on the water retentions curves (WRC) of the GCL and subgrade as well as their initial water contents (especially that of the subgrade). However, when dealing with GCLs, hydration is more complicated than implied above which was based on granular soils. For GCLs, hydration is also affected by factors, such as: (i) the tri-modal pore structure of a GCL (Acikel et al. 2018a, 2018b), (ii) the dependency of the GCLs WRC on the GCLs structure (e.g., Beddoe et al. 2011) and applied stress (e.g., Abuel-Naga and Bouazza 2010, Siemens et al. 2012, Bannour et al. 2014), (iii) the chemistry of the subgrade pore water which can change the bentonite behaviour and its WRC, (iv) the mineralogy of the subgrade, and (v) thermal effects. These factors will be discussed in the following sections.

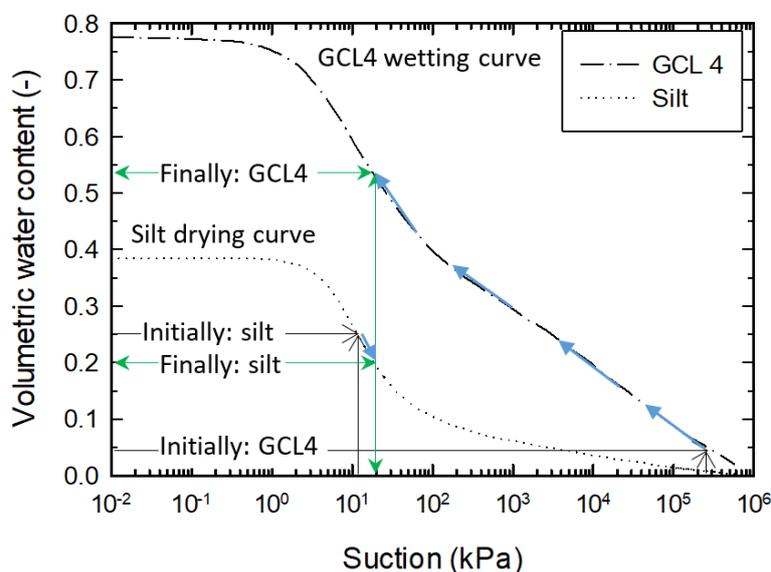


Figure 7. Water retention curves for GCL4 and a silt soil (GCL4 WRC from Beddoe et al. 2011; silt WRC from Siemens et al. 2012)

4.2 Pore structure of a GCL

As reviewed by Acikel et al. (2018a,b) and summarized here, GCLs have a tri-modal pore structure which includes (i) micro-pores (intra-aggregate, inter-particle, intra-particle, inter-layer in the bentonite), (ii) meso-pores (inter-aggregate pores) between the bentonite granules (particles) and intra-aggregate pores of the bentonite granules, and (iii) macro-pores (the geotextile pores). These various pore sizes may range over orders of magnitude and this will affect the moisture uptake and distribution within the GCL. The geotextile pores will often contain some bentonite, especially when the bentonite is powdered or has fine grains. The presence of this bentonite may affect the role of the geotextile pores as a potential capillary

barrier between the subgrade and the bentonite in the core of the GCL. Thus, prior to saturation, the WRC of a GCL, the rate of movement of water from the subgrade into the GCL, and the ultimate suction and equilibrium water content of the GCL will depend on the three types of pores, and hence the structure of the GCL (i.e., both the geotextiles and nature of the bentonite).

4.3 Effect of GCL structure on hydration

Beddoe et al. (2011) reported that the WRC of four GCLs (denoted in this paper at GCLs1-4) exhibited a significant variation in gravimetric moisture content at the same equilibrium suction. The differences were attributed to difference in the method of manufacture and the degree to which the fibres were inter-locked. The four GCLs were those used at the Queen's University Experimental Liner Site between 2006 and 2012 (QUELTS1; Brachman et al. 2007) to be discussed subsequently. Two of the GCLs, GCL1 and GCL2, had fine granular bentonite (Table 3) and were thermally treated (to melt needle-punched fibres passing through the carrier geotextile and bond them to the carrier) with GCL1 having a woven carrier and GCL2 having a scrim-reinforced nonwoven carrier geotextile. The other two GCLs had coarse granular bentonite (Table 3) with GCL3 having a woven carrier and GCL4 a nonwoven carrier geotextile.

Acikel et al. (2018b) concluded that GCL hydration is controlled by bentonite microstructure up to the water entry value (i.e., for $w < \text{about } 30\%$). As w increases above the water entry value, GCL structure assumes an increasingly important role in addition to the effect of bentonite microstructure. Consistent with the findings of Beddoe et al. (2011), Acikel et al. (2018a) reported that the WRC of two thermally treated GCLs with powdered bentonite were also notably affected by the different amount of confinement due to geotextile fibres resulting from different carrier geotextiles (one woven, one scrim-reinforced nonwoven) and bentonite mass per unit thickness (or bentonite density). These were also different to the WRC of a third GCL with coarse granular bentonite, with no thermal treatment and a woven carrier geotextile (i.e., similar to GCL3 tested by Beddoe et al. 2011).

Rayhani et al. (2011) examined the hydration of three of the four GCLs examined by Beddoe et al. (2011) when placed on QUELTS silty sand (Table 3) with an optimum water content, w_{opt} , of 11.4% and a field capacity of 21%. As implied by the difference in the WRCs noted above, the hydration characteristics of the GCLs were quite different on the same subgrade. For example, when the subgrade had a water content $w_{fdn}=16\%$, GCL2 hydrated to $w = 99\%$ while GCL4 hydrated to 114% (Table 4) but, because of its structure, much less water was required to hydrate GCL2 ($w_{ref}=120\%$) compared to GCL4 ($w_{ref}=195\%$) and, therefore, the apparent degree of saturation of GCL2 (83%) was much higher than that of GCL4 (58%) even though the gravimetric water content was lower. Thus, under these conditions, GCL2 (with $S_r > 80\%$) would have been much better barrier to either hydrocarbons or gas than GCL4. Thus, under realistic hydration conditions, the structure of the GCL may affect the suitability of the GCL as hydrocarbon or gas barrier, with the structure allowing a higher degree of saturation to be achieved on a given subgrade being preferable (i.e., GCL2 with the scrim-reinforced and thermally treated carrier in this comparison). As will be seen later, this is also true for other aspect of GCL performance under realistic hydration conditions.

Table 3. Grainsize distribution of GCLs and subgrades considered by various investigators

| Material | D ₁₀ | D ₃₀ | D ₆₀ | D ₉₀ | Reference |
|---------------------------|-----------------|-----------------|-----------------|-----------------|----------------------|
| Powdered bentonite | | | 0.075 | 0.125 | - |
| Fine granular bentonite | 0.15 | 0.29 | 0.35 | 0.67 | Rayhani et al. 2011 |
| Coarse granular bentonite | 0.4 | 0.65 | 1.1 | 1.7 | Rayhani et al. 2011 |
| QUELTS Silty sand (SM) | 0.03 | 0.07 | 0.12 | 0.3 | Rayhani et al. 2011 |
| QU-SYD Silty sand (SM) | 0.06-0.07 | 0.14 | 0.27 | 2.4 | Southen & Rowe 2005a |
| MU Silty sand (SM) | 0.002 | 0.06 | 0.15 | 0.61 | Bouazza et al. 2017c |
| SYD Sand (SW) | 0.16 | 0.44 | 1.0 | 3.0 | Yu et al. 2018 |
| MU Sand (SP) | 0.12 | 0.19 | 0.22 | 0.3 | Acikel et al. 2018b |
| FR Sand (SP) | 0.2 | 0.28 | 0.28 | 0.48 | Chevrier et al. 2012 |
| FR Clay | | | 0.002 | 0.014 | Chevrier et al. 2012 |

Table 4. Hydration of GCLs examined on silty sand and sand

| GCL | GCL Carrier | Subgrade (Table 3) | Bentonite | w_{fdn} (%) | σ_v (kPa) | Final GCL | |
|--------------------|-------------|--------------------------|-----------|---------------|------------------|-----------|-----------------------------|
| | | | | | | w (%) | $S_r \approx w/w_{ref}$ (%) |
| GCL2 ¹ | SRNW* | QUELTS (SM) ^a | Fine | 16 | 2 | 99 | 83 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 16 | 2 | 114 | 58 |
| GCL1 ³ | Woven* | QUELTS (SM) ^a | Fine | 16 | 2 | 102 | 68 |
| GCL6 ⁴ | Woven* | QUELTS (SM) ^b | Powder | 16 | 2 | 125 | 55 |
| GCL9 ⁴ | SRNW* | MU (SM) ^c | Powder | 17 | 2.5 | 122 | 55 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 5 | 2 | 83 | 42 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 10 | 2 | 102 | 53 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 16 | 2 | 114 | 58 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 21 | 2 | 149 | 76 |
| GCL1 ³ | Woven* | QUELTS (SM) ^a | Fine | 10 | 2 | 86 | 57 |
| GCL2 ¹ | SRNW* | QUELTS (SM) ^a | Fine | 10 | 2 | 85 | 71 |
| GCL4 ² | Nonwoven | QUELTS (SM) ^a | Coarse | 10 | 2 | 102 | 53 |
| GCL6 ⁴ | Woven* | QUELTS (SM) ^b | Powder | 10 | 2 | 92 | 41 |
| GCL10 ⁵ | Woven* | MU (SP) ^d | Powder | 10 | 1 | 67 | 33 |
| GCL11 ⁶ | Woven | MU (SP) ^d | Coarse | 10 | 1 | 63 | 30 |
| GCL10 ⁵ | Woven* | QU-SYD (SM) ^e | Powder | 11 | 1.7 | 138 | 69 |
| GCL12 ⁷ | SRNW* | SYD (SW) ^f | Powder | 11 | 20 | 115 | 63 |
| GCL13 ⁸ | SRNW* | SYD (SW) ^f | Powder | 11 | 20 | 131 | 75 |

SRNW= Scrim reinforced nonwoven; * Thermally treated; w_{ref} at 2kPa in distilled water unless otherwise noted; ¹ $w_{ref}^{\#} = 120\%$; ² $w_{ref}^{\#} = 195\%$; ³ $w_{ref}^{\#} = 150\%$; ⁴ $w_{ref}^{\#} = 225\%$; ⁵ $w_{ref} = 202\%$; ⁶ $w_{ref} = 206\%$; ⁷ $w_{ref} = 175\%$ at 20kPa; ⁸ $w_{ref} = 183\%$ at 20kPa; [#] Hosney (unp); ^a Rayhani et al. 2011; ^b Hosney et al. 2016; ^c Bouazza et al. 2017c; ^d Acikel et al. 2018b; ^e Azad et al. 2011; ^f Yu et al. 2018

4.4 Effect of nature of the bentonite on hydration

Hosney et al. (2016) compared the hydration of two GCLs with similar construction including a woven carrier and thermal treatment but one (GCL1) with a fine granular bentonite (Table 3) and the other with powdered bentonite (GCL6) when placed on silty sand (Table 3) at $w_{fdn} = 16\%$. The GCL with powdered bentonite showed a much more rapid rate of initial hydration than that with the granular bentonite. After 2 weeks of hydration, GCL6 with powdered bentonite had $w = 146\%$ at which time the gravimetric water content of fine granular bentonite was only 60%. Subsequently, GCL6 experienced a decrease in water content to $w = 125\%$ ($S_r = 55\%$). This was probably due to a combination of the effects of the time-dependent changes in suction envisaged by Acikel et al. (2018a) and cation exchange triggering a new water distribution between the GCL and the subgrade-soil. This effect was not evident for GCL1 where over the same period w increased monotonically to $w = 102\%$ ($S_r = 68\%$). Thus even with the same GCL construction, the nature of the bentonite affected both the rate of hydration and the ultimate equilibrium water content on the same subgrade. The explanation for this difference in behaviour requires more research but may be due to a combination of factors including the difference in the way granular and powdered bentonite hydrate (e.g., Vangpaisal and Bouazza 2004, Rouf et al. 2016c), the effect of S_r on the time-dependent changes in w , and subtle differences in bentonite mineralogy from different manufacturers.

Primarily because of the range in bentonite particle size and GCL structure, there can be a notable range in both the gravimetric water content ($99\% \leq w \leq 125\%$; Table 4) and degree of saturation ($58\% \leq S_r \leq 83\%$) on the same QUELTS silty sand at $w_{fdn} = 16\%$. Thus on QUELTS silty sand at $w_{fdn} = 16\%$, all the GCLs examined effectively reached $w \geq 100\%$ but the projected performance is substantially different. For example, the implications of the water content can also depend on the nature of the bentonite as discussed with respect to gas permeability. If placed on the QUELTS silty sand at $w_{fdn} = 16\%$, GCL4 (with the coarse granular bentonite at $w = 114\%$ and $S_r = 58\%$) has a projected gas permeability of about 2×10^{-8} m/s (Figure 6) while GCL6 (with powdered bentonite and slightly higher water content of $w = 125\%$ but similar $S_r = 55\%$) might be inferred to have a gas permeability of 1×10^{-11} m/s (Figure 6); about three orders of magnitude lower than for GCL4. Since at QUELTS silty sand at $w_{fdn} = 16\%$ was about 5% above w_{opt} , and since the water content of the subgrade, when it is to be compacted, is rarely specified to be any-

thing except perhaps $w_{opt} \pm 2\%$ to obtain good density, it is by no means certain that w_{fdn} would even approach 16%, raising the question as to how a GCLs hydrated moisture content would be affected by w_{fdn} .

4.5 Effect of foundation water content on hydration

For a soil with the same grain size distribution (e.g., QUELTS silt sand), the initial water content can also have a significant effect on the equilibrium water content and degree of saturations as illustrated for GCL4 in Table 4. The equilibrium water content varied from 83% ($S_r = 42\%$) at $w_{fdn} = 5\%$ to 149% ($S_r = 76\%$) at $w_{fdn} = 21\%$. At a water content, $w_{fdn} = 10\%$, just below $w_{opt} = 11.4\%$, the water content of four different types of GCL ranged from $86\% \leq w \leq 102\%$ and the apparent degree of saturation from $41 \leq S_r \leq 71$. Placed on QUELTS silty sand at $w_{fdn} = 10\%$, GCL4, with the coarse granular bentonite, would hydrate to $w = 102\%$ and at this w has an inferred gas permeability of about 1×10^{-7} m/s (Figure 6). In contrast, GCL6 with powdered bentonite and slightly higher water content of $w = 92\%$ but lower S_r has an inferred gas permeability of 1×10^{-9} m/s (Figure 6); about two orders of magnitude lower than for GCL4. Thus, on QUELTS silty sand at $w_{fdn} = 10\%$, none of GCLs could be expected to be particularly good gas barriers although the finer the bentonite the better the GCL is likely to perform under these non-ideal conditions. This example highlights the need to consider both the moisture content of the subgrade and the choice of the GCL when designing covers as gas barriers.

4.6 Effect of nature of the subgrade on hydration

Several studies (Rayhani et al. 2011, Anderson et al. 2012, Chevrier et al. 2012, Sarabian and Rayhani 2013) concluded that the grain size of the subgrade affects the hydration of a GCL. However, in all these case the clay size fraction was non-plastic or of low plasticity. Bouazza et al. (2017a) explored the effect of mineralogy by examining a needle-punched and thermally treated GCL with powdered bentonite placed on four different subgrades at an initial water content $w_{fdn} = w_{opt} + 2\%$. The subgrade denoted S1 (Table 5) was a silty sand (SM) compacted at $w_{fdn} = 17\%$ moisture content. Placed on this subgrade, after about 150 days the powdered GCL9 hydrated to $w = 122\%$ ($S_r = 55\%$) which was almost identical to the final equilibrium for the powdered GCL6 on the QUELTS silt sand at $w_{fdn} = 16\%$ (Table 4) and at this water content would have an estimated gas permeability (Figure 6) of 1×10^{-11} m/s.

When GCL9 was placed on subgrade S2, a sandy clay (SC) with the clay component being predominantly kaolinite and only 3% smectite, compacted at $w_{fdn} = 20\%$ it hydrated to $w = 87\%$ ($S_r = 40\%$; after about 100 days) with an estimated gas permeability (Figure 6) of 1×10^{-9} m/s (Table 5). On subgrade S3, a low plastic clay (CL) with 10% smectite, compacted to the same $w_{fdn} = 20\%$ as S2, GCL9 only hydrated to $w = 40\%$ ($S_r = 18\%$ after about 30 days) with an estimated gas permeability (Figure 6) of 1×10^{-7} m/s (Table 5). Finally, on subgrade S4, a high plasticity clay (CH) with 39% smectite, compacted at $w_{fdn} = 22\%$ there was virtually no hydration of GCL9 with the final $w = 28\%$ ($S_r = 13\%$ after about 20 days) and an estimated gas permeability of 1×10^{-7} m/s (Table 5). The GCL hydration was reported to be inversely proportional to the percentage of clay-sized particles in the subgrade, but a significant factor here was the smectite content of the subgrade. The smectite greatly influenced the air entry value of the subgrade and limited the hydration that could occur to vapour phase hydration. This example highlights the critical nature of both the subgrade grain size distribution and the mineralogy of the clay size fraction of the subgrade.

Table 5. Properties of the four subgrades and final GCL water content and degree of saturation (adapted from Bouazza et al. 2017a)

| Soil | S1 | S2 | S3 | S4 |
|---|---------------------|--------------------|--------------------|--------------------|
| Soil classification as per USCS | SM | SC | CL | CH |
| Smectite content (%) | 0 | 3 | 10 | 29 |
| Optimum moisture content, w_{opt} (%) | 15 | 17 | 18 | 20 |
| Plastic Limit (%) | | 21 | 23 | 20 |
| Plasticity Index (%) | Non-plastic | 11 | 24 | 34 |
| Foundation w_{fdn} (%) | 17 | 20 | 20 | 22 |
| GCL9 w (%) | 122 | 87 | 40 | 28 |
| GCL9 S_r (%) | 55 | 40 | 18 | 13 |
| Gas permeability – from Figure 6 (m/s) | 1×10^{-11} | 1×10^{-9} | 1×10^{-7} | 1×10^{-7} |

4.7 Effect of temperature on hydration

Most studies for GCL hydration have been conducted under isothermal conditions at room temperature. However, even if hydration conditions are quasi-isothermal, in many practical situations the hydration will not be at room temperature. Chevrier et al. (2012) considered isothermal hydration at a range of temperatures for a poorly graded sand (FR sand; Table 3) and low plasticity clay (FR Clay; Table 3). As might be expected, they showed that the rate of hydration was much faster at 45°C than at 20°C than at 5°C. Thus there was a very substantial (up to 4-fold) difference in the hydration that occurred in 125 days (Table 6). Recent research (Carneiro-Guzmanet al. 2018) suggest there are other factors that also come into play when the GCL is hydrating at temperatures close to freezing. If the GCL is covered quickly by a suitable ballast layer (e.g., by ≥ 0.3 m drainage layer or cover soil) then it will suppress significant thermal cycles (e.g., Rentz et al. 2016) and will allow quasi-isothermal hydration at about the average ambient temperature. But what if the GCL is in an exposed composite liner (contrary to manufacturers recommendations but as commonly occurs in reality)? This question will be addressed in the following subsections.

Table 6. Effect of temperature on w after 125 days, w_{125} (inferred from Fig. 10 of Chevrier et al. 2012)

| Soil | FR Sand | FR Sand | FR Clay | FR Clay |
|---------------------------------------|---------|---------|---------|---------|
| Soil classification as per USCS | SP | SP | CL | CI |
| Subgrade water content, w_{fdn} (%) | 5 | 10 | 15 | 25 |
| w_{125} at 5°C (%) | 35 | 40 | 20 | 25 |
| w_{125} at 20°C (%) | 80 | 95 | 35 | 55 |
| w_{125} at 45°C (%) | 100 | 175 | 90 | 100 |

Note: w_{125} appears to be at the equilibrium w at 45°C but may not be at equilibrium at 20 and 5°C

4.8 Thermal cycles in the field

Take et al. (2015a) examined the temperatures to which a GCL was subjected in an exposed composite liner (i.e., with no cover material over the black GMB) over a four-year period on a 3H:1V south-facing slope and 3% gently-sloping base section at QUELTS (latitude 44°34'15"N). The GMB/GCL interface temperature was related to solar radiation and hence weather conditions, time of day and year, and liner orientation (both inclination and azimuth). In the summer months (June–August) at QUELTS when the average ambient temperature is about 19°C with an average daily high of 25.3°C and low of 13.5°C, the GMB/GCL interface was up to 40°C hotter than the ambient air temperature on a sunny day with a daily thermal cycle of about 20 to 60°C (Take et al. 2015a). Around noon on a sunny day, the average GMB/GCL interface temperature was higher on the south-facing slope than the base. Also, the GCL interface temperature below wrinkles could be 15°C higher than where the GMB and GCL were in direct contact. In winter, when snow covered the liner it acted as insulation and the GCL temperature only decreased to about -2°C even when the ambient air temperature was -23°C.

While the composite liner was exposed, on sunny days the GCL could be subjected to high temperatures (60°C towards the middle of a sunny day). However, after a hot day, the GCL could hydrate while the liner was relatively cool during the evenings and on days when there was extensive cloud cover. Rentz et al. (2016) reported that a white GMB was about 20°C cooler than a black GMB at QUELTS towards the middle of a sunny summer day and so a white GMB reduced the magnitude of the thermal cycles but did not eliminate them.

Solar heating of the GMB has a number of effects. First, it induces wrinkles due to thermal expansion and these thermal wrinkles come and go as a function of liner temperature (Take et al. 2007, Chappel et al. 2012a, Rowe et al. 2012b). For blown film GMBs, one can get regular wrinkles spaced at about half the roll width (i.e., 3.3 m at QUELTS) parallel to the roll. For both blown-film and flat-die GMBs, one can also get regular wrinkles above GCL overlaps spaced at about GCL panel width and wrinkles along welds as well as more random wrinkles (e.g., Rowe et al 2012a, Chappel et al. 2012b). Wrinkles will run both down and across the slope and the base (Rowe et al. 2012a, 2016a). The heat causing the wrinkles also evaporates water from the GCL and most of the water vapour moves to the airspace below wrinkles (Take et al. 2015a). At night, when the GMB cools, the water vapour in the wrinkles condenses and eventually it runs down-slope on the GCL eroding bentonite – a process called down-slope erosion (Take et al 2015b, Brachman et al. 2015, Rowe et al. 2016a,b, Rentz et al. 2016).

Thermal cycles and the associated uptake and loss of water from the GCL can also cause the GCL to shrink (Thiel et al. 2006, Bostwick et al. 2010, Rowe et al. 2010, 2011a) with a potential reduction in

panel overlap or even complete loss of overlap has been reported in the US (Thiel and Richardson 2005, Koerner and Koerner 2005) and at QUELTS in Canada (Rowe et al. 2018a, Brachman et al. 2018).

4.9 Effect of thermal cycles on GCL moisture uptake and loss

The effect of seasonal changes can be appreciated from the variation in water content observed for GCL2 and GCL4 (Table 4) at comparable positions on the base of QUELTS for a liner installed in early September 2006 (Brachman et al. 2007). Over the first six weeks in the fall of 2006, the GCLs hydrated to a water content, $w = 88\%$ for GCL2 and $w = 59\%$ for GCL4 (Table 7). With 42 weeks in the field over the fall, winter and spring, GCL2 had hydrated to 109% ($S_r = 90\%$) and GCL4 to 68% ($S_r = 35\%$). At the end of the summer (54 weeks) both had lost substantial moisture and GCL2 was at 47% ($S_r = 39\%$; Figure 8) and GCL4 to 36% ($S_r = 18\%$; Figure 9). Although both were substantially reduced in the degree of saturation, GCL2 had been well hydrated before dehydration and still had a gel-like structure with desiccation cracks just starting to form (Figure 8). GCL4 with coarse granular bentonite had not hydrated sufficiently to form a gel-like structure over the 54 weeks in the field and coarse granular particles were still evident (Figure 9). There are a number of factors that could contribute to the difference in behaviour including the GCL/bentonite structure, local variations in subgrade water content, and the proximity of a wrinkle (which could affect thermal cycles as indicated above). However, these field observations do raise questions as to what effect leaving a composite liner exposed could have on the GCL's ability to uptake and retain moisture when subjected to thermal cycles and how this may affect the liners long-term hydraulic performance for different GCL/bentonite structures. This question will be addressed in Section 5.

Table 7. Seasonal effects on the hydration of two GCLs at QUELTS (adapted from Brachman, Rowe and Take 2011)

| | Weeks after installation | | |
|-------|--------------------------|--------|---------|
| | 6 | 42 | 54 |
| GCL2 | 88 | 109 | 47 |
| GCL4 | 59 | 68 | 36 |
| Date: | Oct 06 | Jul 07 | Sept 07 |

Rowe et al. (2011b) examined the hydration of GCL1, GCL2 and GCL4 (Table 4) on QUELTS silty sand (Table 3) at w_{fdn} of 5%, 10%, 16% and 21% under simulated daily thermal cycles between about 23 and 60°C. It was shown that, depending on the subgrade water content, the daily thermal cycle significantly decreased the equilibrium moisture content of the GCL (Table 8). For example, for $w_{fdn} = 16\%$, at equilibrium GCL1 had a daily variation in gravimetric water content of 13% between the start and end of a heating cycle with range 30% (at end of heating cycle) $\leq w \leq 43\%$ (at end of a cool cycle), GCL2 had a much better moisture retention with daily range of 2% between 27% (at end of heating cycle) $\leq w \leq 29\%$ (at end of a cool cycle), while GCL4 had a daily range of 10% between 17% (end of heating) $\leq w \leq 27\%$ (end of cool).



Figure 8. GCL2 after 54 weeks, $w = 47\%$ (Table 7)

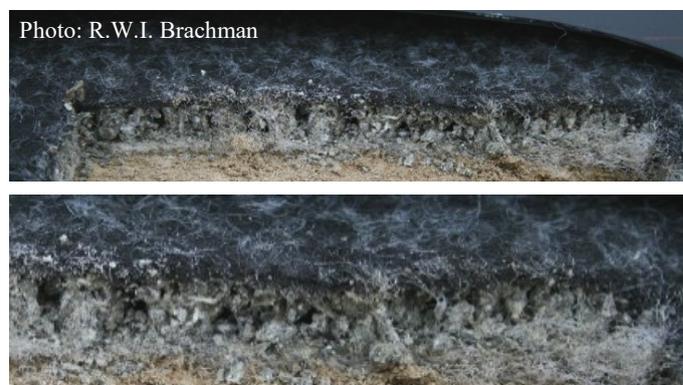


Figure 9. GCL4 after 54 weeks, $w = 36\%$ (Table 7)

There was a stark difference in the results for w_{fdn} of 16% and 21% (Table 8). When $w_{fdn} = 21\%$, even after thermal cycles, all three GCLs had a high water content with $w = 113\%$ ($S_r = 75\%$) for GCL1, $w = 117\%$ ($S_r = 98\%$) for GCL2 and $w = 127\%$ ($S_r = 65\%$) for GCL4. From the results as presented it appears that GCL2 would be least prone to shrinkage while GCL1 and GCL4 would be much more prone to shrinkage – as was indeed borne out by field observations of shrinkage at QUELTS1 where both GCL1 and GCL4

experienced significant shrinkage whereas GCL2 did not (Rowe et al. 2018a, Brachman et al. 2018). Based on these findings, Rowe et al. (2011a) inferred that for a given GCL, shrinkage could vary substantially depending on the water content and grainsize distribution of the subgrade and the nature of the thermal cycles.

Table 8. Hydration of GCLs with daily thermal cycles on QUELTS silty sand (adapted from Rowe et al. 2011b)

| | w_{fdn} (%) | w at end of a heating cycle after 7 weeks (%) | Isothermal equilibrium (Rayhani et al. 2011) (%) |
|------|------------------|---|--|
| GCL1 | 5 | 23 | 33 |
| | 10 | 35 | 86 |
| | 16 | 30 | 102 |
| | 21 | 113 | 141 |
| GCL2 | 5 | 16.0 | 40 |
| | 10 | 16.3 | 85 |
| | 16 | 27 | 88 |
| | 21 | 117 | 116 |
| GCL4 | 5 | 14 | 83 |
| | 16 | 17 | 114 |
| | 21 | 127 | 149 |

The GCLs used at QUELTS1 had fine grained (GCL1 & GCL2) and coarse grained (GCL3 & GCL4) bentonite (Tables 3 & 4) and all experienced significant down-slope erosion (Rowe et al. 2016a). At QUELTS2, GCL2 experienced downslope bentonite erosion within a year whereas GCL5 and GCL6, containing powdered bentonite, did not exhibit erosion in 27 months of monitoring (Rowe et al. 2016b) although the GCLs with powdered bentonite did erode when subjected to a forced flow of distilled water (Ashe et al. 2015, Rowe et al. 2016a). It was observed that in the field the GCLs with powdered bentonite retained moisture much better than an apparently similar GCLs with fine grained bentonite; which begs the question why?

Hosney et al. (2016) followed four weeks of isothermal hydration for GCL6 (powdered bentonite) and GCL2 (fine granular bentonite) on QUELTS silty sand at $w_{fdn}=16\%$ by daily thermal cycles (30-60°C). As expected based on Rowe et al. (2011b), GCL2 lost most of its moisture within about a week of thermal cycles and in this case approached $w \sim 20\%$.

Consistent with the field observation at QUELTS2, GCL6 retained and, in fact, slightly increased its water content from around 140% after 4 weeks of isothermal hydration to about to 160% ($S_r=73\%$) after 3 weeks of daily thermal cycles. From this, it might be inferred that due to the powdered bentonite GCL5 & GCL6 were both able to retain and even gain moisture under thermal cycles similar to those observed at QUELTS. In fact, the performance of GCL6 on this subgrade at $w_{fdn}=16\%$ was similar to that observed by Rowe et al. (2011) for GCL1, 2 & 4 on the same subgrade at $w_{fdn}=21\%$.

What is not yet known are the factors that affected the difference in the performance of GCL6 and the other GCLs. However, based on the data presented in this section, it can be inferred that the excellent retention of moisture by GCL5 and GCL6 on the QUELTS silty sand for the particular grainsize, density and initial foundation moisture content on site (Rentz et al. 2016) and in the test by Hosney et al. (2016) indicates that they have a lower w_{fdn} threshold for retaining moisture under the thermal cycles at QUELTS but that under different circumstance these GCLs are also likely to lose moisture under thermal cycles. This is the subject of current research at Queen's.

4.10 Effect of a steady-state thermal gradient

There are many situations where the material and fluid to be retained by a liner system (e.g., in municipal solid waste landfills, elevated temperature heap-leach pads, and solar/brine ponds; Rowe 2012) have a sustained quasi steady-state elevated temperature. Thus, GCLs are often used as part of a composite liner in barriers where there is quasi steady-state thermal gradient between one side of the liner and the groundwater temperature at some depth below the liner. A thermal gradient from higher temperature above the GMB to lower temperature at depth will cause water vapour to move outward away from the heat source towards areas of lower temperature. This will decrease the water content in the warmer area thereby increasing suctions which will induce inward flow of liquid water toward the heat source. As the water content decreases, it becomes easier for water vapour to migrate away from the heat source and, due

to the consequent decrease in unsaturated hydraulic conductivity, more difficult for liquid water to flow toward the heat source to balance the outward flux of water vapour. When the net outward water flux of vapour exceeds the inward flux of liquid water there will be a decrease in water content of a GCL below an essentially impermeable GMB near the source. Thus there will be a threshold at which the water loss is such as to induce desiccation cracking. This issue has been studied experimentally in the context of landfill applications (Southen and Rowe 2004, 2005a) considering liner temperature of 33–63°C and average thermal gradients of 25–100°C/m at 80 kPa applied stress and more recently for brine ponds where higher liner temperatures and lower applied pressure may be operative (Azad et al. 2011, El-Zein et al. 2014, Bouazza et al. 2014, 2017b, Ghavam-Nasiri et al. 2017, 2018, Yu et al. 2018).

Southen and Rowe (2005a) examined GGL1 and GCL6 (Table 4) on QU-SYD silty sand (Table 3) with about 12% fines and $w_{opr} \sim 11\%$ in twelve different configurations with $4.2\% \leq w_{fdn} \leq 13.6\%$. For the conditions examined, it was experimentally shown that w_{fdn} (the higher the better) and the thermal gradient (the lower the better) were the two most critical factors affecting the potential for desiccation of a GCL. No desiccation was observed when the $w_{fdn} > 12\%$ for a 25 °C/m thermal gradient. Southen and Rowe (2011) reported encouraging agreement between the predictions of the Zhou and Rowe's (2003) fully coupled numerical model with these experimental results. Under the conditions examined, the 25 °C/m temperature gradient lead to predictions of desiccation cracking consistent with when cracking was observed. The modeling results implied that where there was a risk of desiccation cracking, it could occur even if the elevated temperature was only maintained for a relatively short period of time (i.e., if it was going to occur for an initially partially hydrated GCL, it did so relatively quickly).

Hoor and Rowe (2013) used the model calibrated by Southen and Rowe (2011) to perform a parametric study of the potential for desiccation cracking for a GCL with a thermally treated scrim-reinforced nonwoven carrier geotextile (GCL2). This GCL had a WRC with low hysteresis between wetting and drying (Beddoe et al. 2011). They modeled a landfill for applied stresses between 50 and 150 kPa and showed that there was a risk of desiccation even at relatively low temperatures (i.e., 35°C) and that the risk was related to the: (i) liner temperature (lower is better), (ii) overburden stress (higher is better), (iii) depth to aquifer (smaller is better), (iv) initial water content of subgrade (higher is better), and (v) water retention curve of the subsoil.

Considering the high temperatures that can be reached in brine ponds, Yu et al. (2018) performed duplicate column tests with each of two needle-punched, scrim-reinforced GCLs with powdered bentonite and differing only in the mass of dry bentonite per unit area with one at A: 4350 g/m² ($w_{ref}=183\%$ at 20 kPa) and the other at B: 4780 g/m² ($w_{ref}=175\%$ at 20 kPa). The GCLs were placed on a well graded SYD sand (Table 3, SW with 4% fines, $w_{opt} = 13.5\%$) compacted to $w_{fdn}=11\%$ and allowed to hydrate from the subgrade at room temperature and 20 kPa applied stress to $w=105\%$ ($S_r=57\%$) and $w=126\%$ ($S_r=69\%$) for GCL A (after 44 days) and $w=121\%$ ($S_r=69\%$) and $w=141\%$ ($S_r=80\%$) for GCL B (after 56 days). The temperature of the GMB above the GCLs was then increased to 78°C (thermal gradient of 97°C/m) for 39 days (GCL A) and 28 days (GCL B). The thermal gradient caused dehydration of all the GCLs to $w \sim 8\%$ and there was significant desiccation cracking in each case. All the thermal gradients given above are average over the length of the test column. However, Yu and El-Zein (2018) have shown that due to the different thermal conductivities of the various materials (including the sand at different water contents) the thermal gradient is much higher in the upper part of the column with the GCL than lower down and thus for the tests where the average thermal gradient was 97°C/m, the thermal gradient over the top 22.5 cm was 209°C/m.

Rowe and Verge (2013) built on the work of Hoor and Rowe (2013) and applied the Zhou and Rowe (2003) model to brine pond application with stresses below 50 kPa and temperatures above 30°C. This work identified the key role of the GCL WRC and its variability with temperature and applied stress on the potential for GCL desiccation and motivated experimental research on this topic currently in progress at Monash University and Sydney University (e.g., Ghavam-Nasiri et al. 2018). The value of Poisson's ratio and the GCL degree of saturation when the thermal gradient was applied were shown to be less significant at stresses below 50 kPa than in the landfill cases examined by Hoor and Rowe (2013). It was concluded that at the low stresses examined (≤ 50 kPa), an increase in liner temperature of as little as 28 - 40°C above groundwater temperature could cause desiccation cracking of a GCL in a composite liner and hence in the event of a hole forming in the GMB, consideration would need to be given to the implications of the desiccated GCL coming into contact with brine in an assessment of potential leakage through the composite liner with a hole.

Azad et al. (2012) expanded on the Southen and Rowe (2005a) experiments on a single composite liner by considering GCL10 (similar to GCL6; Table 4) as part of a double composite liner system. Two test series (Tables 9 and 10) were conducted with the fully constructed system being left to equilibrate for

about 100 days after assembly before a 100 kPa pressure and the thermal gradient were applied for about 125-170 days. The GCL in the secondary liner rested on QU-SYD silty sand (Table 3) with ~12% fines and $w_{opt} \sim 11\%$.

Table 9. Test series G1 primary liner underlain by a geonet: primary and secondary GCL $w_i=75\%$ except for T5 where primary GCL had $w_i=180\%$ and T7 where secondary GCL had $w_i=12\%$ (adapted from Azad et al. 2012)

| Test | Control | T4 | T7 | T5 | T1-T3 | T8 | T9 |
|------------------------------|---------|-------|-------|-------|------------|-------|--------|
| w_{fdn} | 10.9% | 5.1% | 11.5% | 10.3% | 11-14.1% | 10.7% | 4.8% |
| Thermal gradient (°C/m) | None | 27.0 | 25.0 | 29.0 | 23-28.5 | 66.5 | 59.5 |
| Top temperature (°C) | 23.0 | 29.5 | 29.0 | 31.0 | 29.5-31.0 | 42.5 | 39.5 |
| Primary GCL cracks | None | None | None | None | Narrow | Deep | Deep |
| Secondary GCL cracks | None | None | None | None | None | None | Narrow |
| Final Primary GCL w_{fp} | 61.4% | 61.5% | 60.8% | 102% | 45.4-53.2% | 27.5% | 32.5% |
| Final Secondary GCL w_{fs} | 138% | 58.2% | 64.8% | 70.2% | 62.8-87.0% | 53.0% | 34.1% |

In test series G1 (Azad et al. 2012), the GCLs were mostly hydrated to $w=75\%$ and the primary GCL was underlain by a geonet. No desiccation cracks were observed in the primary GCL for four of seven cases with a GMB temperature of 29-31°C and thermal gradients of 21-29 °C/m for $5.1\% \leq w_{fdn} \leq 11.5\%$ (Table 9). In these cases, the primary GCLs had reduced from an initial $w_i=75\%$ to $w_{fp} \sim 61\%$ (which was similar to a control case with no thermal gradient) and from an initial $w_i=180\%$ to $w_{fp} \sim 102\%$. Narrow cracks were observed in the primary GCL for three of the seven cases, suggesting that the primary GCL was at the threshold of desiccation and in these three cases w had reduced from an initial $w=75\%$ to $45\% \leq w_{fp} \leq 53\%$. Hydraulic conductivity test on the cracked GCLs gave an initial hydraulic conductivity, k , between $2-3 \times 10^{-10}$ m/s for distilled water but with time self-healing of the cracks k reduced to about 2×10^{-11} m/s at 100 kPa. There were no desiccation cracks in the secondary GCL for any of these seven cases for which w had changed from an initial $w_i=75\%$ to $62\% < w_{fs} < 87\%$ for $5.1\% \leq w_{fdn} \leq 11.5\%$. On initial permeation with distilled water they had a k of about 2×10^{-11} m/s at 100 kPa.

When the GMB temperature was increased to 39.5-42.5°C (thermal gradients of 66.5-59.5 °C/m), deep cracks were observed in the primary GCL as w reduced from an initial $w_i=75\%$ to $27.5\% \leq w_{fp} \leq 32.5\%$. On permeation with distilled water at 100 kPa the cracks eventually self-healed and k reduced to about 2×10^{-11} m/s. For these thermal gradients, when $w_{fdn}=10.7\%$, there were no cracks observed in the secondary GCL but w had reduced from $w_i=75\%$ to $w_{fs}=53\%$ which is about the threshold where cracking had occurred in the primary GCL. When the secondary GCL was on $w_{fdn}=4.8\%$, narrow cracks were observed as w had reduced from $w_i=75\%$ to $w_{fs}=32.5\%$. Permeation with distilled water gave an initial $k=8 \times 10^{-11}$ m/s which eventually reduced to about 2×10^{-11} m/s at 100 kPa.

Test series G2 (Azad et al. 2012) involved five tests where the primary GCL rested on QU-SYD silty sand with $10.5\% \leq w_{fdn} \leq 12.6\%$ (Table 10). For a top GMB temperature of 30-32°C (thermal gradients of 20-24 °C/m), no cracking was observed and the primary GCL had $67\% < w_{fp} < 90\%$ while the secondary was at $101\% < w_{fs} < 110\%$ with the variability likely due to subtle differences in foundation grain size and compaction rather than any of the control variables. Interestingly, the primary GCL placed at $w_i=12\%$ (Test T3) hydrated and then dehydrated to essentially the same water content as the primary GCL placed at $w_i=75\%$ (Test T1). When the GMB temperature was increased to 37 °C (thermal gradient of 26 °C/m) the thicker primary liner foundation layer below the primary GCL more than compensated for the higher temperature and thermal gradient and its water content remained essentially unchanged from the as-placed value at $w_{fp}=76\%$ (Test T5; Table 10). When the GMB temperature was increased to 45 °C (thermal gradient of 61 °C/m), there was significant desiccation of the primary GCL as w dropped from $w_i=75\%$ to $w_{fp}=29\%$ (Test T4) and permeation of the cracked specimen with distilled water gave an initial $k=9 \times 10^{-10}$ m/s which eventually reduced to about 2×10^{-11} m/s at 100 kPa. The secondary GCL remained uncracked but its $w_{fs}=80\%$ was well below that obtained for smaller thermal gradients.

For the conditions examined, there appeared to be a water content threshold of about $w=50\%$ where the GCL started to crack. Also, desiccation cracking was observed for the primary GCL: (i) on a geonet when the GMB temperature was about 40°C and the thermal gradient of 60°C/m, and (ii) on the QU-SYD silty sand at a GMB temperature of about 45°C but a similar thermal gradient of about 60°C/m. Unfortunately, the effect of chemical interaction with leachate as permeant was not considered in assessing k of the desiccated GCLs. It may be hypothesized that the amount of self-healing and ultimate low k obtained

in these tests would not be realized had they been permeated by brine to simulate the effect of a hole forming in the GCL.

Table 10. Test series G2 primary liner underlain by QU-SYD silty sand: primary and secondary GCL $w_i=75\%$ except for T3 where primary GCL had $w_i=12\%$. $10.5\% \leq w_{fidn} \leq 12.6\%$ (adapted from Azad et al. 2012)

| Test | T2 | T3 | T1 | T5 | T4 |
|-----------------------------------|-------|-------|-------|-------|-------|
| Thermal gradient (°C/m) | 20.0 | 21.3 | 24.0 | 26.0 | 61.0 |
| Top temperature (°C) | 30.5 | 31.0 | 32.0 | 37.0 | 45.0 |
| Primary GCL cracks | None | None | None | None | Deep |
| Secondary GCL cracks | None | None | None | None | None |
| Final Primary GCL w_{fp} | 90.1% | 68.6% | 67.0% | 76.0% | 29.3% |
| Final Secondary GCL w_{fs} | 101% | 110% | 101% | 110% | 80.2% |
| Primary foundation thickness (mm) | 50.0 | 50.0 | 50.0 | 250.0 | 50.0 |

5 EFFECT OF PORE WATER CHEMISTRY ON GCL HYDRATION AND PERFORMANCE

Most discussion of moisture uptake (and loss) of GCLs from a subgrade (when in a composite liner), or subgrade and cover soil (when the GCL is used alone), has been based on traditional unsaturated soil mechanics where there is no effect of the moisture on the WRC. As already indicated, GCLs are more complicated than traditional unsaturated soils because of (a) their tri-modal pore structure (§4.2), (b) their high compressibility and hence the dependence of the WRC on stress level (§4.10), and (c) especially because the cations in the pore fluid can interact with the bentonite changing its swelling capacity and hence WRC and hydraulic conductivity. The latter factor will now be discussed.

A number of laboratory investigations have examined the effects of cation exchange, interaction with different permeants, wet-dry cycles, and/or freeze-thaw cycles on the hydraulic performance of GCLs (e.g., Shan and Daniel 1991; Boardman and Daniel 1997; Petrov and Rowe 1997; Rowe et al. 2004, Lin and Benson 2000; Shackelford et al. 2000, 2010; Jo et al. 2005; Lee et al. 2005; Rowe et al. 2006; Bouazza et al. 2007; Brown and Shackelford 2007; Benson and Meer 2009; Lange et al. 2010; Rosin-Paumier et al. 2011; Rosin-Paumier and Touze-Foltz 2012; Rowe and Abdelatty 2012; Bradshaw et al. 2013; Mazzieri et al. 2013; Rowe and Hosney 2013; Sari and Chai 2013; Bradshaw and Benson 2014; Makusa et al. 2014; Bouazza and Gates 2014, Liu et al. 2015; Mazzieri and Emidio 2015; Puma et al. 2015; Rowe and Hosney 2015; Zhang et al. 2015; De Camillis et al. 2016; Bradshaw et al. 2016; De Camillis et al. 2017; Joshi et al. 2017; Mazzieri et al. 2017; Parastar et al. 2017; Setz et al. 2017; Chen et al. 2018; Ozhan 2018; Salemi et al. 2018).

Far fewer studies have examined the hydraulic performance of GCLs after field exposure in covers/caps under low applied stress and these studies have given rise to some apparently inconsistent findings (James et al. 1997; Benson et al. 2007, 2010; Meer and Benson 2007; Scalia and Benson 2010, 2011; Buckley et al. 2012; Hosney and Rowe 2013; Hosney and Rowe 2014a,b; Bannour et al. 2015; McWaters et al. 2016).

It is proposed that the apparent inconsistencies are due, in part, to several well recognized factors such as differences in the chemistry of the pore water of the soil adjacent to the GCL, thickness of the cover soil, and the freeze-thaw and/or wet-dry cycles to which the GCL is subjected. However, this list is not sufficient to explain all differences and several additional less discussed factors are considered to contribute to the inconsistencies in observed behaviour. These additional factors are: (i) different methods of GCL construction (e.g., nature of the bentonite, the carrier geotextiles, and needle punching), (ii) the hydration conditions prior to needing to function as a barrier, and (iii) the gradients used in laboratory tests on the exhumed samples. The previous section has examined factors affecting the hydration of the GCL. In the following, consideration will be given to how these differences in hydration can affect GCL performance

5.1 The interaction between hydration and hydraulic conductivity

It is well known that the hydraulic performance of GCLs is substantially improved by hydration with water before permeation with chemically aggressive solutions (e.g., Daniel et al. 1993, Petrov and Rowe 1997, Rowe 1998, Vasko et al. 2001, Lee and Shackelford 2005, Bouazza and Gates 2014, Liu et al. 2015). However, very little attention has been paid to the interaction between the amount of hydration

that can practically occur in different field situations, cation exchange, and subsequent hydraulic conductivity for a given permeant.

Katsumi et al. (2008) sought to address one aspect of this issue, namely the effect of amount of hydration of clean water from a subgrade on GCL hydraulic conductivity when permeated by CaCl_2 . Two subgrades were examined: Toyoura sand (0% fines, $w_{opt} = 17\%$) and decomposed granite soil (16% gravel size, 69% sand size, 15% fines; $w_{opt} = 10.9\%$). Only a few tests relied on uptake of moisture from the subgrade without an external source of water and only these are relevant to the present discussion. Of the two specimens tested for hydraulic conductivity at 20-30 kPa, the specimen hydrated to $w = 52\%$ had $k = 6.2 \times 10^{-11}$ m/s for 0.1M CaCl_2 (4000 mg/L Ca^{2+}) and for the specimen at $w = 99\%$, $k = 1.2 \times 10^{-10}$ m/s for 0.2M CaCl_2 (8000 mg/L Ca^{2+}). Unfortunately, it is not possible to distinguish what was the effect of the different level of hydration due to the k -tests being for very different permeant concentrations; however, in both cases, the k values are considered quite low given the low applied stress and very high Ca^{2+} concentrations in both permeants.

Garcia et al. (2018) and Rowe et al. (2018b) examined GCLs hydrated from QUELTS-M silty sand. This soil was from the same QUELTS site as used in experiments discussed earlier but with some subtle but important difference in characteristics to as QUELTS silt sand that resulted in a little less hydration of the GCLs for the same compacted water content. The average concentration of Ca^{2+} in the pore water was 230 mg/l, 33 mg/L Mg^{2+} , it is, 30 mg/L Na^+ , and 6 mg/L K^+ (Hosney et al. 2016).

When a GCL4 ($w_{ref} = 195\%$ at 2kPa stress) was hydrated on QUELTS-M silty sand at 5% the GCL moisture uptake was in large part as water vapour which is essentially distilled water carrying no cations and only in small part due to pore water movement from the subgrade to the GCL (with cations). As a result, the low subgrade water content GCL hydrated to $w = 61\%$ ($S_r = 31\%$) and the cations that did migrate caused the swell index, SI, to decrease from the virgin value of 24 mL/2g to 15 mL/2g (Rowe et al. 2018b). In contrast, when a GCL4 was hydrated on QUELTS-M silty sand at $w_{fdn} = 16\%$ the GCL moisture uptake was mostly due to pore water movement from the subgrade to the GCL (with cations). In this case GCL4 hydrated to $w = 103\%$ ($S_r = 53\%$) and the additional cations caused the SI to decrease to 10 mL/2g (Rowe et al. 2018b).

When these GCL4 specimens were permeated with tap water (with $\text{Ca}^{2+} \sim 35$ mg/L) at 15kPa and a head difference of 0.6m, the value of k was 4×10^{-11} m/s for $w_{fdn} = 5\%$. For $w_{fdn} = 16\%$, k was 1×10^{-10} m/s. At first sight, this result is surprising since the more poorly hydrated GCL had the lowest k . The explanation arises from the fact that there was less cation exchange at $w_{fdn} = 5\%$, as evidenced by the higher SI, than for $w_{fdn} = 16\%$. Thus, when the partially hydrated GCL on $w_{fdn} = 5\%$ was permeated with tap water, more of the hydration was from the tap water than the pore water. But when partially hydrated GCL on $w_{fdn} = 16\%$ was permeated with tap water, more of the hydration was from the pore water than tap water. When similar partially hydrated GCLs were permeated with simulated municipal waste landfill leachate ($\text{Ca}^{2+} \sim 540$ mg/L, $\text{Na}^+ \sim 760$ mg/L at 70kPa and a head difference ~ 0.5 m) the trend reversed and k was 6×10^{-8} m/s for $w_{fdn} = 5\%$ and 3×10^{-10} m/s for $w_{fdn} = 16\%$. These results are more consistent with traditional expectations that the better hydrated GCL specimen before permeation should have the lower k . The substantial (200-fold) difference in k in this case arises because on $w_{fdn} = 5\%$ the GCL had not been well enough hydrated by the pore water to form a good gel structure before contact with the MSW leachate and the leachate then prevented a good structure from forming. On $w_{fdn} = 16\%$, a better structure had formed before contact with leachate. These findings suggest that the chemistry of (a) the pore water in the subgrade and (b) final permeant will both affect the final hydraulic conductivity in many practical situations. The former finding suggests that when used as part of a pond for relatively clean (low cation) water, the initial water content of the subgrade can be low without detriment (and may even be advantageous for pore water such as in the QUELTS silty sand). The latter finding reinforces the desirability of having the GCL reasonably well hydrated with a relatively benign pore water (even that for the QUELTS silty sand) before being permeated with a more chemically aggressive fluid such as MSW leachate or mining liquors.

Rowe et al. (2018b) and Garcia (2018) also demonstrated that the effect of hydration and interaction was greatly affected by the nature of the bentonite. GCL4 discussed above had coarse granular bentonite (Figure 1-left) and it gave much higher k -values (3×10^{-10} m/s $\leq k \leq 6 \times 10^{-8}$ m/s) than GCLs 1 and 2 (1×10^{-11} m/s $\leq k \leq 1 \times 10^{-10}$ m/s) with fine granular bentonite (Figure 1-centre), while GCL6 with powdered bentonite (Figure 1-right) had $k < 5 \times 10^{-11}$ m/s when all GCLs were hydrated from the same subgrades and permeated with the same MSW leachate at 70kPa. Thus the interactions between the GCL and subgrade had a very substantial effect on the hydraulic performance of the different GCLs when subsequently permeated with MSW leachate.

5.2 Pore water chemistry, needle punching and hydraulic conductivity

Rowe et al. (2017) reported on the performance of four GCLs products (GCLs 1 & 2 with fine granular bentonite and GCLs 3 & 4 with coarse granular bentonite; Table 3) exhumed from below 0.7 m of silty sand on a 3H:1V north-facing silty sand slope at QUELTS after 5 and 7 years in the field. At exhumation there had been complete exchange of bound Na^+ for Ca^{2+} and Mg^{2+} and the SI had reduced from the initial 24-26 mL/2g to 8 -11 mL/2g (Table 11). The exhumed water content ranged from a low 59% ($S_r = 46\%$) for GCL3 to 86% ($S_r = 60\%$) for GCL4, with the highest degree of saturation being for GCL2 with $w = 67\%$ and $S_r = 63\%$ (Table 11).

Considering a reasonable field condition with a 7 cm head acting on the liner, k -tests in a flexible wall permeameter for the four GCLs gave $1 \times 10^{-10} \leq k \leq 5 \times 10^{-10}$ m/s ($7 \leq i \leq 14$). This range of values is considered typical of what one obtains at low (15 kPa) stress after extensive cation exchange. However when the head was increased to 0.49m (a fairly extreme, but possible, value for a cover applications in the field; $50 \leq i \leq 100$) the range in k values widened to more than 1000-fold to 1.9×10^{-10} m/s $\leq k \leq 4.0 \times 10^{-7}$ m/s (Table 11) with a 2-fold decrease from 4.1×10^{-10} to 1.9×10^{-10} m/s for GCL1 (presumably due to the greater seepage drag force with a 7-fold increase in gradient on the same specimen), an increase by about 10-fold increase for GCL2 and GCL3 to 4×10^{-9} m/s, and 4000-fold increase from 1×10^{-10} m/s to 4.0×10^{-7} m/s for GCL4 (Brachman et al. 2009; Rowe et al. 2017). This begs the question as to why the performance was so very different for the four GCLs when they had all been subject to identical exposure conditions?

An inspection of peak peel strength (Table 11) shows a substantial difference between GCL1 (which had good permeability at all gradient) and the rest. Thus, although all GCLs met a typical specified value of 360 kN/m (GRI-GCL3) there is substantial variability. This, and the observation of that the flow of blue dye introduced toward the end of each test was largely passing through the bentonite for GCL1 but focusing at the needle-punched bundles in the k -test for the latter three GCLs (especially GCL4) suggested that the difference was related to the amount of needle-punching combined with cation exchange.

A detailed investigation of the differences in the needle punching of the four GCLs (Table 11 and Rowe et al. 2017) indicated that the percentage of the area with needle-punch bundles of 4% for GCL1, 9% for GCL2 and GCL3, and 14% for GCL4 correlated well with the k values at a head difference of 0.14m or larger (e.g., 0.49m in Table 11). GCL1 achieved its peel strength with the largest number of bundles (114000 per m^2) but with the smallest individual bundles (0.7 ± 0.2 mm) and an average of 9 fibers per bundle. For GCL1, even with complete cation exchange, the bentonite was largely able to seal around the bundle sufficiently to prevent significant preferential flow through the bundles. For GCL2 and GCL3, the bundle size (1.1 mm - 1.2 mm) and number of bundles (94000 & 80000 per m^2) were fairly similar giving a similar area of bundles and a similar increase in hydraulic conductivity due to the greater difficulty in sealing these larger bundles with the available swell pressure and applied stress in a cover where there has been essentially full cation exchange. GCL4 demonstrated that there is a critical % area (between 9 and 14%) and bundle size (between 1.2 and 1.6 mm) at which the swell pressure is easily overcome (at a head greater than 0.07m) and preferential flow through the bundles became so dominant that the k increased by more than three orders of magnitude.

These results (Rowe et al. 2017) suggest that all four GCLs could perform with $k < 6 \times 10^{-10}$ m/s as a single hydraulic barrier in a cover, despite essentially total cation exchange, provided that the head above the GCL was kept very low (e.g., by a suitable drainage layer above the GCL). However, once the head on the GCL passed a threshold of between 0.07m and 0.14m, the head was sufficient to overcome the swell pressure of the bentonite and the flow increased substantially for GCLs with more than 4% of the total area needle-punched bundles and bundles larger than about 0.7mm. GCL1 had also twice the GRI-GCL3 minimum peel but still performed with minimal preferential bundle flow at heads over the range examined (i.e., up to $\Delta h = 1.2\text{m}$, $i = 240$). Substantially greater needle-punching, which increase peel to 4-7 times the minimum required value) had a negative impact of the GCL performance in a cover. Thus, more needle-punching is not necessarily better. Also, the manner of achieving a given peel also made a difference. For example, GCL2 had 36% less needle-punched area than GCL4 but the peel strength of GCL2 was 32% higher; likely due the scrim-reinforced needle-punched carrier giving better anchorage of the needle-punched fibres when combined with the thermal treatment to adhere the fibres to the carrier geotextile.

Table 11 Needle-punching and hydraulic conductivity of GCLs exhumed at 7 years (modified from Rowe et al. 2017)

| GCL | SI (mL/2g) | Exhumed w/S_r^a (%) | k^b at $\Delta h = 0.07\text{m}$ (m/s) | k^b at $\Delta h = 0.49\text{m}$ (m/s) | Peel strength ^c (kN/m) | Bundles/ area (%) | Bundle size (mm) | Number of Bundles (-/m ²) |
|-----|---------------|-----------------------------|--|--|---|-------------------------|------------------------|---|
| 1 | 10 | 72 / 62 | 4.1×10^{-10} | 1.9×10^{-10} | 662±88 | 4 | 0.7±0.2 | 114 000 |
| 2 | 11 | 67 / 63 | 5.4×10^{-10} | 4.4×10^{-9} | 2368±122 | 9 | 1.1±0.5 | 94 000 |
| 3 | 8 | 59 / 46 | 3.8×10^{-10} | 4.0×10^{-9} | 1510±256 | 9 | 1.2±0.2 | 80 000 |
| 4 | 8 | 86 / 60 | 1.0×10^{-10} | 4.0×10^{-7} | 1789±280 | 14 | 1.6±0.5 | 67 000 |

^a $S_r = w/w_{ref}$ at 15 kPa; ^b at 15kPa with 10 mM CaCl₂ permeant; ^c Average ± standard deviation

5.3 The interaction between hydration and self-healing

Holes in GCLs may occur during handling, installation, or placement of cover material (Fox et al. 1998; Sari and Chai 2013), or by down-slope erosion in an exposed composite liner (Bachman et al. 2015, Take et al. 2015, Rowe et al. 2016a). Various researchers have examined the seal-healing of GCLs (e.g., Shan and Daniel 1991; Bouazza et al. 1996; Mazzieri and Pasqualini 2000; Didier et al. 2000b, Reuter and Egloffstein 2000, Sivakumar Babu et al. 2001) who have reported self-healing of holes up to 30 mm in diameter at applied stresses up to 20 kPa with clean water (distilled or tap). Since not all defects are circular, Rowe and Li (2016b) examined the self-healing of slits in GCLs upon hydration with deionized water. They reported that a single 15 mm-wide x 120 mm-long slit fully self-healed but a 25 mm-wide x 120 mm-long slit did not fully self-heal. They also examined two parallel 15 mm-wide x 240 mm-long slits. Full self-healing occurred when a 20 mm-wide GCL strip of undamaged GCL was between the slits, but did not occur when the width of this strip was reduced to 10 mm and 5 mm.

Sari and Chai (2013) investigated self-healing for holes with diameters up to 50 mm for a range of hydrating liquids (tap water, 10 g/l NaCl and 100 ml/l of ethanol solution) and overburden stress up to 200 kPa and reported self-healing for holes less than 30 mm when fully hydrated with tap water or an ethanol-tap water solution. Li and Rowe (2017) examined the self-healing of 25, 30, 35, 41 and 51 mm-diameter circular holes using deionized water and a 10 mM CaCl₂ (400 mg/L Ca²⁺) solution. Holes up to 41 mm-diameter self-healed in distilled water and up to 35 mm in 10 mM CaCl₂ solution highlighting the importance of the hydrating fluid when ample fluid is available. These results raise the question as to how well GCLs will self-heal when they must hydrate from the subgrade moisture, which both limits the water available and also contains cations that could affect the swelling capacity of the GCL.

Rowe and Li (2016a) reported preliminary laboratory experiments on self-healing of fully penetrating holes when GCL1 formed part of a composite liner with a smooth GMB and must hydrate from the QUELTS silty sand subsoil (with 230 mg/L Ca²⁺ in the pore water) at a dry density of 1.6 Mg/m³ and an applied stress of 20 kPa. They reported that when the silty sand was at 16% moisture content, a 13 mm-diameter hole self-healed although the self-healed specimen exhibited a 6-fold increase in hydraulic conductivity compared to an intact specimen. This research is still in progress, but it shows that self-healing is much more challenging when hydration must occur from the subgrade, as is likely in many field situations. The factors affecting hydration of a GCL in a soil with sufficient divalent cations to reduce the SI to 8-10 mL/2g discussed in §5.1 also apply when seeking to both hydrate and self-heal a GCL with a hole. This suggests that the ability of a GCL to self-heal is highly dependent on the interaction between the GCL and the subgrade and probably cannot be relied upon for holes larger than about 15 mm, although in some cases it may occur.

6 GMB-GCL INTERACTION AND LEAKAGE THROUGH COMPOSITE LINES

6.1 GMB-GCL interface transmissivity

Leakage through a hole in a geomembrane forming part of a composite liner with a GCL will depend on the size of the hole, the size of the wrinkle if the hole is in a wrinkle, the head on the liner, and both the hydraulic conductivity of the GCL and the interface transmissivity, θ , between the GMB and GCL. Only a limited amount of research has been conducted into interface transmissivity and mostly using distilled or tap water. AbdelRazek and Rowe (2018) reported an extensive review of the available literature which is briefly summarized below and in Table 12.

Harpur et al. (1993) reported θ , at normal stresses of 7 and 70 kPa for tap water (Table 12). Barroso et al. (2006) indicated that a woven or nonwoven geotextile in contact with the GMB had similar θ . They also concluded that there was little difference in ultimate θ , for GCLs with powdered or granular sodium bentonite. However, θ decreased with an increase in stress from 50 to 200 kPa. AbdelRazek et al. (2016) confirmed the finding that, when fully hydrated with distilled water, GCLs with granular and powdered sodium bentonite had similar values of $1 \times 10^{-11} \leq \theta \leq 2 \times 10^{-11} \text{ m}^2/\text{s}$ at 150 kPa.

Barroso et al. (2006) measured flows at different scales and found that θ from the 1m- and 2.5m-diameter cells were essentially the same or a little lower than obtained from the 0.2 m-diameter cell. Barroso et al. (2008) also concluded that GMB texture had minimal effect on transmissivity.

Mendes et al. (2010) found that, for water permeation at 50 kPa, the transmissivity was $2 \times 10^{-11} \leq \theta \leq 3 \times 10^{-11} \text{ m}^2/\text{s}$ for GCLs with sodium bentonite having $2 \times 10^{-11} \leq k \leq 3 \times 10^{-11} \text{ m/s}$ and for two GCL with calcium bentonite having in one case $k = 5.8 \times 10^{-8} \text{ m/s}$ and in the other case $k = 6.9 \times 10^{-10}$. This suggests that there is no relationship between θ and k ; a finding confirmed by Rowe and Abdelatty (2013) as described below.

All the tests reported above were with tap or distilled water and conventional GCLs. Rowe and Abdelatty (2013) performed two long-term (3-year) tests on a smooth 1.5 mm HDPE GMB with 10 mm hole in contact GCL1 (fine granular sodium bentonite between a needle-punched nonwoven and a woven geotextile) under an applied stress of 100 kPa. The interface was permeated with distilled water and then with a 0.14 M NaCl (3000 mg/L Na^+) solution for 2.5 years. The replacement of distilled water with 0.14M NaCl solution increased the GCL k by 5- to 9-fold (from $4.6 \times 10^{-11} \text{ m/s}$ with distilled water to 2.6×10^{-10} and $4.3 \times 10^{-10} \text{ m/s}$ after permeation by NaCl solution) and decreased θ by a factor of two from $2.3 \times 10^{-11} \text{ m}^2/\text{s}$ for distilled water to $1.1 \times 10^{-11} \text{ m}^2/\text{s}$ for 0.14M NaCl solution. The change in permeant only increased the steady state flow by 3% because the half to one order of magnitude increase in k was offset by 2-fold decrease in θ , with the θ dominating the flow. As with Mendes et al. (2010), there was no direct correlation between θ and k .

Table 12. Summary of published GMB-GCL interface transmissivities

| Reference | Permeant | Normal stress (kPa) | θ (m^2/s) |
|--------------------------------|------------|---------------------|--|
| <i>Conventional GCL</i> | | | |
| Harpur et al. (1993) | Water | 7 | 3×10^{-11} to 2×10^{-10} |
| Harpur et al. (1993) | Water | 70 | 6×10^{-12} to 1×10^{-10} |
| Barroso et al. (2006) | Water | 25 | 6×10^{-12} to 3×10^{-11} |
| Barroso et al. (2006) | Water | 50 | 1×10^{-11} to 4×10^{-10} |
| Barroso et al. (2006) | Water | 200 | 3×10^{-12} to 1×10^{-11} |
| Barroso et al. (2008) | Water | 50 | 1×10^{-11} to 4×10^{-11} |
| Mendes et al. (2010) | Water | 50 | 2×10^{-11} to 3×10^{-11} |
| AbdelRazek et al. (2016) | Water | 150 | 1×10^{-11} to 2×10^{-11} |
| Rowe and Abdelatty (2013) | Water | 100 | 2.3×10^{-11} |
| Rowe and Abdelatty (2013) | 0.14M NaCl | 100 | 1.1×10^{-11} |
| <i>Multi-component GCL</i> | | | |
| | | | θ |
| AbdelRazek and Rowe (2018) | Water | 10 | 6×10^{-11} |
| AbdelRazek and Rowe (2018) | Water | 25 | 4×10^{-11} |
| AbdelRazek and Rowe (2018) | Water | 50 | 3×10^{-11} |
| AbdelRazek and Rowe (2018) | Water | 150 | 2×10^{-11} to 3×10^{-11} |
| <i>Multi-component GCL</i> | | | |
| | | | θ_{f-b} |
| Bannour et al. (2013) | Water | 50 | 3×10^{-11} to 8×10^{-11} |
| Bannour and Touze-Foltz (2015) | Water | 50 | 1×10^{-11} to 9×10^{-11} |

Multicomponent GCLs may take the form of a molten polyolefin layer applied to the carrier geotextile and allowed to solidify or a thin geofilm glued to one side of the GCL. When used alone in a cover/capping system they can improve resistance to gas permeation and, when the coating is placed facing-upward, resistance to desiccation and root penetration (e.g., Egloffstein et al. 2013, Rowe 2016). The low permeability coating/laminate can also separate the bentonite in the GCL from an aggressive leachate (coating-up) or pore water (coating down; Hosney and Rowe 2014b). When used with a GMB in a composite liner they can help mitigate problems of leaving a composite liner exposed (Rowe et al. 2016a,b). When dealing with multicomponent GCLs, one needs to consider the transmissivity between the geofilm

and the bentonite component of the GCL, θ_{f-b} . In addition, if the coating/laminate is placed against a GMB then there is a second transmissivity between the GMB and the geofilm, θ , to be considered.

AbdelRazek and Rowe (2018) investigated the interface transmissivity between the GMB and the geofilm layer for undamaged coated and laminated GCLs in contact with 1.5 mm HDPE smooth GMB for distilled water at a range of stress levels and obtained values of θ ranging between $6 \times 10^{-11} \text{ m}^2/\text{s}$ at 10 kPa to $\theta \leq 2 \times 10^{-11} \text{ m}^2/\text{s}$ at 150 kPa (Table 12). They also showed that short-term (2-week) transmissivity tests tended to overestimate the transmissivity compared to longer-term tests; especially at low stress. For example, at 10 kPa after 2-weeks they obtained $\theta_{2\text{-week}} = 2.3 \times 10^{-10} \text{ m}^2/\text{s}$ and this reduced with time, as the bentonite rearranged itself, to $6 \times 10^{-11} \text{ m}^2/\text{s}$ after 6 months testing. AbdelRazek and Rowe (2018) also examined the effect of the type of multicomponent GCL, GMB stiffness, and GMB textured on the interface transmissivity between a coating and GMB but space does not permit a discussion of those results here.

Banner et al. (2013) and Bannour and Touze-Foltz (2015) conducted tests to establish the transmissivity of the interface between the coating/lamination and the bentonite component of the GCL for three multicomponent GCLs for water as permeate at 50 kPa normal stress. Using a 0.2m-diameter test cell, Banner et al. (2013) obtained values of $3 \times 10^{-11} \leq \theta_{f-b} \leq 4 \times 10^{-11} \text{ m}^2/\text{s}$ for a coated GCL and $3 \times 10^{-11} \leq \theta_{f-b} \leq 8 \times 10^{-11} \text{ m}^2/\text{s}$ for two laminated GCLs. Using 1m-diameter test cell, Bannour and Touze-Foltz (2015) obtained $\theta_{f-b} \sim 1 \times 10^{-11} \text{ m}^2/\text{s}$ for a coated GCL and $8 \times 10^{-11} \leq \theta_{f-b} \leq 9 \times 10^{-11} \text{ m}^2/\text{s}$ for two laminated GCLs. Thus, the difference in test scale had little effect on the results obtained.

7 CONCLUSIONS

This paper has provided a summary of many of the key findings in the 21st century, and especially in the last decade, that have added new insights into the factors affecting hydration of GCLs and how this can affect the ultimate performance of GCLs as advective barriers. It has also touched on the issue of interface transmissivity between GMB and GCL. The paper, although substantially cut from the original draft, is still twice the length requested by the conference organizers and even so it does not cover even the topics addressed in full detail while not even touching on some important topics like the addition of polymers to the bentonite. Nevertheless, it is hoped that it has provided some new insights into a most complex topic that remains an active area of research.

At the outset, this paper highlighted a number of common perceptions held by engineers and owners, they will now be addressed in the context of the research summarised in this paper.

1. 'A GCL will be sufficiently hydrated from the subgrade to have the hydraulic conductivity, k , no higher than that given in the product specifications sheet (e.g., $k \leq 5 \times 10^{-11} \text{ m/s}$)'. This can be true in some cases but, as demonstrated, unless there is a well-specified moisture content of the subgrade, it is far more common that the GCL will be at an apparent degree of saturation, S_r in the range $30\% \leq S_r \leq 70\%$ on non-cohesive soils and lower if there is clay, and especially smectite, in the soil. Indeed, even achieving $w \geq 100\%$ gravimetric is far from certain, and indeed unlikely, in many cases. Even if $w \geq 100\%$ is achieved, it does not assure good performance as an advective barrier without careful consideration of how the GCL was made/structured (see #2-4 below) and the specific application.
2. 'The form of the bentonite (coarse granular, fine granular, powder) does not matter since they will all have same k when hydrated and permeated at the same stress with the same permeant'. Assuming it is the same bentonite source, when fully saturated this is true. But, as indicated in #1 above, in most practical situations other than when a GCL is used alone as liner for potable water, the GCL will be far from fully saturated before it needs to perform its design function and in this case, as demonstrated, the nature of the bentonite does make a difference with finer being better.
3. 'How a GCL is manufactured will not affect performance since it is the hydrated bentonite that controls k '. Assuming it is the same bentonite source, and there is the same mass per unit area of bentonite, and it is fully saturated, and the stresses are high - then this is true. But - that is a lot of qualifiers and they are rarely all met. Under the stresses typical of hydration, the GCL structure can greatly affect the water content needed to achieve saturation and some structures increase the probability of achieving a good degree of saturation for the same subgrade. A scrim-reinforced GCL with thermal treatment offers the opportunity to minimize the amount of water needed to hydrate the GCL due to the confinement it provides by minimizing fibre-pullout at low stresses and hence the void ratio at which the GCL is fully hydrated. The structure can also help minimize the loss of moisture when subject to thermal cycles and hence reduce panel shrinkage.
4. 'Needle-punching only affects peel and shear strength (i.e., does not affect k)'. Needle-punching does play an important role in providing peel strength but more importantly internal shear strength. How-

ever, too much needle-punching will, as demonstrated, decrease the hydraulic performance of GCLs in low stress applications where there is cation exchange (e.g., cover/caps); especially if there is more than minimal head (i.e. $> 0.07\text{m}$). In these applications, the amount of needle-punching is best kept to the minimum needed to achieve the required internal shear strength. Here, method of GCL construction can be beneficial as it was in #3 above. A scrim-reinforced GCL with thermal treatment offers the opportunity to get good anchorage with minimal needle punching and hence represent a means of optimizing performance in covers.

5. 'Leakage through a composite liner is controlled by the head on the liner, the number and size of holes in the geomembrane, and the permittivity (i.e., hydraulic conductivity divided by the thickness) of the underlying clay liner'. These are all important factors affecting leakage – but this list and common perceptions often overlook another critical parameter – the GMB/GCL interface transmissivity which plays an absolutely key role in affecting leakage through holes in a GMB forming part of composite liner.
6. 'Leaving a composite liner exposed for a protracted period of time has no effect on its hydraulic performance'. GCL manufacturers installation guidelines commonly recommend covering a GCL, be it alone or in a composite liner, in a timely manner. Failure to do so can result in a number of totally avoidable problems, particularly for GCLs in composite liners where the GCL and the problems are hidden. The risk of leaving the liner exposed can be minimized with careful selection of GCL.

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