Performance of GCLS in liners for landfill and mining applications*

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The available evidence suggests that both geosynthetic clay liners (GCLs) and composite liners with a geomembrane (GMB) over a clay liner have performed extremely well at controlling leakage in field applications for a couple of decades. However, there have also been some problems reported and recent research has allowed us to have a much better understanding of the key design and construction factors affecting good and poor performance. This paper examines some of these issues including factors affecting GCL performance such as the water retention curve of GCLs, subgrade grain size and initial water content, GCL water content and normal stress on the GCL, the effect of daily thermal cycles on hydration, GCL panel shrinkage and cation exchange. Factors affecting composite liner performance examined include the potential for desiccation of the clay liner under a sustained thermal gradient, GMB/GCL interface transmissivity, wrinkles in the GMB when the ballast layer is placed over the composite liner and the potential interaction between wrinkles and GCL panel overlaps. Recent insights regarding leakage through composite liners are discussed. Although a number of potential issues with liner performance are discussed, it is concluded that all can be addressed by appropriate design, material selection, construction and operations.

Introduction

Liners have been an essential component of modern municipal solid waste (MSW) and hazardous waste landfills for 20–30 years and, more recently, are becoming an essential component of many mining undertakings where applications include ponds for storage of liquids generated by mining, and liners for tailings dams and heap leach pads. Likewise, covers have been an important part of landfill design for decades. In mining, for many years, there has been a recognized need for engineered covers for minimizing impacts due to acid-generating waste rock; however, there is growing need for covers for other mine waste (e.g., arsenic bearing gold mine tailings).

High-density polyethylene (HDPE) geomembranes (GMBs) have been used in landfill liners and covers, and for liners in ponds and heap leach pads for mining applications, but there has also been growing use of linear low-density polyethylene GMB liners in heap leach applications. Geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) have been used alone in covers and in some bottom liners; however, GCLs used in landfill applications are most commonly used with a GMB to form a composite liner.

Given the long history of the use of liners in landfill applications and the research and monitoring that have been conducted with respect to that application, it is known that well-designed and

-constructed composite bottom liners have performed very well in landfills (Bonaparte *et al.*, 2002; Mitchell *et al.*, 2007; Rowe 2005, 2012a). However, there have also been challenges when the liners have been exposed to conditions not anticipated in the design and where, until very recently, there has been a paucity of research. An example of this is landfills that, due to their operations (e.g., as bioreactors) or the nature of the waste being disposed (e.g., combustion ash, aluminum production wastes etc.), are resulting in temperatures (Table 1) on or near the liner that raise concerns regarding their long-term and, in some cases, even short-term viability (Jafari *et al.*, 2013). High liner temperatures can also be found in mining applications involving, for example, brine ponds and some heap leach pads (Table 1). There is a need for research to examine the effect of these temperatures and the exposure to different chemicals on short- and long-term liner performance.

Liners in landfill and mining covers/caps have exhibited both good and poor performance over the years. If intact, GMBs are excellent barriers to the advective migration of fluids (liquids and gases), but once they have holes or openings (e.g., due to inferior welding), they can readily transmit relatively large volumes of fluid through the hole(s), and it is for this reason that they are often used in conjunction with a clay liner to form a composite system (e.g., Rowe *et al.*, 2004; Rowe 2005, 2012a).

When used alone, but also in some cases when used as part of a composite liner, GCLs used in covers have had mixed success

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Environment	Temperature: °C	Ref. ^a
Normal MSW landfills (limited moisture addition)	30–40	1–5
Wet landfills (e.g., bioreactor landfills) where there is a significant amount of moisture	40–60	5–7
Unusual MSW landfills	60–80 ^b	5
	50–60 ^c	5
Ash monofills	46	8
	50–90 ^b	5
	65–70 ^c	5
MSW with aluminum production waste and leachate recirculation	85 ^d	9, 10
	>143 ^e	9, 10
Nickel heap leach pad	70	11
Ponds for highly saline fluid	70–93	12

^aReference: (1) Brune *et al.* (1991); (2) Rowe (2005); (3) Koerner and Koerner (2006); (4) Needham and Knox (2008); (5) author's files; (6) Yoshida and Rowe (2003); (7) Koerner *et al.* (2008); (8) Klein *et al.* (2001); (9) Calder and Stark (2010); (10) Stark *et al.* (2012); (11) Abdelaal *et al.* (2011); (12) Lichtwardt and Comer (1997).

^bNo monitors on liner so liner temperature is unknown; temperature given is in waste about 3 m above liner.

^cLeachate temperature.

^dTemperature in leachate collection pipes.

^eTemperature in waste.

Adapted from Rowe (2012a).

Table 1. Temperature on (or near) liners for different environments

(sometimes performing very well and sometimes not) in both landfill and mining applications (e.g., Adu-Wusu *et al.*, 2002; Benson *et al.*, 2010; Hosney and Rowe, 2013; Melchior, 2002; Meer and Benson, 2007; Renken *et al.*, 2005; Scalia and Benson, 2011), begging the question as to what are the factors affecting good versus poor performance?

This paper seeks to examine some recent advances in the understanding of factors affecting the performance of liners in both bottom liner and capping systems for landfill and mining applications, and the implications of this new understanding regarding strategies that might be considered for improving liner performance in these applications. Since the theme of this paper is recent advances, emphasis will be placed on research published in the last few years and research about to be published, although other publications will be referenced when required to place the current advances in context. Also, because of space limitations, attention will be focused on advances in understanding related to leakage through GCLs both when used alone and when used in composite liners. The many recent advances with respect to understanding GMB performance, diffusion through liners and liner stability relevant to the performance of both bottom liners and capping systems are not addressed here.

Geosynthetic clay liners

GCLs are manufactured and delivered to site on rolls that are laid down with adjacent panels overlapped to provide a continuous layer of GCL. As manufactured, the most commonly used GCLs comprise a lower “carrier” geotextile, a layer of bentonite and an upper “cover” geotextile. The GCL is held together by needle-punching the upper cover geotextile fibres through the bentonite and into the carrier geotextile. Many GCLs meet this broad description. For example, one single Canadian manufacturer has over 50 different GCLs that they manufacture fitting this description, with the different products having different characteristics suitable to different design/site conditions. Understanding why GCLs perform remarkably well in many situations and not well in some others requires an understanding of the many factors that can affect the performance of a GCL which include (but are not limited to) (a) the type of bentonite; (b) whether or not there is a polymer in the bentonite; (c) the mass of bentonite per unit area, M_A ; (d) the type and mass per unit area of the geotextiles used; (e) the amount of needle-punching; (f) whether or not the needle-punched fibres are thermally fused to the carrier geotextile; (g) the presence or absence of a geofilm bonded to the GCL, the nature of the geofilm and how the geofilm is bonded to the carrier geotextile; (h) the characteristics of the GCL panel overlap; (i) whether or not the GCL is part of a composite liner; (j) the presence of wrinkles in the GMB; (k) the initial water content and particle size distribution of the soil above and/or below the GCL; (l) geochemical interactions between the bentonite and the pore water in the soil adjacent to the GCL; (m) possible interaction of the bentonite with the fluid to be retained; (n) the amount of cover soil over the GCL; (o) the level of exposure to thermal cycles; (p) sustained thermal gradients; and (q) the stress on the GCL. The following subsections will explore some aspects of the performance of GCLs and will include consideration of the role of some of the factors noted above. Ongoing research will shed light on other factors not discussed below.

Water retention curve of GCLs

The performance of a GCL as a barrier to fluids (either liquid or gas) is intimately linked to the uptake of moisture by the bentonite in the GCL and its resulting degree of saturation. It is often implicitly assumed by designers that the GCL will be hydrated when it is needed to act as a fluid barrier. However, whether or not this assumption is realized will depend on many factors. One key factor is the water retention curve (WRC) of the GCL itself (e.g., Acikel *et al.*, 2011; Barroso *et al.*, 2006; Beddoe *et al.*, 2010, 2011; Daniel *et al.*, 1993; Southen and Rowe, 2007). A GCL's WRC describes the relationship between the water content of the GCL and the suction in the bentonite. The off-the-roll GCL has a very low water content and very high suction. When the GCL is placed on a subgrade with lower suction, the GCL will uptake (suck) water from that soil. This will cause the GCL water content to increase and its suction to decrease. One can expect that the uptake of water would continue until the suction in the GCL had decreased sufficiently to come into equilibrium with the suction in the soil in direct contact with the GCL (i.e., the adjacent soil). Thus, intuitively, one may expect that the final equilibrium water content of the GCL will depend on the

WRC of the GCL (discussed in this section) and on the WRC of the adjacent soil together with the initial water content of this soil which will control its suction.

Under isothermal conditions one can expect the GCL to start at a very high suction (corresponding to its off-the-roll water content) and to move up what is called the wetting curve as it takes up moisture until it comes into equilibrium with the adjacent soil. As the GCL takes up moisture, the bentonite swells and is constrained by the needle-punching between the cover and carrier geotextiles and the overburden stress. When the overburden stress is low, most of the resistance is provided by the needle-punched fibres. If the needle punched fibres are not well anchored, they can be pulled out of the carrier geotextile and there is a permanent change in the GCL. The extent of this change will depend on how well the fibres are anchored (e.g., thermally fused or not). As the GCL pulls out fibres, the reduction in resistance allows the void ratio of the GCL to increase and hence more water is required to saturate the GCL than if the fibres had not pulled out (or if there were a higher overburden stress).

If a GCL has experienced an increase in water content by moving up the wetting curve and is then heated (as discussed in later sections), the heat can drive the moisture out of the GCL and the suction increases as the water content decreases along what is called the drying curve. In general, the drying curve is different to the wetting curve and the greater the pullout of fibres during wetting the greater one might expect the difference between the wetting and drying curves to be. Thus to fully understand the hydration of a GCL, one needs to know the WRC in wetting. To understand how the GCL will respond to thermal cycles, one also needs to understand the WRC in drying.

Despite its importance to the uptake of moisture, the WRC of GCLs has received very little study, probably because of the inherent difficulty of experimentally obtaining the WRC of the bentonite when encased in geotextiles and the wide range of suctions that need to be investigated (Beddoe *et al.*, 2010). Beddoe *et al.* (2011) obtained the wetting and drying WRCs of four GCL products under 2 kPa of normal stress. They showed that this wetting curve varied quite substantially depending on the characteristic of the GCL as manufactured. At a given suction, the gravimetric water content was lowest for a GCL (denoted as GCL2) which was thermally treated to fuse the needle-punched fibres to the scrim-reinforced nonwoven (i.e., a combination of a woven and nonwoven) carrier geotextile. This GCL reached a higher degree of saturation at a given moisture content than the other GCLs tested. The wetting curves for GCL1 (which was thermally treated to fuse the needle-punched fibres to the woven carrier geotextile) and GCL4 (with a simple needle-punched nonwoven carrier and only mechanical bonding) crossed at a suction of 10 kPa. GCL3 (with a woven carrier and only mechanical bonding) had the highest water content at any given suction.

There is always variability in manufactured products like GMBs, GCLs and geotextiles. Recognizing this, manufacturers produce

GCLs to meet minimum average roll values. The effect of the GCL characteristics, as manufactured, and the related variability is most evident for a GCL that is fully hydrated at low stress (e.g., below a GMB with little or no cover over the GMB). When saturated, there was a significant difference in the average water content and variation in saturated water content for the four most commonly used GCLs in North America (Table 2). At saturation, GCL2 had by far the lowest water content and the lowest variability (standard deviation) because the needle-punched fibres were most effectively and consistently bonded to the carrier geotextile thereby minimising fibre pull-out as the bentonite hydrates and providing the best confinement of the bentonite. For GCL1, the thermal treatment resulted in the next lowest saturated water content, but the bonding to the woven carrier was not as consistent as that to the scrim-reinforced nonwoven carrier of GCL2. GCL4 had a substantially higher saturated water content than GCL1 or GCL2. GCL3 had the highest mean water content and by far the highest variability, indicating that the mechanical bonding of the needle-punched fibres to a woven GCL was least effective and most inconsistent in terms of constraining the bentonite as it tried to swell at low stress. Since it is the degree of saturation, rather than the actual water content, that most affects GCL performance and since both the hydraulic conductivity and diffusion coefficient are lower with a lower bulk void ratio (Lake and Rowe, 2000a, 2000b; Petrov and Rowe, 1997), it follows that the lower the saturated water content, the better the performance as a hydraulic and diffusive barrier (other things being equal).

Swelling of the GCL at low stress results in some pull-out of fibres that are not well anchored. This is manifested as a difference in the drying and wetting WRCs and the degree of hysteresis if the GCL is subjected to drying after hydration. The hysteresis was by far the least for GCL2 for which there was very little difference between the wetting and the drying curves. Thus in field applications where the GCL may be exposed to wetting and drying cycles, such as when a GCL is below a GMB that is left exposed, one might infer that GCL2 will be less susceptible to the moisture changes that result in shrinkage of the GCL and hence predict less shrinkage for GCL2 than the other three GCLs in a real field situation.

Product	Water content at saturation	
	Mean: %	SD: %
GCL1	166	10
GCL2	130	5
GCL3	205	16
GCL4	194	8

Adapted from Beddoe *et al.* (2011).

Table 2. GCL Gravimetric water content of four different GCL products at saturation at 2 kPa

Southen and Rowe (2007) demonstrated that the WRC for a GCL was dependent on the applied stress based on tests at 0.5 and 100 kPa. This is important in modelling moisture loss and possible desiccation of GCLs when subject to a sustained thermal gradient discussed later. At present, there is very limited data on GCL WRCs at stresses greater than 2 kPa. Thus, more research is required to obtain WRCs for different GCLs at different stress levels.

When a GCL is placed on soil containing water, the suctions in the bentonite will induce moisture migration from the soil to the GCL until the suction in the GCL is in equilibrium with the suction in the adjacent soil. The rate at which this process takes place and the time to equilibrium will be dependent on the hydraulic conductivity of the soil adjacent to the GCL. This hydraulic conductivity will depend on the water content of the soil and can be expected to reduce as water is transferred from the soil to the GCL. The suction at which equilibrium is reached will depend on the WRCs of both the GCL and soil from which it is hydrating. Despite its importance, this has received remarkably little attention. Daniel *et al.* (1993) reported that an initially air dry GCL reached water content, w , of 88% after 40–45 days resting on sand at 3% gravimetric water content. Eberle and von Maubeuge (1998) showed that an initially air dry GCL resting on a sand with a water content, w_{fdn} , of 8–10%, reached $w = 100\%$ in less than 24 h and $w = 140\%$ after 60 days. However, the effect of GCL type, subsoil grain-size distribution and water content has only recently been published (Anderson *et al.*, 2012; Chevrier *et al.*, 2012; Rayhani *et al.*, 2011).

Rayhani *et al.* (2011) examined the moisture uptake of three GCLs [those denoted as GCL1, GCL2 and GCL4 in the Beddoe *et al.* (2011) study and described above] in a composite liner under isothermal conditions at 22°C. Tests were conducted for the GCLs resting on a silty sand subgrade (SM: 35% non-plastic fines and standard Proctor optimum water content, w_{opt} , of 11.4%; Table 3) and a poorly graded sand subgrade (SP: 5% non-plastic fines, $w_{\text{opt}} = 10.3\%$; Table 4). Because of the presence of an overlying GMB, all water uptake was from the subgrade below.

When the GCLs were placed on the silty sand subgrade at a water content corresponding to field capacity ($w_{\text{fdn}} = 21\%$), GCL2 was essentially hydrated in 5 weeks ($S_r = 97\%$, Table 3) and GCL1 and GCL4 had S_r of about 90%. All GCLs had fully hydrated after 30 weeks; however, there was a significant difference in the final water content, w_f , between GCL2 ($w_f = 116\%$) and GCL1 ($w_f = 141\%$) and GCL4 ($w_f = 149\%$). When the GCLs were placed on silty sand at $w_{\text{fdn}} = 10\%$ (i.e., just below w_{opt}), GCL2 hydrated to $S_r = 74\%$ ($w_f = 85\%$) in 20 weeks, GCL1 took 30 weeks to reach $S_r = 62\%$ ($w_f = 86\%$) and GCL4 took 30 weeks to reach $S_r = 68\%$ ($w_f = 102\%$). Thus when placed on silty sand at w_{fdn} just below w_{opt} , the GCLs would only be partially hydrated from the subgrade at low stress. If the stress on the GCL increased (e.g., due to placing sufficient cover soil or material to be contained by the liner), one would expect an increase in S_r (Siemens *et al.*, 2012).

		Week	5	10	20	30	30
GCL	Subgrade (w_{fdn}): %	Degree of saturation (S_r): %		w_f : %			
GCL1	5	25	25	24	24	34	
GCL1	10	52	57	62	62	86	
GCL1	16	60	68	72	73	102	
GCL1	21	91	100	100	100	141	
GCL2	5	32	33	34	34	40	
GCL2	10	63	69	74	74	85	
GCL2	16	66	70	75	77	88	
GCL2	21	97	100	100	100	116	
GCL4	5	32	41	50	55	83	
GCL4	10	50	61	66	68	102	
GCL4	16	57	68	73	76	114	
GCL4	21	89	94	99	99	149	

Adapted from Rayhani *et al.* (2011).

Table 3. Hydration of GCLs with time resting on silty sand at different initial water contents, w_{fdn}

		Week	5	10	20	30	30
GCL	Subgrade (w_{fdn}): %	Degree of saturation: %		w_f : %			
GCL2	2	26	27	27	27	31	
GCL2	10	68	75	76	78	90	

Adapted from Rayhani *et al.* (2011).

Table 4. Hydration of GCLs with time resting on poorly graded sand at different initial water contents

For the same soil initial water content, $w_{\text{fdn}} = 10\%$, the GCL placed on the sand (SP; Table 4) hydrated faster and to a slightly higher final water content than when on the silty sand (SM; Table 3). When GCL2 was placed on soil close to its residual water content (5% for the silty sand and 2% for the sand), it only hydrated to $S_r = 34\%$ ($w_f = 40\%$) and $S_r = 27\%$ ($w_f = 31\%$), respectively, highlighting the need for the GCL to be placed on soil with sufficient moisture to allow reasonable hydration of the GCL.

Rayhani *et al.* (2011) reported that the hydration was not significantly affected by whether the cover or carrier GCL rested on the subgrade and inferred that the WRC of the GCLs was not affected by whether the carrier geotextile was placed up or down.

Anderson *et al.* (2012) examined the hydration of GCL1, GCL2 and GCL3 resting on a clayey sand (Table 5). The clayey sand had 21% fines (12% clay size) and $w_{opt} = 11.3\%$. When the subsoil had a water content of 20%, all GCLs hydrated to a S_r of about 90%. When the subsoil water content was at a little below optimum ($w_{fdn} = 10\%$), GCL2 hydrated to a $S_r = 67\%$ ($w = 79\%$) compared to $S_r = 59\%$ ($w_r = 85\%$) for GCL1 and $S_r = 48\%$ ($w_r = 90\%$) for GCL3. At a subsoil water content of 5%, there was very little hydration and after 22 weeks S_r was only 18%, 16% and 12% for GCL2, GCL1 and GCL3, respectively.

Anderson *et al.* (2012) compared their results with those obtained by Rayhani *et al.* (2011) under otherwise similar conditions and concluded that the subsoil affected both the rate and the degree of hydration. For example, the time it took to reach a value of $S_r = 60\%$ ranged from 2 weeks over the sand (SP), to 5 weeks over the silty sand (SM) and to 8 weeks over the clayey sand (SC).

Also, for otherwise comparable conditions, the final equilibrium value of S_r was (slightly) higher for the GCL over the sand (SP) than over the silty sand (SM) which was higher than for the GCL over the clayey sand (SC). These differences are due to the different WRCs of the three subgrades.

Chevrier *et al.* (2012) obtained similar findings with respect to the effect of subgrade grain size and initial water content but at a stress of 4 kPa which was slightly greater than the 2 kPa used in the Rayhani *et al.* (2011) and Anderson *et al.* (2012) studies. Chevrier *et al.*

(2012) also demonstrated that the rate of hydration was temperature dependent, with faster hydration at 45°C than at 20°C than at 5°C.

The French Committee for Geosynthetics (Fascicule, 1998) requires that the water content of the bentonite in GCLs used in liners should be at least 100%, presumably with the objective of ensuring that the GCL has a high degree of saturation prior to contact with leachate. The work described above has indicated that whether or not this will happen is highly dependent on the initial moisture content and grain-size characteristics of the subgrade below the GCL. The work cited above also shows that the degree of saturation when this criterion is met can be highly dependent on the type of GCL. For example, at $w = 98\text{--}102\%$, GCL1, GCL3 and GCL4 had S_r of 67–73%, 52% and 68%, respectively (see Tables 3 and 5). When GCL2 was at $w = 116\%$, it had $S_r = 100\%$, but at a similar $w = 114\%$, GCL4 only had $S_r = 76\%$ (see Table 3). Thus, while $w = 100\%$ would appear to be a reasonable requirement for the scrim-reinforced and thermally treated GCL2, it appears quite inadequate for the other GCLs (especially GCL3).

Modelling isothermal moisture uptake

Siemens *et al.* (2012) used the WRCs from Beddoe *et al.* (2011) together with the isothermal hydration data from Rayhani *et al.* (2011) to calibrate a numerical model for GCL hydration. They then performed sensitivity analyses to examine the effect of different subgrades (with different WRC and w_{fdn}). These results showed that, for a given GCL WRC, the final equilibrium water content, and hence S_r , was governed by the initial suction in the subgrade (which depended on the subgrade WRC and w_{fdn}). Based on this observation, they proposed a method for assessing the likely equilibrium water content of the GCL (and hence S_r). In essence, knowing the WRC of the subgrade (which can be inferred from its grain-size distribution) and w_{fdn} , one can infer the suction in the subgrade and then, using the wetting WRC of the GCL (e.g., from Beddoe *et al.*, 2011), deduce the value of w_r for that suction and hence calculate the likely value of S_r (knowing the likely saturated water content for that GCL). Conversely, knowing the desired value of S_r , one can calculate the required equilibrium value of w_r for the GCL and, hence, from the WRC, the corresponding suction. Using this suction and the WRC for the subgrade, one can then deduce the value of w_{fdn} required to achieve the desired hydration of the GCL.

To apply the approach above, one needs the wetting WRC of the GCL. This has only been developed for a limited number of GCLs and mostly at low stress (≤ 2 kPa); there is a need for wetting WRC for a range of hydrating stresses. This information void leaves open the question as to what effect does the stress on the GCL at the time of hydration have on the WRC and hence the value of S_r that can be achieved for a given subgrade? To provide some insight, Siemens *et al.* (2013) used the WRC data from Beddoe *et al.* (2011) and that at 0.5 and 100 kPa from Southen and Rowe (2007), the consolidation characteristics of GCLs from Lake and Rowe (2000a), and the GCL hydraulic conductivity data at various confining stresses from Rowe and Hosney (2013) in conjunction with the numerical

Week		1	22	22
GCL	Subgrade (w_{fdn}): %	S_r : %		w : %
GCL1	5	17	16	24
GCL1	10	26	59	85
GCL1	15	28	67	98
GCL1	20	29	90	130
GCL2	5	18	18	22
GCL2	10	26	67	79
GCL2	15	27	75	88
GCL2	20	29	90	106
GCL3	5	13	12	23
GCL3	10	21	48	90
GCL3	15	22	52	99
GCL3	20	24	92	174

Adapted from Anderson *et al.* (2012).

Table 5. Hydration of GCLs with time resting on clayey sand at different initial water contents

procedure developed by Siemens *et al.* (2012) to provide the basis for a numerical investigation of the possible effects of higher confining stress on the hydration behaviour of GCLs. Their results indicated that hydration of a GCL at a higher confining stress would result in a higher S_r (other things being equal), with the magnitude of this difference being dependent on w_{fdn} . These findings provide encouragement for laboratory studies of the effect of stress on the WRC of GCLs.

Since adequate hydration of a GCL is key to good performance as a barrier, their performance in covers and liners can be improved by paying attention to the water content of the subsoil upon which they are placed and the selection of an appropriate GCL, especially under more challenging conditions.

Effect of moisture uptake and stress on gas permeability

An example of the linkage between the GCL WRC and moisture uptake and the potential engineering performance of GCLs as a gas barrier has been recently reported by Rouf *et al.* (2013). They examined the gas permeability of a GCL somewhat similar to GCL2 discussed earlier (the main difference being the use of powdered Trugel bentonite in this case and granular Wyoming bentonite in GCL2). Experiments were performed for a range of water contents and suctions for stresses of 2 and 20 kPa.

At low water content ($w < 50\%$ and suctions > 1.6 MPa), the gas permeability was very high and not much affected by stress. However, as the water content increased, there was not only a substantial (orders of magnitude) decrease in gas permeability but also a significant effect of the difference in stress between 2 and 20 kPa. This was likely due to the change in the WRC with applied stress which resulted in a higher degree of saturation and lower void ratio at a given water content at 20 kPa than at 2 kPa.

GCL moisture uptake with daily thermal cycles

Isothermal conditions, as examined above, represent ideal conditions for hydration. If a GCL is used as part of a composite liner that is left exposed to the sun, the GCL will be subject to thermal cycles. Rowe *et al.* (2011b) examined the same GCLs and silty sand subsoil as Rayhani *et al.* (2011) (discussed in a previous section) but subjected the GCL to daily thermal cycles. Based on observations at the Queen's University environmental liner test site (QUELTS) located north of Kingston, Ontario, Canada, in the summer the GMB can heat to up to 60°C on a sunny day and cool to 20°C in the evening. For the laboratory study, this was idealized as a daily cycle where a GMB above the GCL resting on the silty sand was heated to 60°C for 12 h and then allowed to cool to 20°C over the next 12 h.

For GCLs over silty sand with w_{fdn} of 5%, 10% and 16%, after 7 weeks of daily thermal cycles the GCLs at the end of the heating cycle had S_r of only 9–24% (Table 6). These values are very low compared to the values obtained under isothermal conditions, especially for subsoil with w_{fdn} of 10% and 16% (Table 3). However, for $w_{fdn} = 21\%$ (just below field capacity), even with daily thermal

GCL	Subgrade (w_{fdn}): %	Week		
		1	7	7
		S_r : %		w : %
GCL1	5	15	16	23
GCL1	10	23	25	35
GCL1	16	24	22	30
GCL1	21	52	81	113
GCL2	5	16	14	16
GCL2	10	15	14	16
GCL2	16	20	24	27
GCL2	21	66	100	117
GCL4	5	13	9	14
GCL4	16	10	11	17
GCL4	21	45	85	127

Values given are immediately following the heating period (adapted from Rowe *et al.*, 2011b).

Table 6. Hydration of GCLs resting on silty sand when subjected to daily thermal cycles of 20–60°C

cycles S_r was 100% for GCL2, 81% for GCL1 and 85% for GCL4 (Table 6). Thus the effect of the daily cycles was very sensitive to w_{fdn} .

A key consideration with respect to possible shrinkage of the GCLs is the change in water content during a daily cycle (i.e., between the end of the cool period and the end of the hot period). After a few weeks of daily cycles, for $w_{fdn} = 16\%$ GCL1 experienced a ~13% change in water content during a cycle compared to ~10% for GCL4 and ~2% for GCL2. These differences are related to the difference in the WRC discussed earlier. Thus, Rowe *et al.* (2011b) predicted that, for the conditions examined and to the extent that shrinkage is dependent on a change in moisture over a daily cycle, the susceptibility to shrinkage would be $GCL1 \geq GCL4 > GCL2$.

Anderson *et al.* (2012) examined the performance of GCL2 and GCL3 over the same clayey sand subgrade as examined for isothermal conditions and discussed in the previous section (Table 5). For w_{fdn} of 5%, 10% and 15%, after 6 weeks of daily thermal cycles the GCLs at the end of the heating cycle had S_r of only 9–14% (Table 7). Comparing results for GCL2 in Tables 6 and 7, it appears that the clayey sand suppressed the hydration of the GCLs even more than the silty sand at the end of the heating cycle. This effect is even more evident when comparing the results for subsoil with w_{fdn} of 20–21% where, for the silty sand, GCL2 was fully hydrated ($S_r = 100\%$) but, for the clayey sand, it only reached $S_r = 56\%$.

For a GCL in an exposed composite liner, the cases of isothermal hydration at 20°C and daily thermal cycles from 20°C to 60°C

	Week	1	6	6
GCL	Subgrade (w_{fdn}): %	S_r : %		w : %
GCL2	5	11	11	13
GCL2	10	11	13	16
GCL2	15	12	14	16
GCL2	20	21	56	66
GCL3	5	9	9	16
GCL3	10	9	10	20
GCL3	15	9	10	18
GCL3	20	25	48	92

Values given are immediately following the heating period (adapted from Anderson *et al.*, 2012).

Table 7. Hydration of GCLs resting on clayey sand when subjected to daily thermal cycles of 22–56°C

represent two extremes in one sense but neither represents a worst case for GCL shrinkage and neither is likely to be realised given that the weather and cloud cover are likely to change from day to day. A worse case, for example, is if there is a period of cloudy weather where the GCL can hydrate almost isothermally followed by a hot sunny day when the moisture can evaporate or be driven back into the soil, followed by another period of cooler/cloudier weather, thereby allowing larger changes in the water content of the GCL when heated.

GCL Shrinkage

GCL manufacturers recommend that the GCL be placed under dry weather conditions and be covered with a ballast layer (typically 0.3 m or more of cover soil) shortly after placement. When covered by a GMB to form a composite liner, this recommendation is often more honoured in the breach than in the observance. There can be a variety of reasons for this but a common one is that the cover soil on the side slopes cannot be adequately placed quickly for the length of slope that has been installed and so the liner system is left exposed for months and sometimes many years. Covering the composite liner in a timely manner avoids a number of potential problems not the least of which is the potential for shrinkage of the GCL below the exposed GMB.

The potential for shrinkage was reported by Thiel and Richardson (2005) for cases where a GMB was opened to discover that the GCL had shrunk to the point that the GCL panels that had originally been overlapped by 150 mm had shrunk sufficiently to leave a significant gap between the panels. Koerner and Koerner (2005) and Thiel *et al.* (2006) reported other cases (Table 8) which corresponded to shrinkage of the overlap by 300–1350 mm and shrinkage strains ranging from 7% to 31%. These cases demonstrated that there could be significant shrinkage in periods of as little as 2 months on both relatively flat (2–4°) slopes and side slopes of 18° to 34°.

GCL ^a	Slope	Movement: mm	Exposure: months
W/W	22°	450	60
N/W	18°	350	15
N/W	4°	450	2
N/N	34°	1350	36
N/N	18°	450	5
N/N	4°	600	2
N/N	2–4°	300	2

^aCover geotextile/carrier geotextile. W, woven geotextile; N, nonwoven geotextile.

Data from Koerner and Koerner (2005) and Thiel *et al.* (2006).

Table 8. Summary of observed GCL panel overlap movement (gap + original design overlap of 150 mm)

However, there are also cases where GCLs have been installed and no significant shrinkage was observed. Thiel and Rowe (2010) discussed a number of such cases as briefly summarized below.

GCLs (similar to GCL3 and GCL4) that had experienced significant shrinkage in several cases reported in Table 8 were installed on a 3H:1V (18.4°) slope with a silty clay subgrade having $w_{\text{fdn}} = 5\%$ (CETCO, 2006). Water was sprayed on the GCL after placement to raise the GCL water content to 40–45% and it was then covered with a GMB. Over a 10-month period, during which GMB temperatures were reported to reach over 60°C, the GCL water content was reported to have gone from an initial high of about 45% to a low of 11%. The GCL panels only experienced shrinkage strains of 0.6–0.9% and overlap movements of only 25 to 37 mm. In this case, the low shrinkage was probably due to a number of factors including the low initial water content of the subsoil (which limited the rate and amount of hydration in cool periods) and the fact that the GMB did not appear to have been welded, so there was potential for moisture loss at the GMB panel edges to the atmosphere that could be expected to have reduced the moisture cycles.

Gassner (2009) installed a GCL very similar to GCL1 on a 55-m-long 3H:1V slope and covered it with a GMB and a white geotextile. After 18 months of exposure in Melbourne, Australia, the inspection of 1 m of the overlap one-third of the way down the slope indicated shrinkage of only 50 to 80 mm and the 300-mm overlap used in this case appeared adequate.

Thiel and Rowe (2010) reported that four different GCL test plots were constructed on a 40-m-long 3H:1V slope at one of the sites where there had been significant panel separation on relatively flat areas (Table 8). After it was covered with a GMB, the overlaps below the GMB were periodically inspected. Over a period of 7 months, there was reported to be no notable panel shrinkage, but a high value of S_r , “flowing” water and internal bentonite erosion resulting from the flowing water were reported.

It is apparent that the shrinkage is a result of wet–dry cycling. However, the fact that, in some cases, there was shrinkage that caused a large gap between the GCL panels and, in other cases, there was no significant shrinkage indicates that this is a complex issue. The potential for GCL shrinkage has been the subject of a number of laboratory studies (Bostwick *et al.*, 2010; Brachman *et al.*, 2010; Joshi *et al.*, 2011; Rowe *et al.*, 2010a, 2011a; Thiel *et al.*, 2006) as briefly summarized below.

Experiments have been conducted on GCLs placed in a pan and subjected to artificial wet–dry cycling by adding a prescribed amount of water and then drying the GCL in an oven at 60°C (Bostwick *et al.*, 2010; Rowe *et al.*, 2011a; Thiel *et al.*, 2006). These experiments showed that all eight GCLs tested have the potential to shrink significantly, although the method of manufacture did have an effect with some types of GCL shrinking more than others. However, when the GCL is used as part of an exposed composite liner in the field, the moisture cycles experienced by the GCL will depend on the WRCs of the GCL and the subgrade (which will depend on the type of GCL and grain-size distribution of the subgrade), the initial water content of the subgrade, and the length and nature of the thermal cycles as discussed earlier.

Bostwick *et al.* (2010) reported that the dry mass per unit area of a GCL did not significantly affect shrinkage provided that the bentonite was evenly distributed. However, much higher shrinkage was reported for GCLs with an uneven distribution of bentonite (generally, samples with a low average mass per unit area). GCLs with a lower mass per unit area appear to have an increased probability of variability in the distribution of bentonite, and GCLs with little to no bentonite in some areas experience higher shrinkage under otherwise similar test conditions. Thus the level of quality control needed to ensure sufficient bentonite at every location on a GCL roll appears to increase as the average mass of bentonite per unit area is decreased. Bostwick *et al.* (2010) also noted that the maximum shrinkage of 14.4% observed for GCL4 in their study was well below the maximum of 23% observed by Thiel *et al.* (2006) for nominally the same product using the same test method, suggesting that there can be a difference in shrinkage of different rolls of nominally the same product under otherwise similar conditions which, presumably, is related to the difference in the variability of the product being produced at different times but having the same designation. Bostwick *et al.* (2010) and Rowe *et al.* (2011a) found that some products exhibited considerable variability, while other products had quite small variability.

Rowe *et al.* (2011a) examined eight different GCLs subjected to laboratory wetting and drying cycles. They reported that the off-the-roll water content could affect the initial shrinkage but did not significantly change the final shrinkage (i.e., after many cycles). They also reported that when GCLs with granular bentonite were wetted to a water content $\geq 60\%$ in each cycle, the actual water content did not have much effect on the final equilibrium shrinkage but it did change the rate of shrinkage. A higher water content in the hydration cycle resulted in the maximum shrinkage being reached in fewer cycles.

The authors found that the shrinkage of a needle-punched GCL with a thermally treated scrim-reinforced nonwoven carrier geotextile and granular bentonite (GCL2) was less than that for a needle-punched GCL with a simple nonwoven carrier and granular bentonite (GCL4). It is significant that, in their experiments, the shrinkage strain required to cause the loss of a 150–300-mm panel overlap could be developed in as little as about five wet–dry cycles, and this helps explain why panel overlap has been lost in as little as 2 months in some field situations (Table 8). Thus the conditions that would allow this number of significant hydration cycles become important.

The uptake of moisture and the potential of a change in water content are highly dependent on the initial water content and the WRC of the soil below the GCL, and on the WRC of the GCL. The thermal cycles experienced by the GCL will also depend on weather conditions as discussed earlier.

Shrinkage may be suppressed by bonding between GCL panels. This could occur due to “gluing” of panels together when a supplemental bentonite between GCL panels gets wet and then dries (Brachman *et al.*, 2010), although this is not a reliable method of suppressing shrinkage (e.g., it will be lost when the supplemental bentonite at a location is rehydrated). A potentially more reliable means of suppressing shrinkage is to heat tack the overlaps. Limited evidence suggests that, when well heat tacked, there is sufficient bond to resist at least some wet–dry cycles (Joshi *et al.*, 2011; Rowe *et al.*, 2010a; Thiel and Thiel, 2009), although it is not yet clear to what extent the bond would be sufficient to resist overlap movement under the conditions that resulted in the loss of panel shrinkage reported in Table 8.

The laboratory studies reported above have provided insight regarding the relative performance of different GCLs for idealized conditions; however, to date, there has been no published study examining the field performance of different GCLs side by side under similar field conditions. Brachman *et al.* (2007) described the construction of the Queen’s University environmental liner test site (QUELTS) north of Kingston, Ontario, Canada, in 2006 to examine the relative performance of four commonly used North American GCLs (GCLs 1–4 discussed earlier) in six different exposed composite liner configurations (some smooth, some textured GMBs) under as identical conditions as possible (Figure 1). This experiment was terminated in 2011 after approximately 5 years. The GMBs and GCLs placed in 2006 were removed in May 2012, and seven new test sections were constructed and have been monitored since that time (Figure 2). Papers describing the findings from QUELTS are in preparation; suffice it to say that some GCLs experienced significant shrinkage, while one experienced very little shrinkage in almost 5 years of exposure.

Based on the available evidence to date, it is expected that GCL shrinkage is not a concern if the GCL is placed in accordance with good construction practice and the composite liner is quickly covered with a ballast layer (e.g., cover soil or leachate collection system). If the GCL must be left exposed, its performance in covers

Figure 1. Queen's University environmental liner test site (QUELTS) north of Kingston Ontario, Canada, during construction in 2006

Figure 2. QUELTS II following reconstruction in 2012

and liners can be improved by (a) placing panels with 300 mm of overlap, (b) heat tacking the overlaps and (c) using a GCL that has shown low shrinkage in the field. These three strategies (especially if used together) will minimize the risk of panel separation. However, at this time, there is no assurance that they will prevent panel separation under worst case conditions; the composite liner should still be covered as quickly as possible.

Cation exchange

Cation exchange is a well-recognised mechanism whereby the sodium ions in the smectite, which is the component of sodium bentonite responsible for its low hydraulic conductivity, are exchanged with other cations in the permeating fluid, the pore water of the soil adjacent to the GCL or, especially for activated sodium bentonite, in calcium-bearing minerals in the bentonite itself. There

have been instances where cation exchange (probably coupled with wet–dry cycles) has resulted in substantial increases in hydraulic conductivity, k , from the low (typically $k \leq 5 \times 10^{-11}$ m/s) values for GCLs as they come off the roll. For example, Benson *et al.* (2007) reported that, after 15 months in a landfill final cover, a GCL similar to GCL4 discussed above and with 760 mm of soil above the GCL experienced an increase in k to between 1.8×10^{-7} and 6.9×10^{-7} m/s and a decrease in swell index (SI) from ≥ 24 mL/2 g to 7–15 mL/2 g. These changes were attributed to the exchange of Ca^{2+} and Mg^{2+} in the adjacent soils for Na^+ in the bentonite together with dehydration.

Meer and Benson (2007) reported findings for GCLs exhumed from four different landfill covers, with 0.75–1 m of soil above the GCL. High k (10^{-8} – 10^{-6} m/s) was reported for samples with water content less than 85%, while the k ranged between 10^{-10} and 10^{-9} m/s for samples with a water content greater than 100% (with the lowest values being obtained from well-hydrated samples exhumed after 11 years). Thus the water content of the sample appears to be an important factor.

Scalia and Benson (2011) exhumed GCLs from six composite liners with 0.3–1.1 m of cover soil (thickness depended on site) in landfill final covers after 4.7 to 6.7 years. The SI dropped to 7–11 mL/2 g (i.e., typical of calcium bentonite) at four sites, whereas it was 12–22 mL/2 g at the two other sites. There was an almost 5 order of magnitude variation in k over the six sites ($9.3 \times 10^{-12} \leq k \leq 2.1 \times 10^{-7}$ m/s).

Rowe and Abdelatty (2012a) examined cation exchange, and its effect on k , for a GCL resting (a) directly on calcium-rich soil (pore water: 1700–1800 mg/L Ca^{2+}), (b) on a 0.3-m foundation layer (pore water: ~200–300 mg/L Ca^{2+}) over the calcium-rich soil and (c) on the foundation layer alone. All soils were silty sand at an initial water content of 13.9%.

For the GCL on the foundation layer alone, the GCL w increased to a final equilibrium value of 113% after 500 days. There was no change in the k of the GCL. For the GCL directly on the calcium-rich soil, w increased to a maximum of 86% and then decreased to 67% due to cation exchange under isothermal conditions, showing that simple chemical interaction with the subgrade can result in a decrease in GCL water content (other things being equal). A similar trend was observed for the case where the GCL was on the foundation layer over the calcium-rich soil but the maximum w was 96% and it reduced to 80% at equilibrium. There was no desiccation cracking of the GCLs. The value of k (at 15 kPa) increased from the initial value of 3×10^{-11} to 2×10^{-10} m/s when resting directly on the calcium-rich soil and 7×10^{-11} m/s (after 3 years) when on the foundation layer over the calcium-rich soil.

Hosney and Rowe (2013) examined the field performance of three needle-punched GCL products covered with up to 1 m of cover soil (gravelly sand) as part of a cover over an abandoned gold mine in Nova Scotia, Canada. One GCL (GCL1 discussed earlier) had

sodium bentonite sandwiched between a woven and a nonwoven geotextile. The other two GCLs had polymer-enhanced sodium bentonite and a nonwoven cover geotextile but different carriers: one a scrim-reinforced nonwoven geotextile, the other a woven geotextile laminated with a polypropylene film. GCL samples were exhumed after 1 and 2 years. Almost all the moisture uptake occurred in the first year and there was very little change at year 2. All exhumed GCLs had $w > 80\%$.

After 2 years, GCL1 with untreated sodium bentonite experienced almost complete cation exchange (SI dropped from 26 to 8–10 mL/2 g) but still maintained $k \leq 5 \times 10^{-11}$ m/s at locations where there was ≥ 0.7 m of cover soil above the GCL. The SI of GCL with polymer-enhanced bentonite decreased from 24 to 14 mL/2 g and $k \leq 3 \times 10^{-11}$ m/s when there was ≥ 0.7 m of cover soil above the GCL. The SI of the GCL with polymer-enhanced bentonite and a carrier geotextile coated with a geofilm decreased from 25 to 13–15 mL/2 g, but because the k is controlled by the thin geofilm, the k value did not change and remained around 5×10^{-12} m/s (virgin k value). After two years of exposure to the natural climatic cycles in this humid climate, all GCLs were performing adequately despite cation exchange when the cover soil was ≥ 0.7 m. When the cover above the GCL was reduced to 0.5 m, GCL1 experienced a similar change in SI but k increased to 1×10^{-10} m/s.

The work described above highlights the complex interaction between variables, such as the availability of exchangeable cations (especially Ca^{2+} and Mg^{2+}), w_{fdn} of the subgrade, w of the exhumed GCL, the amount of cover soil above the GCL, and the type of GCL, on the k of GCLs used in covers. While there are certainly cases where there has been a very substantial increase in k of the GCL in covers, there are also cases where it has performed very well, suggesting that performance is related to both local conditions (soil and climate) and the details of the design (including the type of GCL used).

In addition to ensuring that the subgrade below the GCL has adequate moisture to allow reasonable hydration of the GCL, as discussed earlier, the performance of GCLs in low-stress applications (especially those where they could be subjected to wet–dry cycling) can be improved by (a) ensuring there is sufficient cover soil above the GCL (the amount needed will depend on local conditions/climate) and (b) selecting the appropriate GCL for the application.

GCL Desiccation in composite liners

A GCL may desiccate as a result of one or more wet–dry cycle. This may occur because the GCL is in an exposed composite liner (i.e., the mechanisms giving rise to shrinkage discussed earlier), the GCL is in a cover liner without adequate cover soil to protect it from significant wet–dry cycles due to climatic cycles or because it is in a composite bottom liner that initially hydrates and is then dried by the thermal gradient generated by hot waste (e.g., municipal solid waste where there is leachate recirculation or disposal of combustion ash). When it desiccates, the GCL k

value will be high but, provided that there is not too much cation exchange, it can quickly reduce again to low values (Southen and Rowe, 2005) because of the ability of the sodium bentonite to swell and self-heal on re-wetting (i.e., when it comes into contact with the fluid that is to be contained). However, as indicated by some of the cases cited in the previous section, when desiccation is combined with cation exchange the self-healing capacity is reduced or lost, with the magnitude of the effect depending on (a) the amount of cation exchange, (b) the extent of the cracking and the size of the desiccation cracks and (c) the stress on the GCL (higher stress increases the ability of the GCL to self-heal, other things being equal). The ability to rehydrate to a low k may also be reduced by the chemical composition of the permeant (Petrov and Rowe, 1997) even if there was little initial cation exchange.

The size of the desiccation cracks can be expected to affect how well it can self-heal. The larger the cracks, the more difficult it will be for the bentonite to self-heal, especially after some cation exchange and at low stress. It is well recognised that desiccation of a GCL is caused by wetting followed by drying; however, it is not well recognised that the size of the desiccation cracks is a function of a number of factors. For example, Take *et al.* (2012a, 2012b) showed that the size of cracks developed in a GCL's bentonite core depended on both the type of GCL and the rate of drying. They examined the desiccation of GCL2 and GCL4 under isothermal drying at 20°C and 60°C. As discussed earlier, GCL2 had more effective anchorage of its needle-punched fibres than GCL4 (due to the combination of needle-punching to the scrim-reinforced carrier geotextile and the thermal bonding of the fibres in GCL2). As a result, GCL2 had much thinner cracks when desiccated than GCL4 (which relied on mechanical anchorage to a nonwoven carrier geotextile for fibre anchorage). Also, for GCL4, the rate of drying was important to crack size, with slow drying giving significantly larger cracks than rapid oven drying at 60°C. The effect of drying rate was much less for GCL2.

A laboratory study of the potential for desiccation of a GCL in a composite liner due to sustained thermal gradient was reported by Southen and Rowe (2004, 2005). This work was extended to consider double composite liners by Azad *et al.* (2011). These studies showed experimentally that, under some circumstances, desiccation would occur, whereas in others there was no desiccation. Factors affecting whether or not there was desiccation included the (a) initial subsoil water content (higher w_{fin} decreased the potential for desiccation); (b) type of GCL; (c) bentonite M_A (higher M_A appeared to reduce potential desiccation); (d) carrier geotextile thickness (higher M_A appeared to reduce potential desiccation); and (e) temperature gradient (lower gradient decreased the potential for desiccation).

The numerical model DESICCATE (Zhou and Rowe, 2003) has been successfully used to model the experimental data discussed above (Azad *et al.*, 2012; Southen and Rowe, 2011) and used to examine the effects of factors such as liner temperature, overburden stress, subsoil initial water content, grain size of the subgrade and depth to the water table (Hoor and Rowe, 2013; Rowe and Verge, 2013).

Based on the studies to date, and more research is required, it appears that the potential for desiccation can be reduced, and hence the performance of liner systems improved, by ensuring an adequate water content of subsoil and by one or more of the following: (a) limiting the temperature gradient (e.g., by avoiding leachate recirculation or disposing of waste such as combustion ash that would increase liner temperatures; Hoor and Rowe, 2013), (b) removing heat (Rowe *et al.*, 2010b) or (c) providing insulation (Hoor and Rowe, 2012).

Composite liners over a drainage layer

GCLs may be used as part of a primary composite liner in a double liner system. When a GCL is to be placed over a relatively uniform gravel or geonet/geocomposite drainage layer (e.g., a leak detection layer), there are two issues that need careful consideration in design. First, there is the issue of hydration. Consideration should be given to how the GCL will hydrate when placed on a material that typically has very low water content as placed. For example, if the GCL is hydrated from the leachate, it may increase the hydraulic conductivity of the GCL (Petrov and Rowe, 1997). Second, there is the potential for internal erosion of the bentonite in the GCL when it rests on a gravel or geocomposite/geonet layer. Rowe and Orsini (2003) showed that different types of GCL had different susceptibility to internal erosion with GCLs having a scrim-reinforced carrier performing better than those with either a woven or a nonwoven carrier.

One design solution to these issues is to place the GCL on a well-graded foundation layer that can act as a filter to prevent internal erosion and also provide a source of moisture for hydration of the GCL. An added benefit is that the layer provides at least partial insulation that could reduce the temperature on the secondary liner (Rowe and Hoor, 2009) and hence reduce the many negative impacts of higher temperature (e.g., higher leakage, higher diffusion, reduced GMB service life, potential desiccation of the secondary clay liner; e.g., Rowe, 2005). This will increase cost but will improve long-term performance.

GMB/GCL Interface transmissivity

Rowe (2012a) reviewed the published data relating to GMB/GCL interface transmissivity, θ . Considering permeation with water, published values fall in the range $6 \times 10^{-12} \text{ m}^2/\text{s} \leq \theta \leq 2 \times 10^{-10} \text{ m}^2/\text{s}$ with an average of about $4 \times 10^{-11} \text{ m}^2/\text{s}$ for reinforced GCLs over a range of stresses from 7 to 70 kPa. For GCLs containing sodium bentonite, the average θ was about $2 \times 10^{-11} \text{ m}^2/\text{s}$ (at 50 kPa). A study of the effect of applied stress in the range 25–200 kPa (Barroso *et al.*, 2010) did not indicate a strong relationship between stress and θ for the cases considered. It did not appear to matter greatly either whether the GMB is smooth or textured in terms of θ for the conditions examined by Barroso *et al.* (2008).

Perhaps the most interesting recent finding is the lack of correlation between θ and k arising from the works of Mendes *et al.* (2010) and Rowe and Abdelatty (2012b, 2013).

For otherwise similar conditions (50 kPa, smooth GMB and permeation with water), Mendes *et al.* (2010) showed that two calcium bentonite GCLs had almost identical values of θ despite a 2 order of magnitude difference in k . Specifically, for the GCL with $k = 5.8 \times 10^{-8}$ m/s ($M_A = 5730$ g/m²), θ was 3.0×10^{-11} m²/s, while for the GCL with $k = 6.9 \times 10^{-10}$ m/s ($M_A = 10\,590$ g/m²), θ was 2.8×10^{-11} m²/s. These values of θ were only slightly larger than the two values obtained for two different sodium bentonite GCLs (viz: $\theta = 2.4 \times 10^{-11}$ m²/s for a GCL ($M_A = 7400$ g/m²) with $k = 1.6 \times 10^{-11}$ m/s and $\theta' = 2.6 \times 10^{-11}$ m²/s for a GCL ($M_A = 5410$ g/m²) with $k = 3.2 \times 10^{-11}$ m/s, respectively). Comparing the extreme cases, a 360 000% increase in k of the GCL only corresponded to an increase in θ by 25%. Thus k and θ do not appear to be correlated, suggesting that θ is controlled by factors other than k .

Rowe and Abdelatty (2012b, 2013) arrived at a similar general finding by a very different route. They performed four experiments to examine contaminant transport through a hole in a GMB overlying a GCL (at 100 kPa). These tests were of much larger diameter than previous GMB/GCL transmissivity tests. Rowe and Abdelatty (2012b) initially permeated the simulated barrier system with distilled water, and from the measured flows at steady state Rowe and Abdelatty (2013) deduced $\theta \approx 2.3 \times 10^{-11}$ m²/s. The permeant was changed to a sodium chloride solution and, at steady state, θ had decreased to 1.1×10^{-11} m²/s. Thus, despite the fact that the k of the GCL increased up to a factor of 8 from about 5×10^{-11} m/s when permeated with water to $2\text{--}4 \times 10^{-10}$ m/s when permeated with a 0.14 mol/L of sodium chloride solution, the value of θ decreased by a factor of 2, a totally opposite trend. This is attributed to an improvement in the interface characteristics of the GMB/GCL interface as the GCL consolidated in response to the chemical interaction that increased k . This also demonstrates that, for the same GCL, the values of k and θ are uncoupled when the permeant is changed. This is good news for GCLs since Rowe and Abdelatty (2013) showed that, for the conditions they examined, an increase in k due to clay–leachate interaction did not significantly increase leakage through the composite liner and the GCL continued to fulfill its primary function of minimizing leakage through a hole in the GMB.

The available evidence suggests that, even with good construction, the GMB/CCL interface transmissivity is several orders of magnitude higher than for a GMB/GCL (Rowe, 2005, 2012a).

Wrinkles

Although design drawings show composite liners with GMBs directly and continuously on the underlying clay liner, in reality when it comes time to cover the GMB with the ballast or leachate collection layer, there will usually be wrinkles in the GMB (Figure 3). Although the presence of wrinkles in GMBs has long been recognised and Rowe (1998) developed an equation for calculating leakage through GMBs with wrinkles, it is only recently that the geometry and connectedness of wrinkles have

been well documented (Chappel *et al.*, 2012a, 2012b; Rowe *et al.*, 2012a, 2012b; Take *et al.*, 2007). Wrinkles arise from the thermal expansion of the GMB when heated (e.g., by the sun). They may align with geometrically regular features (e.g., creases arising from manufacture of blown film GMBs, seams which run parallel to the roll, or GCL panel overlaps), or they may occur at random locations (all of these are evident in Figure 3). The height and width of wrinkles as well as the percent area of a liner below the wrinkles and the length of connected wrinkles have been documented for a range of sites, times of day and times of year in the references cited above.

The studies cited above were conducted in eastern Canada. For the conditions examined, it appears that, if the GMB were to be covered by the leachate collection layer before 8:00 a.m. or after 4:00 p.m., there would be about six to seven connected wrinkles per hectare each with connected length $L \leq 200$ m. The length of connected wrinkles would increase with more solar radiation with the maximum connected wrinkle length often being observed (on a sunny day) at around 1:00 p.m. For an unrestrained area of GMB of about 0.2 ha, there could be a connected wrinkle with a length of up to 2000 m at around 1:00 p.m. Assuming a similar situation for each part of the GMB covered, there could be five such connected wrinkles per hectare and a relatively high probability that at least one hole in the GMB will align with a long connected wrinkle per hectare. As the restrained area that is covered at a given time increases, so too does the length of the longest connected wrinkle. For example, Chappel *et al.* (2012b) reported the case of a GMB area of 0.61 ha where the longest connected wrinkle was 5330 m.

The studies cited above have indicated that, at least in eastern Canada, wrinkles in HDPE GMBs induced by thermal expansion may reach heights of 0.2 m, and occasionally more, but are typically about 0.06 m in height, and wrinkle widths may reach up to 0.5 m but are usually in the 0.2–0.3-m range.

Overlaps

The potential for shrinkage of GCL panels causing a loss of overlap was discussed earlier. Any such gap would be problematic if it were beneath a hole in the GMB since the composite liner action would be lost at that location. However, even more problematic would be the situation where there was a hole in a wrinkle that either ran directly above the overlap (as may happen in some cases; Figure 3) or if the wrinkle were to cross the point where there was a loss of overlap (which can be easily envisaged based on Figure 3). In this case, the hole no longer needs to align directly with the loss of overlap because fluid (leachate or gas) could easily migrate through a hole anywhere in the wrinkle and then laterally below the wrinkle to a point where the wrinkle intersects the place where overlap is lost and again composite liner action is lost. This further highlights the need to avoid loss of panel overlap.

Where significant wrinkles (i.e., with height > 30 mm at the time they are covered) coincide with panel overlaps, the overlap below

Figure 3. Wrinkles in GMB at QUELTS. In this photo, GMB rolls run east–west (left to right) and GCL panels run north–south (top to bottom) (modified from Rowe *et al.*, 2012b and Rowe 2012a).

the wrinkle will be unloaded after the waste or cover soil is placed. Thus, even if there is no loss of panel overlap, a significant reduction in panel overlap could represent a weak point for leakage as noted by Brachman *et al.* (2011). Current work at Queen’s University is examining the potential for leakage through panel overlaps using unique equipment (geosynthetic landfill liner simulators with internal diameters up to 1 m). This equipment allows consideration of different overlaps, presence and absence of supplemental bentonite, heat tacking, etc. on the hydraulic performance of overlaps both parallel and perpendicular to the wrinkle for applied stresses up to 250 kPa.

Leakage through composite liners

It has been well recognised for many years (e.g., Giroud and Bonaparte, 1989; Rowe, 1998) that leakage through a composite liner will depend on the head on the liner, the number and size of holes in the GMB and the k of the clay component of the liner. Less well recognised has been the importance of the interface transmissivity, θ , between the GMB and the GCL, and the role of wrinkles, although there have been some significant advances in understanding with respect to these two parameters over the last

few years as discussed in previous sections. Rowe (2005, 2012a) examined the use of the Rowe (1998) equation for calculating leakage through the primary liner (allowing for wrinkles) in double-lined landfills and compared calculated and observed values. In its simplest form (assuming no interaction between adjacent wrinkles and negligible hydraulic resistance of the material below the clay liner), the Rowe (1998) equation is:

$$1. \quad Q = 2L[kb + (kD\theta)^{0.5}]h_d/D$$

where Q is the leakage (m^3/s), L is the length of the connected wrinkle with a hole (m), $2b$ is the width of the wrinkle (m), k is the hydraulic conductivity (m/s) of the clay liner, θ is the transmissivity of the GMB/clay liner interface (m^2/s), h_d is the head loss across the composite liner (m) and D is the thickness of the clay liner (m).

In 2005, there was a paucity of data on connected wrinkle length and the equation was used to infer what wrinkle length was required to explain the observed leakages. In 2012, the data on wrinkles discussed earlier was available and Rowe (2012a) showed that the

Rowe (1998) equation explains the observed leakage in landfills for heads and connected wrinkle lengths typical of those observed in construction provided that the liner is not covered in the middle of a sunny day.

Rowe and Hosney (2010) and Rowe (2012a) have examined the effect of some of the key factors discussed above on the calculated leakage through composite landfill bottom liners. Some of their conclusions are summarized below assuming good liner construction and liner temperature less than 40°C. The justification for these comments is not repeated here, and the interested reader is referred to the original papers for that information.

- An increase in liner temperature (Table 1) can greatly increase the calculated leakage, with the leakage at 60°C and 80°C being about double and triple that at 20°C, respectively, other things being equal.
- Well-constructed composite liners substantially reduce leakage compared to a GMB, GCL or CCL alone.
- Leakage through a composite liner with a GMB/GCL is substantially less than through a GMB/CCL.
- Advection begins to dominate contaminant transport when leakage, Q , exceeds about 200 lphd, and careful consideration must be given to the potential impact on groundwater for these situations.
- Assuming typical landfill design parameters (see Rowe, 2012a), the calculated leakage through a GMB/GCL composite was $Q \leq 14$ lphd for $L \leq 200$ m and $Q \leq 50$ lphd for $L \leq 700$ m. For a GMB/CCL (0.6 m thick), the corresponding leakage was $Q \leq 83$ lphd for $L \leq 200$ m and $Q \leq 580$ lphd for $L \leq 700$ m.
- Provided that the connected wrinkle length is kept relatively low ($L \leq 125$ m), then a GMB/GCL composite liner can be expected to give $Q < 50$ lphd (Darcy flux < 0.002 m/a) for leachate heads less than 3 m and hence remains modest. These leakages are considered small and usually of no practical consequence for MSW landfills. At these leakages, diffusion is likely to be the dominant contaminant transport mechanism for contaminants (e.g., volatile organic compounds) that can readily diffuse through a GMB.
- Provided that the connected wrinkle length is kept relatively low ($L \leq 125$ m), then a GMB/CCL composite liner can be expected to give $Q < 200$ lphd for leachate head ≤ 1.5 m.
- Leakage through composite liners used in lagoons may be substantially larger than through landfill liners. This is because of the much lower stress on the liner and, typically, much higher heads. If the ballast above the GMB is sufficient to ensure composite liner action, the leakage can be reduced by using a composite liner involving a GMB/GCL/CCL. In this case, the GCL provides good interface properties thereby minimizing leachate flow at the GMB/GCL interface and the CCL controls the leakage where leachate can migrate between the GMB and the GCL. Rowe (2012a) showed that the performance of the GMB/GCL/CCL system was substantially better than either a GMB/GCL or a GMB/CCL system.

Construction issues

Composite liner performance is highly related to construction issues (Rowe, 2012a, 2012b). With respect to the issues discussed in this paper, the performance of composite liners can be improved by considering the following:

- Ensure a suitably prepared CCL surface for placing the GMB (without stones, clods, etc.) since this will influence the interface transmissivity and hence potential leakage.
- Ensure no linear features/irregularities in the surface of the CCL (e.g., tyre tracks).
- Keep the CCL surface sufficiently moist to avoid desiccation cracks before the GMB is placed.
- Ensure that the subgrade below the GCL is firm and unyielding ($>90\%$ standard Proctor density) with no abrupt changes in elevation (e.g., ruts). It should be proof rolled with a smooth drum roller immediately prior to placement of the panels. There should be no foreign matter or stones loose on the surface or penetrating out of the subgrade >10 mm.
- The subgrade upon which the GCL is to be placed should be at an appropriate water content to allow hydration of the GCL.
- Cover the composite liner with the protection layer and drainage or ballast layer quickly to avoid (a) desiccation cracking of a CCL which, as shown by Rowe (2012a), can substantially increase leakage, or (b) significant GCL shrinkage and opening of a gap between GCL panels. Of these, the most critical is the need to cover a GMB over a CCL since severe desiccation can occur in a matter of hours on a hot sunny day when a black GMB can heat to over 60°C or, in some locations, even 70°C.
- Minimize wrinkles by ensuring that the GMB is covered with the ballast/soil layer early in the morning or late in the day when the number of wrinkles is smallest (Chappel *et al.*, 2012a, 2012b; Rowe *et al.*, 2012a, 2012b; Take *et al.*, 2012b).

To ensure the desired performance, good inspection is required during construction to check that the design conditions are actually achieved and factors such as those highlighted above (plus other issues not discussed here; e.g., see Rowe, 2012b) are addressed. The old adage “you get what you inspect, not what you expect” should always be kept in mind.

Conclusions

Recent advances in the understanding of factors affecting the performance of liners in both bottom liner and capping systems for landfill and mining applications have been explored with respect to GCL and composite liner performance. Some of the implications for improving liner performance are highlighted below.

The available evidence suggests that both GCLs and composite liners have performed extremely well at controlling leakage in field applications for a couple of decades. However, there have also been some problems and recent research has allowed us to have a much better understanding of the key design and construction

factors affecting performance. There are also operational issues that can affect the performance of the system. Particular attention must be given to factors that could cause the liner temperature to exceed 40°C since they can have many negative effects on liner performance (e.g., higher leakage, higher diffusion, reduced GMB service life and potential desiccation of the clay liner). Special design will be required for liners to be used in an environment where the liner temperature will exceed 35–40°C.

Factors that can affect the performance of a GCL include (a) the type of bentonite; (b) the mass per unit area of bentonite; (c) the type and mass per unit area of the geotextiles used; (d) the amount of needle-punching; (e) whether or not the needle-punched fibres are thermally fused to the carrier geotextile; (f) the presence or absence of a geofilm bonded to the GCL, the nature of the geofilm and how the geofilm is bonded to the carrier geotextile; (g) the characteristics of the GCL panel overlap; (h) whether or not the GCL is part of a composite liner; (i) the presence of wrinkles in the GMB; (j) the initial water content and particle size distribution of the soil above and/or below the GCL; (k) geochemical interactions between the bentonite and the pore water in the soil adjacent to the GCL; (l) interaction of the bentonite with the fluid to be retained; (m) the amount of cover soil over the GCL; (n) the level of exposure to thermal cycles; (o) thermal gradients; and (p) the stress on the GCL.

A key parameter affecting GCL performance as a fluid barrier (to liquid or gas) is the degree of saturation. A GCL should have a high degree of saturation before it is required to restrict the migration of either gas or liquids (especially liquids that could chemically interact with the bentonite). The degree of saturation of the GCL will depend on the type of GCL (since they have different water retention curves) and on the grain-size distribution and initial water content of the subgrade (or cover soil if no GMB is present). As discussed, techniques have been developed that allow the estimation of a target water content required to achieve a desired degree of saturation of the GCL for a given subgrade.

GCLs should be covered with at least 0.3 m of ballast (e.g., leachate collection system or cover soil) shortly after GCL placement to minimize the risk of a number of problems including shrinkage of GCL panels that can occur when subjected to thermal cycles (e.g., when a composite liner is left exposed to heating by the sun). There are strategies that can be adopted to minimize the risk of panel separation in cases where the liner must be left exposed as discussed herein. Additional insights regarding issues arising from leaving composite liners exposed, and mitigation measures if they must be left exposed, will be provided when the findings from the studies at QUELTS are published.

GCLs used in covers are particularly prone to problems if not properly designed and constructed because of the combination of low stress and potential for wet–dry cycles. The risk of problems can be substantially reduced by (a) ensuring that the subgrade below the GCL has an adequate water content to allow reasonable hydration of

the GCL, (b) ensuring there is sufficient cover soil above the GCL and (c) selecting the appropriate GCL for the application (some types of GCLs will perform much better than others).

Presently available evidence suggest that, under some circumstance, GCLs (or CCLs) used in a composite liner where the temperature may exceed 35°C could be desiccated by the thermal gradient. Although more research is required, it appears that the potential for desiccation can be reduced and hence the performance of liner systems improved, by ensuring an adequate water content of subsoil, and one or more of the following: (a) by limiting the temperature gradient (e.g., by avoiding leachate recirculation or disposing of waste such as combustion ash that would increase liner temperatures), (b) by removing heat or (c) by providing insulation to control the liner temperature.

When GCLs are used in primary liners as part of double liner systems, special consideration should be given to how the GCL will hydrate and the potential for internal erosion of the bentonite in the GCL if the GCL rests over a uniform gravel or geonet/geocomposite drainage layer. One design solution to these issues is to place a well-graded foundation layer between the GCL and the leak detection system. This layer can act as a filter to prevent internal erosion and a source of moisture for hydration of the GCL. In addition, this layer will provide at least some insulation to reduce the temperature on the secondary liner.

For a well-constructed composite liner, the interface transmissivity, θ , between the GMB and the clay liner is at least as important as the hydraulic conductivity, k , of the liner. Recent research suggests that k and θ are not correlated and hence that θ is controlled by factors other than the k of the GCL (or CCL). One study showed that, for the conditions examined, permeation of a composite liner with a salt solution caused k to increase by almost an order of magnitude but θ decreased by a factor of 2 and there was negligible change in leakage through the hole in the GMB.

Well-constructed composite liners substantially reduce leakage compared to a GMB, GCL or CCL alone; however, the leakage through composite liners is highly dependent on the length of connected wrinkles that intersect a hole in the GMB. Wrinkles present at the time the GMB is covered with the ballast layer increase the area of the underlying clay liner in contact with leachate and hence leakage. Even more problematic would be the situation where there was a hole in a wrinkle intersecting a location where there has been loss of GCL panel overlap (e.g., due to panel shrinkage). In this case, the hole in the GMB does not need to align directly with the loss of overlap because fluid (leachate or gas) could easily migrate through a hole anywhere in the wrinkle and then laterally below the wrinkle to a point where the wrinkle intersects the place where overlap is lost. In this case, composite liner action is lost. This further highlights the need to avoid loss of panel overlap.

When a composite liner involves a CCL, the performance is highly dependent on the interface transmissivity between the GMB and

the CCL, and on the desiccation of the surface of the CCL either before or after the GMB is placed. The available evidence suggests that, even with good construction, the GMB/CCL interface transmissivity is orders of magnitude higher than for a GMB/GCL. As a consequence, leakage through a composite liner with a GMB/GCL is substantially less than through a GMB/CCL.

This paper has discussed a number of potential problems with liner performance. However, all can be avoided by appropriate design, material selection, construction and operations. There are many examples where liners have exhibited excellent long-term performance.

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