Some Factors affecting Geosynthetics used for GeoEnvironmental Applications

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Abstract

A number of factors potentially affecting the performance of geosynthetic clay liners (GCLs) and HDPE geomembranes (GMs) in geoenvironmental applications are reviewed. These include: the method of manufacture of GCLs; the interaction between GCLs with municipal solid waste (MSW) leachate, acid rock drainage, gold mine leachates, and hydrocarbons; the effect of freeze-thaw cycles; field exposure in the arctic; the effect of the degree of saturation; the effect of subzero temperatures on the permeability of saturated and unsaturated GCLs; the potential for internal erosion of GCLs; susceptibility of GCLs and CCLs to shrinkage and desiccation when used as part of a composite liner; diffusion of volatile organic compounds and ions through both GMs and GCLs; leakage through single GMs and composite liners; the long-term performance of GMs in air, water and MSW leachate; and the effect of immersion in hydrocarbons on the depletion of antioxidants in GMs.

Introduction

Geosynthetics such as geosynthetic clay liners (GCLs) and geomembranes (GM) can play a very significant role in providing cost effective barriers for environmental protection for a wide range of applications. However like all engineering materials they need to be carefully selected to meet the design criteria, placed in accordance with best construction practice, and protected from damage after placement. This paper seeks to provide a review of a number of factors that should be considered in selecting GCLs and GMs for different design situations. The paper summarizes a large body of fairly recent (mostly post 2000) published data and findings. The reader unfamiliar with the use of geosynthetics in barrier applications is referred to Rowe et al. (2004) for background details. Two other key references relevant to the issues discussed in this paper are Rowe (1998) and Rowe (2005).

Effect of method of GCL manufacture

The method of GCL manufacture can impact on engineering properties ranging from shear strength to diffusion coefficient and hydraulic conductivity (permeability), and the susceptibility of the GCL to internal erosion as will be discussed subsequently in this paper. Factors affecting these characteristics include the type and mass of bentonite, the initial water content of the bentonite, the nature of the cover and carrier geosynthetic and whether or not a nonwoven carrier geotextile is scrim reinforced, whether the GCL is needle-punched (and if so the amount of needle-punching), and whether the GCL has been heat burnished.

The engineering characteristics such as the hydraulic conductivity (Petrov et al., 1997) and diffusion coefficient (Lake and Rowe, 2000b) can be both directly related to the bulk void

5th ICEG Environmental Geotechnics, Thomas Telford, London 2006.

ratio of the GCL. Petrov et al. (1997) showed that needle-punching has a significant effect on the bulk void ratio by comparing results for a needle-punched GCL and an otherwise similar GCL without needle punching (i.e., fibre-free) (columns 2 and 3 of Table 1). Lake and Rowe (2000a) also demonstrated that heat burnishing (thermal treatment) of needle-punched fibres can also significantly influence the bulk GCL void ratio (compare columns 3 and 4 of Table 1). The effect of heat burnishing is greatest at low confining stress when the combination of needle-punching and thermal treatment reduce the amount of swelling and hence the bulk void ratio.

Table 1 presents results for tests where the stress is applied prior to hydration. Lake and Rowe (2000a) showed that the effect of thermal treatment is even more significant for cases where the sample is allowed to hydrate at a low confining stress (e.g., 6 kPa) and then, after hydration, the stress is applied. This is a likely situation in many environmental applications where a GCL below a GM hydrates by taking up moisture from the underlying soil with only the leachate collection system in place and the waste is not placed until after hydration has occurred. In this case the effect of heat burnishing is manifest throughout the stress history because the fibres thermally locked to the carrier geotextile are far more resistant to pull out of the carrier geotextile during hydration at low stress than when they are simply held by needle-punching.

Table 1: Effect of GCL Structure on Bulk Void Ratio (Confined Swell Test)

	Final Bulk Void Ratio, e_B		
Needle-punching:	No[1]	Yes	
Thermally- treated:	N/A	No[1]	Yes[2]
Confining Stress (kPa)			
6	7.6	5.1	4.0
25	4.0	3.2	3.0
100	2.6	2.3	2.2
200	2.0	1.7	1.7

[1] Petrov et al. (1997); [2] Lake and Rowe (2000a)

Compatibility – hydraulic conductivity

Municipal solid waste (MSW) leachate

Numerous researchers (e.g. Schubert, 1987; Shan & Daniel, 1993; Daniel et al., 1993; Dobras & Elzea, 1993; Ruhl & Daniel, 1997; Petrov et al., 1997; Petrov & Rowe, 1997; Kodikara et al., 2002; Shan and Lai, 2002; Ashmawy et al., 2002; Kolstad et al., 2004; Katsumi and Fukagawa, 2005; Lee and Shackelford, 2005; Guyonnet et al., 2005; Jo et al., 2005) have examined GCL-leachate compatibility and its impact on the hydraulic conductivity of GCLs for use as base liners for landfills. This research has shown that the hydraulic conductivity of a GCL is highly dependent on: the hydrating conditions, the applied effective stress during permeation, the method of GCL manufacture, and the mass of bentonite in the GCL (see Rowe, 1998). For example, the effect of applied stress on the hydraulic conductivity with respect to both water and synthetic municipal solid waste (MSW) leachate is illustrated in Table 2. For low stress at the time of permeation there is an order of magnitude increase in hydraulic conductivity to about $6x10^{-10}$ m/s as the permeant was changed from water to MSW leachate. At higher stress, more typical of likely field conditions, the effect is far less significant with a hydraulic conductivity to MSW leachate still very low at $3x10^{-11}$ m/s. This demonstrates how consolidation during permeation (as double layers contract) can mitigate the effects of clay-leachate interaction on hydraulic conductivity.

Table 2: Effect of applied stress on hydraulic conductivity with respect to water and MSW leachate (after Petrov and Rowe,1997).

Hydration Stress (kPa)	Hydrated Thickness (mm)	Hydraulic Conductivity to water (m/s)	Hydraulic Conductivity to MSW Leachate (m/s)
3	12.3	$6x10^{-11}$	$55x10^{-11}$
115	6	$0.75x10^{-11}$	$3x10^{-11}$

As a consequence of the large number of variables affecting the hydraulic conductivity (k), Petrov et al. (1997) found that there was substantial scatter amongst data when k was plotted as a function of GCL thickness. However, they were also able to demonstrate that by plotting k against the bulk void ratio, e_B, one can obtain a good correlation for a given permeant. Thus for a particular GCL and MSW leachate it can be shown that there is a relatively straightforward relationship between k and e_B, viz:

$$-11.4 + 0.42e_B < \log_{10} k \text{ (m/s)} < -11.2 + 0.42e_B \qquad (1)$$

This relationship may be expected to vary from one product to another and from one leachate to another. However it shows that for a particular combination of the two, a relatively well bounded relationship can be developed. Particular care may be needed for ashfills or other waste leachate where the concentrations of salts (especially those with divalent cations) are higher than found in typical MSW leachates.

Mine waste waters

An ongoing challenge for the mining industry is the need to control metal and metalloid contamination derived from waste rock and mine tailings. Past remediation efforts have focussed on covers which reduce acid production by limiting infiltration and oxygen. However recent research has suggested that potentially toxic elements, particularly arsenic (As) and selenium (Se), and in some cases nickel (Ni) and zinc (Zn) are mobile under neutral-pH conditions. Furthermore, the reductive dissolution of As-bearing minerals has resulted in the release of As (Stichbury et al., 2000). As a consequence, there is now movement in the mining industry towards segregating the most hazardous material for separate disposal in a lined containment facility. Under sub-aqueous containment, GCLs represent a potentially attractive means of controlling contaminants either alone or in combination with a GM as part of a composite liner.

Several researchers have examined attenuation of single metal and multi-metal permeants by sodium bentonite and similar clay combinations (e.g. Brain, 2000; Li and Li, 2001; Cooper et al., 2002; Abollino et al., 2003). Abollino et al. (2003) identified the primary mechanisms controlling metal mobility in sodium bentonite as (i) cation exchange within the clay lattice structure; and (ii) cation attraction to broken bonds at the edges of the clay mineral. Other mechanisms include (iii) limited anion exchange (30 meq/100g) where the anions typically attach to the clay structure by substitution of hydroxides at the edges of gibbsite sheets (McKelvey, 1997), and (iv) attenuation of metals by precipitation (Yong, 2001). Soil pH, redox, and soil solution composition can have a significant impact on metal mobility (Yong, 2001).

Lange et al. (2004, 2005) examined the potential for metal (Al, Fe, Mn, Ni, Pb, Cd, Cu, Zn) migration through GCLs from an acid rock drainage (ARD) solution (pH 3.9). In these tests, Mn behaved similarly to Cl, indicating that it was the least attenuated metal. The pH of the ARD effluent remained neutral for 11 pore volumes of permeation and Al, Fe and Cu were highly retarded and retained within the clay. Ni, Zn, and Cd were moderately attenuated. The pH then decreased over time to a value of 3.9 after 35 PVs of ARD permeation at which point the buffering capacity of the bentonite had been exhausted. The shift in pH resulted in some metals in the ARD solution being remobilized from the bentonite back into solution. This illustrates that for ARD solutions there is considerable potential to retard metals but that this potential is limited by the buffering capacity of the bentonite. This, in turn, will be related to the amount of bentonite in the GCL and the amount of flow through the GCL. The hydraulic conductivity of the GCLs permeated with ARD increased from 2.8×10^{-12} m/s to 3.7×10^{-11} m/s after 35 pore volumes of permeation.

Lange (2005) expanded on this earlier study and examined both ARD and gold mine leachate (GML) as described below. The GML permeant had much higher concentration of Ca, Na and Mg than the ARD (Table 3). However the concentration of these cations in the effluent from the ARD tests was much greater than for the GML tests. This was attributed to cation exchange resulting from the high metal loading together with displacement by H^+ ions. The exchange of divalent and trivalent metals for monovalent (Na) ions can be expected to cause a contraction of the diffuse double layer and a consequent increase in the hydraulic conductivity due to permeation by the ARD samples.

The Fe, Zn, Mn, As, Pb and Al in the ARD leachate were mostly attenuated in the upper portion of the GCL. There was evidence to suggest that Fe and Mn were primarily attenuated by precipitation of Fe-Mn oxyhydroxides. Ni and Cu were fairly uniformly attenuated throughout the thickness of the GCL.

There was a substantially higher retention of sulphate for the GML tests than for the ARD tests, with much of the sulphate being retained in the upper portion of the GCL as gypsum. The attenuation of Cd was tentatively related to precipitation of gypsum because Huang et al. (1999) demonstrated that Cd can adsorb to gypsum during its crystal growth. The attenuation of arsenate was also partly attributed to gypsum precipitation with As oxyanions substituting for SO_4^{2-} in the gypsum structure.

In summary, Lange (2005) found that there was strong attenuation for a large number of metals and metalloids present in an acid rock drainage leachate (ARD) and a neutral-pH gold mining leachate (GML). Based on an analysis of both the layers of bentonite in the GCL and the porewater concentrations it was found that:

(a) sulphate was retained as gypsum in the GCLs permeated by GML samples but not in the GCLs permeated by ARD samples;
(b) there was more attenuation of arsenic for the ARD samples than the GML samples. This was attributed, in part, to retention onto Fe/Mn oxyhydroxides in the ARD samples.

Table 3: Initial Concentrations of Permeant Liquids examined by Lange (2005)

Parameter*	Gold Mine Leachate (GML)	Acid Rock Drainage (ARD) Leachate
Calcium (Ca^{2+})	110.1	0.7
Sodium (Na^{+})	964.0	457.7
Sulphate (SO_4^{2-})	2447.0	2932
Potassium (K^{+})	8.0	779.9
Magnesium (Mg^{2+})	83.5	0.15
Strontium (Sr^{2+})	2.2	n/a
Manganese (Mn^{2+})	2.1	26.59
Aluminum (Al^{3+})	3.56	88.73
Iron (Fe^{2+})	0.41	214.4
Copper (Cu^{2+})	n/a	19.7
Chloride (Cl^{-})	268.0	69
Cadmium (Cd^{2+})	2.1	4.9
Nickel (Ni^{2+})	n/a	20.2
Arsenic (As^{5+})	4.0	4.2
Zinc(Zn^{2+})	n/a	107.2
Lead (Pb^{2+})	n/a	13.9
pH	6.85	3.7

All units in mg/L, with exception of pH; *the valence indicated refers to how the ion was initially introduced.

Hydrocarbons

It has long been recognised that permeation by hydrocarbons can have a negative impact on the hydraulic conductivity of clayey soils (Brown et al., 1983, 1984; Fernandez and Quigley, 1985; Lo and Yang, 2001). For example, Lo and Yang (2001) permeated compacted bentonite with gasoline and found a five fold increase in hydraulic conductivity relative to water. The hydraulic conductivity, k, of GCLs has been examined for a number of organic permeants including neat and diluted ethanol (Petrov et al., 1997), gasoline (Shan and Lai, 2001) and Jet A-1 (Rowe et al., 2004). Shan and Lai (2001) reported no flow of gasoline under a hydraulic gradient of 150 in the short-term (3 week) test. Rowe et al. (2006) performed flexible wall hydraulic conductivity tests and also found that there was a threshold pressure (Figure 1) below which there was no flow of Jet A-1 into a hydrated GCL. In this case a difference in the pressure on the two sides of the GCL of about 21kPa (corresponding to a gradient of 390) was required before there was any flow of Jet A-1 for samples with no freeze-thaw (this threshold dropped to 14kPa with freeze-thaw as discussed later). This suggests that the GCL will be an excellent barrier to hydrocarbons provided that the hydrocarbon head does not exceed the threshold value; a likely situation in many practical applications. Rigid wall permeameter tests were also conducted and the greater gradients and flows through the specimen yielded a hydraulic conductivity of $2x10^{-11}$m/s which is still very small and similar to that with respect to water. There was however a three-fold increase in the intrinsic permeability which is masked by the effects of different density and viscosity when simply looking at the hydraulic conductivity. Rowe et al. (2005a) also demonstrated that in rigid wall permeameter tests the hydraulic conductivity of GCLs permeated with Jet A-1 increases with increasing hydraulic gradient. It was hypothesized that this is because higher pressures overcome interfacial tensions in the smaller pore thereby opening up more flow paths than were available at lower gradients. This implies that k values deduced for tests in rigid wall permeameters at high gradients may considerably overestimate the k that would actually be mobilized in field applications.

In summary, it appears that while hydrocarbons (such as Jet A-1) can increase the intrinsic permeability of the bentonite in a GCL, there is a breakthrough pressure below which there is negligible flow and above this breakthrough pressure the effect on intrinsic permeability is largely masked by the effect on density and viscosity such that the hydraulic conductivity of GCLs remains low and it appears that the specific GCLs tested by Rowe et al. (2004, 2006) can provide good containment of hydrocarbons for many practical applications for hydrated samples not subjected to freeze-thaw or desiccation (the effect of freeze-thaw or desiccation are discussed below).

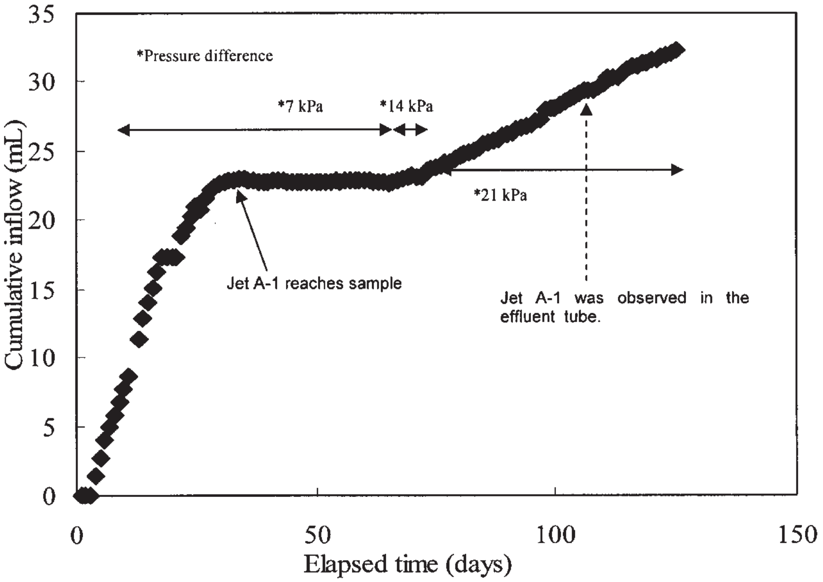

Figure 1: Cumulative inflow volume through the GCL subjected to 12 freeze and thaw cycles in FWP test (after Rowe et al., 2005c).

Freeze-thaw

While there are many applications where a GCL will not be subjected to freezing, there are also many parts of the world where GCL used in caps, for secondary containment or as primary containment for contaminant spills, will be subjected to freezing and to cycles of freeze-thaw. Hewitt and Daniel (1997) and Kraus et al. (1997) reported that the hydraulic conductivity of a GCL with respect to water did not change after three and 20 freeze-thaw cycles respectively. However these tests did not address the effect of freeze-thaw on the hydraulic conductivity with respect to hydrocarbons. An example application where this is important has been described by Bathurst et al. (2006) where a composite (fluorinated HDPE and GCL) liner is being used to contain a hydrocarbon spill at a former DEW-Line site on Brevoort Island in the Canadian arctic (near Baffin Island) until there can be future remediation. In this case permafrost, which is located at a relatively shallow depth, provides a natural barrier to prevent significant downward migration of hydrocarbons. However there is still the potential for lateral spreading of the hydrocarbon plume in the active zone (above the permafrost) following infiltration by rainwater and snow melt. The geosynthetic composite barrier was installed to cut-off flow to the sea in the active zone above the permafrost in 2001. A GM was also used to cover the area between the source of the plume and the barrier to minimize infiltration of rainwater or runoff into the contaminated zone. While the barrier is unfrozen in the summer months, it is subjected to freeze-thaw cycles and freezing during other parts of the year. The previous section has addressed the hydraulic performance of GCLs that have never been frozen. There remains the question of how the GCL will behave unfrozen after being subjected to freeze-thaw and how it will perform when frozen. These two questions will be addressed in this and the following section.

Rowe et al. (2004, 2006) performed accelerated freeze and thaw tests using flexible wall (FWP) and rigid wall (RWP) permeameters respectively. These tests were on the scrim-reinforced, nonwoven-nonwoven, needle-punched thermally-treated GCL used at the Brevoort site (Bentofix NWL™). The samples were hydrated for five days under low confining pressure (15 ±3 kPa), subjected to 0, 5-6 or 12-13 freeze and thaw cycles, and then first permeated with de-aired water followed by jet fuel A-1. They also performed tests on samples recovered from the field after 1 and 3 years natural exposure to freeze-thaw in the arctic.

Tests performed with the flexible wall permeameters (Rowe et al., 2004) found that the hydration conductivity with respect to water was between 3×10^{-11} and 6×10^{-11} m/s before freeze-thaw and 2×10^{-11} and 5×10^{-11} m/s after 12-13 freeze-thaw cycles confirming the findings by Hewitt and Daniel (1997) and Kraus et al. (1997) that the hydraulic conductivity of a GCL with respect to water did not change after up to 20 freeze-thaw cycles. The hydraulic conductivity with respect to Jet A-1 was about one order of magnitude lower than that with respect to water. This was largely due to the difference in viscosity and density of Jet A-1 and the intrinsic permeability of the GCL was, except for one case, similar to that with respect to water. However in these tests there was limited permeation of Jet A-1 through the samples (0.34 pore volumes or less). This then raises the question as to what effect greater permeation of hydrocarbon (at higher gradients) would have on the hydraulic conductivity.

Rowe et al. (2006) used RWP to permeate GCLs with many pore volumes (in excess of 10) of Jet A-1 until equilibrium was reached. They found that the mean equilibrium hydraulic conductivity with respect to Jet A-1 was about 8.0×10^{-11} and 14.5×10^{-11} m/s for 5 and 12 freeze-thaw cycles, respectively (i.e. about 4.0 and 5.6 times greater than the initial value with respect to water). Thus the combination of high gradients and many pore volumes of permeation did cause a change in the bentonite structure which increased both the intrinsic permeability and hydraulic conductivity. This was confirmed by SEM images which showed that the bentonite pore size for GCLs subjected to up to 12 freeze-thaw cycles was 2 – 3 times larger than that of the bentonite in the virgin GCL. Olsen's (1961) cluster model was used to estimate double layer and free-pore space voids in the tests conducted by Rowe et al. (2006). This model suggests that the double layer contracted by 20 – 40 % after permeating with Jet A-1 while the free-space expanded 1.2 – 2.5 times that before Jet A-1 permeation.

The GCLs recovered from the field after 1 and 3 years had a mean equilibrium hydraulic conductivity with respect to Jet A-1 of 6.2×10^{-11} m/s. This was about 6.4 times greater than the initial value with respect to water, but less than that observed for the samples subjected to 5 and 12 freeze-thaw cycles in the laboratory. Thus it can be concluded that the combined effect of freeze-thaw cycles and Jet A-1 permeation at high gradient is to increase in the GCL permeability. Notwithstanding the increase, the hydraulic conductivity with respect to Jet A-1 was 1.6 x 10^{-10} m/s or less, and hence could be expected to continue to perform well as a barrier to hydrocarbons for at least 12 freeze thaw cycles or up to 3 years in the field. Test are currently in progress to examine the effect of 50 and 100 freeze-thaw cycles and samples will continue to be recovered from the field and tested.

Rowe et al. (2006) also conducted tests on a GCL with no needle-punching and no freeze-thaw cycles and this GCL had a higher hydraulic conductivity than measured for the needle-punched GCL subjected to up to 12 freeze-thaw cycles. This suggests that the effect of GCL manufacture (i.e. with or without needle-punching) is more significant than either the effect of up to 12 freeze-thaw cycles in the laboratory or 3 years field exposure in the arctic.

Degree of hydration and freezing

The previous section examined the performance of fully hydrated GCL permeated with Jet A-1 at room temperature after having been subjected to freeze-thaw cycles. In secondary containment applications or the containment of spills such as described above at Brevoort Island (Bathurst et al., 2006) there is potential for the GCL to be unsaturated at the time it comes into contact with the hydrocarbon and there is also potential for it to be frozen at that time (since the freezing point of hydrocarbons, like Jet A-1, used in cold climates is below -47 °C). Both scenarios are examined in this section.

Daniel *et al.* (1993) reported that for GCLs on sand with an initial gravimetric water content higher than 5%, the water content of the bentonite in the GCL reached approximately 100% (or higher) in the first five days, and 130 – 190% after 45 days. For sand with an initial water content of 2-3%, the water content in the bentonite of the GCL reached approximately 35-40% after 5 days and approximately 80% after 45 days. The findings of Daniel et al. (1993) are summarized in Table 4.

Table 4: Approximate water contents of GCLs depending on subgrade (after Daniel et al., 1993).

Subgrade soil	Approximate water content, w_c of bentonite (%)
Extremely dry soil, does not support plant growth (soil suction > 1500 kPa)	< 50
Damp soil, supports sparse growth of plants (100 kPa ≤ soil suction ≤ 1500 kPa)	50 – 100
Moist soil, supports lush vegetation (0 kPa ≤ soil suction ≤ 100 kPa)	100 – 140
Wet soil (practically saturated), soil suction (≅ 0 kPa)	> 140

Using a flexible wall permeameter, Daniel et al. (1993) permeated unsaturated GCLs with benzene, gasoline, methanol, tert-butylethylether (MTBE), and trichloroethylene. They reported that for gravimetric water contents < 50% the bentonite part of the GCL was very permeable ($k \cong 10^{-7}$ m/s) but the hydraulic conductivity was very low ($k < 10^{-11}$ m/s) for water contents greater than 100%.

Rowe et al. (2005a) used a rigid wall permeameter to investigate the effect of water content and temperature on the hydraulic conductivity of GCLs permeated with Jet A-1. They found that the hydraulic conductivity (with respect to Jet A-1) of unfrozen samples decreased as the water content increased (Table 5) with values of less than 3×10^{-10} m/s being measured for gravimetric water content of 80% or greater. At subzero temperatures k decreased as the bulk void ratio decreased for a given water content. It was hypothesized that as the bulk void ratio decreases, the size of the flow paths available decreases. Thus, even in the unfrozen state one would expect that higher gradients would be needed to overcome interfacial tensions while at subzero temperatures the freezing water would expand and further constrict the flow paths giving a large decrease in hydraulic conductivity with respect to Jet A-1.

Table 5: Hydraulic conductivity of GCLs permeated with Jet Fuel A-1 (adapted from Rowe et al. 2006).

Unfrozen			Frozen		
Degree of saturation (-)	Gravimetric water content, w_c (%)	Hydraulic conductivity, k (m/s)	Degree of saturation (-)	Gravimetric water content, w_c (%)	Hydraulic conductivity, k (m/s)
$S_r \cong 0$	$\cong 8$	2×10^{-6}	$S_r \cong 0$	$\cong 8$	2×10^{-6}
$S_r \leq 0.70$	60-80	$> 10^{-8}$			
$S_r \geq 0.77$	80	$\leq 3 \times 10^{-10}$	$0.70 < S_r < 0.85$	90	1.8×10^{-11} to 2.5×10^{-10}
$S_r \cong 1$	120	3.4×10^{-11}	$S_r \geq 0.85$	$\geq 110\%$	$\leq 10^{-12}$

Rowe et al. (2005a) found that there was high variability in k for unsaturated samples at sub-zero temperatures due to different mass per unit area of bentonite and localization of ice masses within the GCL. Nevertheless, degrees of saturation between 70% and 0.85% gave 2.5×10^{-10} m/s < k < 1.8×10^{-11} m/s (Table 5). For degrees of saturation greater than 85%, the frozen GCL was essentially impermeable to Jet A-1 ($k \leq 10^{-12}$ m/s). For samples first permeated with Jet A-1 at 5°C and then Jet A-1 at -5°C, the hydraulic conductivity with respect to Jet A-1 drops, but some of the flow paths opened at 5°C remain open at -5°C.

In summary, the higher the degree of saturation, the greater the decrease in hydraulic conductivity with respect to Jet A-1 at all temperatures but especially for GCLs at -5 or -20 °C. There was a greater effect due to freezing at -20°C than at -5°C, suggesting that there is some difference in the effect of temperature for sub-zero temperatures.

Based on the results of Daniel et al. (1993) one might anticipate if the GCL is placed on even a damp to moist soil, the GCL would be sufficiently hydrated (water content of 90% or higher and degree of saturation greater than 85%) to provide a good barrier to Jet A-1. However it should be noted that Daniel et al. (1993) only considered a GCL on sand and more work needs to be done to confirm the level and rate of hydration for other soils.

Internal erosion

GCLs are now commonly used in composite liners for landfills and as the liner for ponds and lagoons. Given the relatively thin nature of GCLs, these applications can give rise to high gradients and the question arises as to the potential for internal erosion. This is especially true in applications where the GCL is placed in contact with gravel or a geonet (e.g. in a double lined landfill). Giroud and Soderman (2000) indicated that bentonite migration into a geonet drainage layer should not exceed 10 g/m^2, however they did not address the question as to how much migration might occur for a given GCL and indeed as to whether the GCL structure has any effect on the potential for internal erosion of bentonite. The fact that internal erosion can be a problem was highlighted by Stam (2000) who reported a field example where there was abnormal leakage through a GCL used to line a lake. Excavation found "patchy" bentonite piping from the core of the GCL through the lightweight nonwoven geotextile resting on the coarse sand subgrade.

Rowe and Orsini (2003) examined the behaviour of five different GCLs (see Table 6 for a definition of the GCLs) over a geonet (opening size of 0.8 cm and a diagonal span of 1.2 cm), 6 mm uniform gravel ($d_{85} \approx$ 7mm, $d_{50} \approx$ 6mm, $d_{15} \approx$ 3.6mm and $d_{10} \approx$ 3mm), and sand ($d_{85} \approx$ 1.1mm, $d_{50} \approx$ 0.17mm, $d_{15} \approx$ 0.043mm and $d_{10} \approx$ 0.03mm). Their findings are summarized in the following paragraphs.

It was found that when placed on the geonet, four of the five GCLs tested (BWD, NWD, WD, SNWD; see Table 6) experienced internal erosion (bentonite loss) and an increase in hydraulic conductivity by at least one order of magnitude for heads ranging from 8 m to 45 m. In contrast the BSNWD scrim-reinforced GCL with a total carrier geotextile mass per unit area of 350 g/m^2 did not exhibit any sign of internal erosion (at heads of up to 55 m).

When placed directly over the 6 mm gravel GCLs with a single woven geotextile (BWD, WD, and NWD with the woven down) in contact with the geonet and the NWD (with the light nonwoven geotextile in contact with the geonet) all experienced internal erosion. In these cases the hydraulic conductivity increased by at least one order of magnitude for water heads ranging from ~8 m to ~90 m. In contrast, the scrim-reinforced GCLs (SNWD, BSNWD) did not experience any detrimental effects at hydraulic heads of 40-60 m for the conditions examined.

All of the GCLs tested (single nonwoven geotextile down, NWD; a single woven carrier geotextile down, BWD; and a scrim-reinforced carrier geotextile down, SNWD) performed well when placed over the sand subgrade. For these cases even heads in the range 50-80m did not cause any significant bentonite loss and there was no evidence of internal erosion for this sand subgrade.

Increasing amounts of bentonite loss were accompanied by increased hydraulic conductivity. However failures could initially be quite localized and in some cases failure was associated with relatively little bentonite loss. Rowe and Orsini (2003) concluded that designs involving GCLs over a gravel or geonet subgrade need to be carefully examined since internal erosion at water heads as low as 8 m caused an increase in the hydraulic conductivity by one to two orders of magnitude. Both the gravel and geonet used in their tests meet the subgrade criteria of ASTM D6102, and thus it appears that GCL installations meeting this standard could experience internal erosion and fail under water heads encountered in reservoirs, lagoons or landfills where leachate mounding occurs. These tests showed that the choice of GCL carrier geotextile could significantly affect GCL performance. A GCL with a woven geotextile down (i.e. in contact with the 6 mm gravel and geonet) did not perform as well as the other GCLs. GCLs with a nonwoven down performed better than the GCLs with woven geotextile down for the gravel subgrade, but there was no significant difference between the two cases when over the geonet; neither was acceptable. The heavy scrim-reinforced GCLs performed best with BSNWD working well for all cases examined. For the specific sand subgrade tested, all GCLs performed well. This highlights the need to carefully consider the choice of GCL in the context of the expected gradient and subgrade conditions.

Table 6: GCLs used in internal erosion tests (after Rowe and Orsini, 2003).

GCL	Product Descriptor	Upper Geotextile[1]	Core Sodium Bentonite	Lower Geotextile[1]	Total mass/ unit area (g/m^2)	Bentonite Moisture Content (%)
BWD[2]	BFG5000	Bentonite filled ($800\ g/m^2$) nonwoven $300\ g/m^2$	Powder $4200\ g/m^2$	Slit film woven $200\ g/m^2$	5500	<15
WD[2]	NS	Staple fibre nonwoven $200\ g/m^2$	Granular $4340\ g/m^2$	Slit film woven $105\ g/m^2$	4645	<12
NWD[3]		Nonwoven $220\ g/m^2$	Granular $4800\ g/m^2$	Woven $100\ g/m^2$	5100	22
SNWD[2]	NW	Staple fibre nonwoven $200\ g/m^2$	Granular $4340\ g/m^2$	Slit film woven, nonwoven composite $305\ g/m^2$	4845	<12
BSNWD[2]	B4000	Nonwoven $300\ g/m^2$	Powder $4700\ g/m^2$	Slit film woven ($100\ g/m^2$), nonwoven ($250\ g/m^2$) composite	5350	<15

[1] Polypropylene; [2] Bentofix, thermally-treated and needle-punched; [3] Bentomat, needle-punched

Shrinkage and desiccation cracking of GCLs

GCLs (and compacted clay liners, CCLs) are susceptible to both shrinkage and desiccation cracking. This is especially true when the clay liner is below a GM in a composite liner. When exposed to the sun, GM temperature may often range between 60°-70°C and can reach 80°C (Felon *et al.*, 1992). This can cause evaporation of water from the underlying GCL into any air space between the GCL and the GM and subsequent movement of this water down-slope upon cooling of the GM. It can also cause movement of moisture from the GCL into the subsoil. Field examples involving desiccation of CCLs and shrinkage of GCLs have been reported by Corser et al. (1992), Basnett and Bruner (1993), and Thiel and Richardson (2005).

Information regarding the desiccation of CCLs and GCLs under thermal gradients is quite limited. Work conducted by Heibrock (1997), Döll (1997), Zhou and Rowe (2003, 2005), Southen and Rowe (2004, 2005a,b) and Southen (2005) has been reviewed by Rowe (2005). Döll's (1997) SUMMIT program uses temperature and capillary pressure (suction) as the basic variables for the analysis of thermally driven moisture movement, subject to the assumptions of a rigid, heterogeneous, unsaturated medium.

Heibrock (1997) used Döll's (1997) SUMMIT program to model composite liners involving several CCLs. For a silt loam CCL with a top of the liner temperature of 40°C, cracking was predicted to a depth of 1 m in 20 years. However no cracking was predicted for a loess CCL with a much higher unsaturated hydraulic conductivity than the silt loam. This highlights the need to define criteria for the design of CCLs to withstand likely liner temperatures generated by the biodegradation of MSW or hydration of ash.

Southen and Rowe (2005a) used Döll's SUMMIT program to analyse their large-scale laboratory experiments. They found that the predicted water contents in the subsoil were in reasonable agreement with experimental results and, while less accurate, the predictions of temperature in the subsoil were also in reasonable agreement with experimental results. In contrast, the SUMMIT model underestimated the volumetric water content in the GCL by as much as a factor of two, primarily because of the assumption of a rigid media.

Zhou and Rowe (2003) developed a model that incorporates consideration of fully coupled heat-moisture-air flow, a non-linear constitutive relationship, the dependence of void ratio and volumetric water content on stress, capillary pressure and temperature, and the effect of mechanical deformation on all governing equations. Southen (2005) used this to model their large-scale laboratory tests. The predicted volumetric water contents fit the general trends observed in the experimental data, and agreement was especially good within the GCL and in the upper 5cm of the subsoil. The temperature distribution was also reasonably modelled. Due to its ability to model deformable media and calculate stress changes arising from the thermo-hydro-mechanical response, it gave excellent predictions of the significant change in GCL void ratio and also predicted tensile horizontal stresses consistent with the observed desiccation cracking of the GCL.

Based on the numerical studies conducted by Heibrock (1997) and Southen (2005), and the experimental data published by Southen and Rowe (2004, 2005b), Rowe (2005) reached a number of tentative conclusions as described below.

Temperature is a key factor affecting the potential desiccation of composite liner systems (both GM/GCL and GM/CCL). Temperature may be a function of landfill operation and the likely temperatures to be experienced at the liner need to be considered in landfill design. For single composite liners involving a GCL, it was suggested that:

(a) The unsaturated soil characteristics and initial water content of the foundation layer beneath the GCL greatly influences the potential for desiccation.

(b) The greater the overburden stress at the time of GCL hydration, the lower is the risk of desiccation. Thus both the potential for short term (e.g., solar induced) and long term (waste temperature induced) desiccation can be minimized by placing the waste over the composite liner as quickly as possible after the liner construction. This finding has significant implications of the manner in which many landfills are developed.

(c) Increasing distance to the underlying watertable increased the risk of desiccation for aquifer depths up to about 5m below the GCL, but relatively little change was predicted for increased depths beyond 5m due to the offsetting effects of reduced water content and temperature gradient.

For single composite liners involving a CCL, it was suggested that:

(a) The unsaturated soil characteristics of the liner had a significant effect on the distribution of moisture and stress.

(b) The effect of overburden stress was not as significant as for a GCL, although it did still reduce the risk of desiccation.

More research is needed into the potential for long-term desiccation of clay liners making up part of a composite liner, especially with respect to the paucity of relevant soil parameters. Current research suggests that there is real potential for desiccation but also suggests that this can be mitigated by appropriate design and construction.

Effect of hydrocarbons on peel strength

In short term hydrocarbon spill containment applications, one potential failure mechanism involves a loss of slope stability due to the low internal friction angle of the bentonite used in GCLs and the low confining stress in secondary containment applications. Unreinforced GCLs have a reported internal friction angle of around 10° (Shan and Daniel, 1994). Needle-punching can substantially increase the internal stability of GCLs (Shan and Daniel, 1994). In the event of a tank failure, one might expect that a GCL will be exposed to hydrocarbons for a short period of time during clean up and while repairs are made. For the GCL to retain its internal shear strength it is important that the needle-punched fibres, commonly made from polypropylene, do not fail. Hurst and Rowe (2006) examined the question of whether exposure to Jet A-1 can break down the polypropylene fibres and weaken the needle punching of the GCL for the short exposure periods (1-2 weeks) that may be anticipated during clean-up of a spill.

GCL peel strength (ASTM 6496) has been correlated with internal shear strength by several researchers (Heerten et al., 1995; Richardson, 1997; Olsta and Crosson, 1999; Mackey and von Maubeuge, 1999). Olsta and Crosson (1999) indicated that needle-punched GCLs with a peak peel strength of 65N should result in an internal shear strength sufficient for most low normal load applications (approximately 24 kPa).

Hurst and Rowe (2006) performed a series of peel strength tests (ASTM D6496) on saturated GCLs exposed to Jet A-1 at 14 kPa applied stress. They found that there was no statistically significant difference in average bonding peel strength for 0, 4 and 7 day exposure compared to dry exposed samples for the same period. Samples exposed to Jet A-1 for 14 days had a lower average bonding peel strength than initially, although the average bonding peel strength was still sufficient for a berm with a 3(h):1(v) slope and 3m or less cover based on a factor of safety of 1.5 based on Mackey and von Maubeuge (1999). This, and the previous discussion of compatibility, suggests that, subject to suitable design and construction, the GCLs tested would perform adequately for temporary containment of hydrocarbons such as in a secondary containment application.

Diffusion through GCLs and GMs

Assessment of long-term impact for containment of contaminated fluids (e.g. in lagoons, landfills etc.) requires contaminant transport modelling which considers both advective and diffusive transport. This has now received a lot of attention in the literature as described, for example, by Rowe et al. (2004) and Rowe (2005). Thus only a brief summary is presented here. Evidence suggesting the likely diffusion of volatile organic compounds through geosynthetic liners arises from field observations reported by Workman (1993) and Othman et al. (1996).

Diffusion through GCLs

Lake and Rowe (2004) examined diffusion of several volatile organic compounds (DCM, DCA, TCE, benzene and toluene) through a GCL at room temperature. They reported diffusion coefficients of between about 2×10^{-10}m^2/s to 3×10^{-10}m^2/s (at room temperature and a confining pressures less than 10 kPa). Rowe et al. (2005b) extended this work by examining the effect of temperature on the diffusion of benzene, toluene, ethylbenzene, m&p-xylene and o-xylene (BTEX). They showed that the geotextile component of a GCL was the primary contributor to sorption of hydrocarbons by the GCL, and partitioning coefficients (K_d at 22°C and 7°C in ml/g) for the entire GCL were: m&p-xylene (42, 25) > ethylbenzene (36, 22) > o-xylene (27, 14) > toluene (15, 8.7) > benzene (4.4, 2.6). The diffusion coefficients (at 22°C and 7°C in m^2/s) followed the order benzene (3.7×10^{-10}, 2.2×10^{-10}) > toluene (3.1×10^{-10}, 1.8×10^{-10}) > ethylbenzene (2.9×10^{-10}, 1.7×10^{-10}) > m&p-xylene (2.5×10^{-10}, 1.5×10^{-10}) ≈ o-xylene (2.6×10^{-10}, 1.5×10^{-10}). While the change in temperature from 22 °C to 7°C reduced both the diffusion and sorption coefficients, these reductions had opposite effects on mass transport through the GCL with the decrease in mass transport due to a reduced diffusion coefficient dominating over the increase due to smaller sorption. Thus the net effect was less mass transport at lower temperature.

The sodium bentonite typically used in GCLs provides relatively little sorption for volatile organic compounds (Lake and Rowe, 2005). Sorption can be increased by replacing the normal bentonite by organoclays or a mixture of bentonite and activated carbon. Batch tests reported by Lake and Rowe (2005) for four different organoclays showed two to three orders of magnitude higher sorption to DCM, DCA, TCE, benzene, and toluene than for conventional Na-bentonite. A mixture of 2% of powdered activated carbon with powdered bentonite (2% PAC/PB) gave even higher sorption than for the organoclays for TCE, benzene, and toluene. To assess engineering relevance of the potential improvement in GCL sorption due to the use of these alternative materials, contaminant transport modelling was conducted and it was shown that due to the small thickness of the GCL even large increases in GCL sorption, corresponding to what might be realized by using the alternative materials, had relatively little effect on contaminant migration. Hence it would appear that the increased costs associated with modifying GCLs to improve sorption are probably not justified for most practical applications for GCLs as part of the liner system for MSW landfills.

Lake and Rowe (2000a) examined the diffusion of sodium chloride through GCLs and showed that there was a direct correlation between the diffusion coefficient and the bulk void ratio of the GCL. They found that the chloride diffusion coefficient ranged between $1 \times 10^{-10} m^2/s$ and 4×10^{-10} m^2/s for the range of conditions examined.

Diffusion through geomembranes and composite liners

The diffusive flux of contaminants from an aqueous source (e.g. leachate) on one side of a GM to water on the other side, can be written in terms of a permeation coefficient (called the permeability in the polymer literature), P_g, viz:

$$f = -P_g \frac{dc_f}{dz} \tag{2}$$

where P_g takes into account the partitioning and diffusion processes.

The permeation coefficient, P_g, for HDPE varies substantially depending on the nature of the contaminant. For example, based on Eloy-Giorni et al. (1996) $P_g \leq 2.3 \times 10^{-16}$ m^2/s for water. Based on chloride diffusion tests that have been running for about 12 years, Rowe (2005) reported a very low value of permeation coefficient with $P_g \leq 3 \times 10^{-17}$ m^2/s. The permeation coefficient is also very low for heavy metal ions such as Zn^{2+}, Ni^{2+}, Mn^{2+}, Cu^{2+}, Cd^{2+}, and Pb^{2+} (August and Tatzky, 1984). However many hydrocarbons such as benzene, toluene, ethylbenzene and xylenes (BTEX) and chlorinated solvents such as dichloromethane (DCM) can readily diffuse though HDPE GMs (see Sangam and Rowe, 2001; 2005). For example, the permeation coefficient for DCM through a 2mm thick HDPE GM is about $4\times10^{-12}m^2/s$ and at this value DCM will break through the GM in about 10 days.

The permeation coefficient will vary depending on a number of factors such as the crystallinity of the GM, temperature and, in some cases, the chemical composition and concentrations in the contaminant source. Thus published values should only be used as an initial guide and if the parameter is important with respect to assessing contaminant impact then values should be obtained for the GM, temperature and contaminant source of interest. The diffusion of hydrocarbons such as BTEX can also be reduced by a factor of between about 2 and 5 by using a fluorinated HDPE as an alternative to a conventional GM (Sangam and Rowe, 2005).

In summary, HDPE GMs are an excellent diffusion barrier to water and readily water soluble contaminants such as metal salts. However, they will allow diffusion of volatile organic compounds. Control of the migration of these compounds will depend on the clay liner and any attenuation layer between the GM and any receptor aquifer. Additional control can be provided by using a fluorinated HDPE GM.

Leakage through composite liners

Data from the leak detection system of landfill cells with a double liner provides considerable insight regarding leakage through different primary liners including single GM primary liners, GM/GCL composite primary liners, GM/CCL composite primary liners (Bonaparte et al., 2002). The maximum peak leakage through a single GM liner (1820 lphd) was substantially higher than through the GM/CCL (390 lphd) and GM/GCL (54 lphd) composite liners underlain by a geonet (GN) leak detection system (LDS). This illustrates the benefit of composite liners in terms of reducing peak leakage through holes in GMs. It also suggests that the leakage through the GM/GCL liners was substantially less than through the GM/CCL liners. However all of the leakages for composite liners were small and consequently, the contaminant transport by advection appears to have been very small.

Rowe (2005) attributed, in part, the difference in leakage between GM/CCL and GM/GCL composites to difference in the contact conditions between the GM and underlying clay liner. Research has shown that compacted clay liners may have protrusions related to particle size distribution in the liner material and rutting caused by construction equipment either during construction of the liner or when the overlying GM and leachate collection layer is being placed. These undulations/ruts provide zones where the GM will not be in intimate contact with the CCL (e.g., Cartaud et al., 2005). In contrast GCLs are usually placed on a subgrade that is much stiffer than a CCL (and hence less susceptible to construction induced rutting) while also having the potential to swell such that bentonite can fill many of the small irregularities that might occur at the GM/GCL interface. Rowe (1998) indicated that Giroud and Bonaparte's (1989) characterization of typical GM - CCL contacts as "good" and "poor" could be related to average transmissivities of the GM/CCL interface of 1.6×10^{-8} m^2/s and 1×10^{-7} m^2/s respectively for a typical CCL ($k=10^{-9}$ m/s). In contrast, Harpur et al. (1993) reported GM/GCL interface transmissivities of between $2\times10^{-12}m^2/s$ and $2\times10^{-10}m^2/s$ (at 7kpa). This corresponds to between a two and five order of magnitude difference in transmissivity compared to that for GM/CCL.

Transmissivities given above can be used in empirical equations (Giroud and Bonaparte, 1989; Giroud, 1997) or analytical equations (Jayawickrama et al., 1988; Rowe, 1998; Rowe and Booker, 2000; Touze-Foltz et al., 1999, 2001b) to calculate leakage through holes in the

GM component of composite liners assuming direct contact between the GM and clay liner. However, as shown in Table 7 the calculated leakage assuming direct contact (minor wrinkles for poor contact, but no major wrinkles) and typical size and number of holes (typically 12 or less; Nosko and Touze-Foltz, 2000) in GMs significantly underestimated the observed leakage for both the GM/CCL or GM/GCL systems.

Table 7: Comparison of calculated (direct contact solution) and observed leakage during the active period for 0.9m thick CCL and GCL.

Liner	k (m/s)	θ (m^2/s)	Leakage for stated number of holes/ha[1] (lphd)			Observed[2] (lphd)	
			2.5	12	40	Range[3]	Peak[4]
0.9m CCL	$1x10^{-10}$	$1.6x10^{-8}$	3	16	50	60-160[5]	390
0.9m CCL	$1x10^{-9}$	$1x10^{-7}$	20	100	350		
GCL[5]	$5x10^{-11}$	$2x10^{-12}$	0.0006	0.003	0.009	0-11	54
GCL[5]	$2x10^{-10}$	$2x10^{-10}$	0.03	0.1	0.4		

Rounded; [1] Hole r_o=5.6mm; h_w=0.3m, h_a=0; [2] based on data reported by Bonaparte et al. (2002) for systems with a GN LDS; [3] Weighted average flow; [4] Maximum peak flow; [5] Calculations assume thickness of 0.01m.

There is considerable evidence to suggest that in many practical situations GMs will have significant wrinkles (Stone, 1984; Pelte et al., 1994; Soong and Koerner, 1998; Touze-Foltz et al. 2001a; Rowe et al., 2004). Assuming that there is a hole in a GM wrinkle and unobstructed lateral flow along the wrinkle of length, L, and width, 2b (where L >> b) Rowe (1998) developed a solution for leakage, Q, for wrinkles assumed to be spaced at a distance 2x apart, viz:

$$Q=2\,L\,k\,[b+\{1-\exp(-\alpha\,(x-b))\}/\alpha]\,h_d\,/\,D \qquad (3)$$

Where k is the hydraulic conductivity of the clay liner; h_d is the head loss across the composite liner; $\alpha = [k/(D\theta)]^{0.5}$; θ is the transmissivity of the GM-clay liner interface; and D is the thickness of the clay liner. Assuming no interaction with an adjacent wrinkle, the leakage, Q, is given by:

$$Q = 2\,L\,[\,k\,b + (k\,D\,\theta)^{0.5}]\;h_d\,/\,D \qquad (4)$$

Table 8 shows the calculated leakage (using Eq. 3 and accounting for interaction assuming equal spacing of the wrinkles) through GM over a 0.9m CCL for wrinkles of total length 3m and 30m together with the typical observed leakage range previously shown in Table 7. Three different liner conditions were examined: (a) low hydraulic conductivity liner and good interface conditions; (b) typically specified liner and good interface conditions; and (c) typically specified liner and poor interface conditions. The typical range of observed average leakage could be explained by 12 holed winkles/ha (3 to 30m long) with a typical liner and good contact (Case (b)). The peak leakage could be explained by about 15 holed wrinkles/ha and good interface conditions (Case (b)) or by 6 holed wrinkles/ha and poor interface conditions (Case (c)). Thus the typical observed leakage for composite liners involving CCLs, can be readily explained by holes in wrinkles for a reasonable number of holes/ha.

Table 8 also shows observed leakage and the calculated leakage for two cases involving a GM/GCL: (d) low hydraulic conductivity GCL (assuming no significant clay-leachate interaction) and the lowest interface transmissivity measured by Harpur et al. (1993); and (e) high hydraulic conductivity GCL (assuming significant clay-leachate interaction) and the highest interface transmissivity measured by Harpur et al. (1993) to bracket the likely situation. It can be seen for the very best conditions (Case (d)) about 2.5 to 12 holed 3-30m long wrinkles/ha are needed to explain the typical observed range while for the worst condition 2.5 (or less) 3-30m long wrinkles/ha are needed to explain the typical observed range and the peak value can be explained by about 6 holed 3-30m long wrinkles/ha. Thus the typical observed leakage for composite liners with GCLs, also can be readily explained by holes in wrinkles for the typical number of holes/ha and reasonable combinations of other parameters.

Table 8: Comparison of calculated (with wrinkles) and observed leakage during the active period for 0.9m thick CCL and GCL.

Case	Liner	k (m/s)	θ (m^2/s)	Leakage for stated number of holed wrinkles/ha[1] (lphd)		Observed[2] (lphd)	
				2.5	12	Range[3]	Peak[4]
(a)	0.9m CCL	$1\text{x}10^{-10}$	$1.6\text{x}10^{-8}$	2-20	10-65	60-160	390
(b)	0.9m CCL	$1\text{x}10^{-9}$	$1.6\text{x}10^{-8}$	7-70	30-310		
(c)	0.9m CCL	$1\text{x}10^{-9}$	$1\text{x}10^{-7}$	16-160	80-580		
(d)	GCL[5]	$5\text{x}10^{-11}$	$2\text{x}10^{-12}$	0.2-2	1.2-12	0-11	54
(e)	GCL[5]	$2\text{x}10^{-10}$	$2\text{x}10^{-10}$	1.6-16	8-75		

Rounded; [1] Range of calculated values corresponds to L=3 and 30m (accounting for interaction); Hole r_o=5.6 mm; h_w=0.3m, h_a=0, 2b=0.2m; [2] based on data from Bonaparte et al. (2002) for systems with a GN LDS; [3] Weighted average flow; [4] Maximum peak flow; [5] Calculations assume thickness of 0.01m.

As discussed by Rowe (2005), the amount of fluid collected in a LDS is controlled by (a) the leachate head, (b) the number and size of GM wrinkles with holes, (c) the transmissivity of the GM/clay liner interface, (d) the hydraulic conductivity and thickness of the liner, (e) the hydraulic characteristics of the material above the GM, (f) consolidation of the liner, (g) the initial degree of saturation of the soil and geosynthetics below the GM, and (h) the potential for the GCL significantly reducing the transmissivity of an underlying geonet drainage layer. The reader is referred to Rowe (2005) for a discussion of these issues. With respect to the last item, it is noted that the design and construction of systems with a geonet LDS must ensure that the swelling and intrusion (under vertical stress) of any overlying GCL does not compromise the drainage function of the underlying geonet (Shaner and Menoff, 1992; Legge and Davies, 2002).

Service life of geomembranes for MSW landfills

The long-term performance (service life) of a GM will depend on the properties of the GM (e.g. its stress crack resistance, crystallinity, and oxidative induction time), the tensile strains in the GM (which can be induced by the overlying drainage material and wrinkles in the GM), the exposure to chemicals in the leachate, and temperature. The limited data concerning the service life of GMs have been summarized by Rowe (2005).

Chemical ageing of GMs is considered to have three distinct stages (Viebke et al., 1994; Hsuan and Koerner, 1998): (a) depletion time of antioxidants; (b) induction time to the onset of polymer degradation; and (c) degradation of the polymer to decrease some property (or properties) to an arbitrary level (e.g., to 50% of the original value). The consumption of antioxidants and subsequent oxidation reaction in polyethylene can be increased in the presence of transition metals (Osawa and Saito, 1978); Wisse et al., 1990; Hsuan and Koerner, 1998) present in leachate (e.g., Co, Mn, Cu, Pd and Fe). Since it would take far too long to establish the service life under actual field conditions, tests are conducted at elevated temperatures to accelerate ageing and the results are extrapolated to temperatures expected at the base of a landfill (e.g. Hsuan and Koerner, 1998; Sangam and Rowe, 2002; Mueller and Jacob, 2003; Rowe, 2005)

Sangam and Rowe (2002) examined the depletion of antioxidants in air, water and simulated MSW leachate while Rowe (2005) reported results for simulated liner systems with a collection layer over the geotextile protection layer, the GM and a GCL on a sand subgrade. They used the laboratory data together with Arrhenius modelling to deduce the time required or antioxidant depletion for the HDPE GMs studied. The results shown in Table 9 indicate the range of times required to deplete the antioxidants to be between 50 and 510 years at 10 °C and between 10 to 80 years at 35°C. At 60°C, the depletion times are all short (3-15 years). These results illustrate the critical importance of liner temperature and the nature of the chemical exposure on antioxidant depletion times.

The simulated liner results presented in Table 9 represent the best current information on depletion time of antioxidants for GM liners in landfills. This represents only the first stage of the service life. To obtain estimates for stages 2 and 3, Rowe (2005) used data obtained by Viebke et al. (1994) for polyethylene gas pipe with minimal antioxidant and a wall thickness comparable to a GM thickness (2.1mm). The antioxidant depletion times (Stage 1) for the simulated liner (Table 9) were combined with the service life projections for Stages 2 and 3 based on the activation energies given by Viebke et al. (1994) to obtain the "unadjusted" estimates of GM service life given in Table 10. Since Viebke et al.'s (1994) tests were with water on the inside and air on the outside of the pipe wall, the unadjusted values may be expected to overestimate the service life of a GM in a landfill. Thus these values were adjusted to reflect the observed difference between exposure to air, water and a simulated liner exposed to leachate on one side as described by Rowe (2005) to obtain the "adjusted" estimates given in Table 10. It can be seen that for temperatures in the range 10-20°C, service lives are projected to be of the order of 565 to 2775 years and hence a service life of 600 years (or more) could be anticipated at a temperature less than 20°C. For liners at a temperature of 35°C, the service life is of the order of 130-190 years. Finally at temperatures of 50-60°C, the service lives are very short (15-50 years).

Table 9: Estimated antioxidant depletion time for an HDPE geomembrane (modified from Rowe 2005).

Temperature (°C)	Air[1] t_{air} (years)	Water[1] t_{water} (years)	Leachate[1] $t_{leachate}$ (years)	Simulated Liner[2] t_{sl} (years)
10	510	235	50	280
20	235	110	25	115
30	110	55	15	50
35	80	40	10	35
40	55	30	8	25
50	30	15	5	10
60	15	8	3	6

All times greater than 10 have been rounded to nearest 5 years.

[1] *2mm HDPE, OIT_o= 133 minutes (ASTM D3895), crystallinity = 44%; based on data from Sangam and Rowe (2002)*

[2] *1.5mm HDPE, OIT_o= 135 minutes (ASTM D3895), crystallinity = 49%*

The service lives presented in Table 10 provide a general idea of order of magnitude of the GM service-life and highlight the importance of liner temperature. However, they should be used with considerable caution since only the results for Stage 1 are based on actual tests on GMs typically used in landfill application in a simulated liner configuration.

Table 10: Estimated service lives for an HDPE geomembrane for a MSW landfill (modified from Rowe 2005).

Temp (°C)	Service Life (years)	Service Life (years)
	Unadjusted t_{SL}	Adjusted t_{SLa}
10	2775	1690
20	900	565
30	315	205
35	190	130
40	120	80
50	50	35
60	20	15

All times have been rounded to nearest 5 years.

The calculated antioxidant depletion times (Table 9) and service lives (Table 10) all assume a constant temperature. Rowe (2005) examined the effect of the liner temperature varying with time. This showed that while operational features such as leachate recirculation may shorten the period of high temperatures on the liner, the increase in temperature associated with recirculation can actually decrease the overall service life. This highlights the importance of considering the mode of landfill operation when developing a liner design.

Effect of hydrocarbons on GM service life

To assess the potential effect that contact with hydrocarbons may have on the service life of a GM, Rowe et al. (2005) immersed both conventional HDPE and fluorinated HDPE (f-HDPE) GM specimens in Jet A-1 and then examined the change in oxidative induction time with the period of immersion. They found that immersion in Jet A-1 accelerated antioxidant depletion relative to that observed in water or municipal solid waste (MSW) leachate by Sangam and Rowe (2002). Fluorination of the HDPE GM significantly (by a factor of 2.6) reduced antioxidants depletion relative to conventional HDPE. At 23°C, the total antioxidant depletion time was estimated to be 2.3 and 6.1 years for untreated and fluorinated GMs respectively. This can be compared with projected depletion times of 20 years and 90 years (at 23°C) based on Sangam and Rowe's (2002) tests for GM immersed in MSW leachate and water respectively.

Conclusions

A number of factors potentially affecting the performance of GCLs and GMs in geoenvironmental applications have been reviewed. It can be concluded that for the specific materials and conditions discussed:

- The method of manufacture of GCLs can influence their performance as both a hydraulic and diffusive barrier, especially for GCLs that will hydrate at relatively low stress levels. Of the GCLs tested, needle-punched heat burnished CGLs provided the best performance.
- At low stress at the time of permeation, there is an order of magnitude increase in GCL hydraulic conductivity to about $6\text{x}10^{-10}$ m/s as the permeant was changed from water to MSW leachate. At higher stress, more typical of likely field conditions, the effect is far less significant with a hydraulic conductivity to MSW leachate still very low at $3\text{x}10^{-11}$ m/s.
- GCLs provided strong attenuation for a large number of metals and metalloids present in acid rock drainage (ARD) leachate and a neutral-pH gold mining leachate (GML). The hydraulic conductivity of the GCLs permeated with ARD increased from $2.8\text{x}10^{-12}$ m/s to $3.7\text{x}10^{-11}$ m/s after 35 pore volumes of permeation. There was no significant change in hydraulic conductivity for GCLs permeated with GML.
- There is a breakthrough pressure below which there is negligible flow of hydrocarbons through a saturated GCL. Above this breakthrough pressure the effect on intrinsic permeability is largely masked by the effect on density and viscosity such that the hydraulic conductivity of GCLs remains low and it appears that GCLs such as that tested can provide good containment of hydrocarbons for many practical applications.
- The hydraulic conductivity with respect to Jet A-1 decreased as the water content increased with values of less than $3\text{x}10^{-10}$ m/s being measured for gravimetric water content of 80% or greater.
- Up to 12-13 freeze-thaw cycles had very little effect on the hydraulic conductivity of GCLs permeated with water and only a modest (4 to 6 fold) effect on the permeability of Jet A-1.
- The GCLs recovered from the field in the Canadian arctic after 1 and 3 years had a mean equilibrium hydraulic conductivity with respect to Jet A-1 of 6×10^{-11} m/s. This was about 6 times greater than the value with respect to water but still very low.
- There was high variability in k for unsaturated GCLs at sub-zero temperatures due to different mass per unit area of bentonite and localization of ice masses on freezing. Nevertheless, degrees of saturation between 70% and 0.85% gave 2.5×10^{-10} m/s < k < 1.8×10^{-11} m/s. For degrees of saturation greater than 85%, the frozen GCL was essentially impermeable to Jet A-1 ($k \leq 10^{-12}$ m/s).

- The choice of GCL carrier geotextile could significantly affect GCL performance in applications where there is potential for internal erosion. GCLs with a woven geotextile down (i.e. in contact with the underlying subgrade) did not perform as well as the other GCLs. GCLs with a nonwoven geotextile down performed better than the GCLs with a woven down but still experience some difficulties over a geonet at high heads. In contrast, the scrim-reinforced GCL with a carrier geotextile mass of 350 g/m^2 did not exhibit any sign of internal erosion when placed over the geonet, gravel or sand tested at heads of 40-60m.
- Both GCLs and CCLs may be susceptible to shrinkage and desiccation when used as part of a composite liner. This may occur due to exposure to solar radiation prior to placement of adequate cover or after placement of waste due to heat generated by the waste. The potential for shrinkage and desiccation will depend on the temperature gradient, the characteristics of the GCL or CCL, the unsaturated soil characteristics and initial water content of the foundation layer beneath the clay liner, the overburden stress, and the distance to the underlying watertable. The available information suggests that while there is potential for desiccation and shrinkage, this can be mitigated by appropriate design and construction.
- GCL samples exposed for to Jet A-1 for 14 days had a lower average bonding peel strength than initially, although the average bonding peel strength was still sufficient for typical applications involving secondary containment.
- Volatile organic compounds can diffuse through both GMs and GCLs. Diffusion of hydrocarbons is much slower for fluorinated HDPE (f-HDPE) than conventional HDPE GMs. Typical diffusion coefficients have been reported for both HDPE and fluorinated HDPE GMs as well as GCLs. Ionic contaminants exhibit negligible diffusion through intact HDPE GMs. The diffusion coefficient for ionic contaminates through GCLs is a function of the bulk void ratio of the GCL.
- Field data indicates that the leakage through single GM liners is typically substantially higher than that through composite liners. The observed leakage through a GM/CCL composite liner was typically one to two orders of magnitude higher than that observed for GM/GCL composite liners.
- The calculated leakage obtained assuming direct contact (no major wrinkles) and typical size and number of holes in GMs using commonly used equations significantly underestimated the observed leakage for both GM/CCL and GM/GCL systems.
- The typical observed leakage for composite liners with CCLs and GCLs can be readily explained by holes in wrinkles for the typical number of holes/ha and reasonable combinations of other parameters using the Rowe (1998) equation.
- The design and construction of systems with a geonet LDS must ensure that the swelling and intrusion (under vertical stress) of any overlying GCL does not compromise the drainage function of the underlying geonet.
- The long-term performance of a GM will depend on the properties of the GM (e.g. its stress crack resistance, crystallinity, and oxidative induction), the tensile strains in the GM (which can be induced by the overlying drainage material and wrinkles in the GM), the exposure to chemicals in the leachate, and temperature.
- The service life of HDPE GMs meeting GRI GM-13 and used in MSW landfills are projected to be of the order of 600 years or more at a temperature less than 20°C. At a temperature of 35°C, the service life is projected to be of the order of 130-190 years. At temperatures of 50-60°C, service lives are very short (15-50 years).
- Immersion of HDPE GMs in Jet A-1 accelerates antioxidant depletion relative to that observed in water or municipal solid waste (MSW) leachate. The antioxidant depletion time was estimated to be 2.3 and 6.1 years for untreated and fluorinated GMs,

respectively, at 23°C. This can be compared with a projected 20 years and 90 years based on Sangam and Rowe's (2002) tests for GM immersed in MSW leachate and water respectively (at 23°C).

The available data suggests that GCLs and GMs can play a very beneficial role in providing environmental protection. However like all engineering materials there is a need for site specific design, strict adherence to construction specification, and appropriate protection of the geosynthetics after construction. In particular, given the diversity of available GCLs, GCLs should be selected based on the required engineering properties, not just price.

Acknowledgements

The author is indebted to the many students and collaborators who have contributed to the research summarized in this paper. This work was funded by a variety of agencies including the Natural Sciences and Engineering Research Council of Canada (NSERC), the North Warning System Office of the Department of National Defense Canada, CRESTech (an Ontario Centre of Excellence), Terrafix Geosynthetics Inc., and NAUE GmbH & Co. The value of discussion with Mr. K. Von Mauberge and B. Herlin is gratefully acknowledged. The author is also very grateful to Dr. Dalinaidu Arnepalli, Dr. David-Huw Owen and Ms. Sera Sheridan for their assistance in the preparation of this paper.

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