Short- and long-term leakage through composite liners. The 7th Arthur Casagrande Lecture[1]

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Abstract: The factors that may affect short-term leakage through composite liners are examined. It is shown that the leakage through composite liners is only a very small fraction of that expected for either a geomembrane (GM) or clay liner (CL) alone. However, the calculated leakage through holes in a GM in direct contact with a clay liner is typically substantially smaller than that actually observed in the field. It is shown that calculated leakage taking account of typical connected wrinkle lengths observed in the field explains the observed field leakage through composite liners. Provided that care is taken to avoid excessive connected wrinkle lengths, the leakage through composite liners is very small compared to a typical GM or CL alone. It is shown that the leakage through composite liners with a geosynthetic clay liner (GCL) is typically much less than for composite liners with a compacted clay liner (CCL). Finally, factors that will affect long-term leakage through composite liners are discussed. It is concluded that composite liners have performed extremely well in field applications for a couple of decades and that recent research both helps understand why they have worked so well and provides new insight into issues that need to be considered to ensure excellent long-term liner performance of composite liners — especially for applications where the liner temperature can exceed about 35 °C.

Key words: leakage, composite liner, geosynthetic clay liner, geomembrane, landfill, municipal solid waste, lagoons.

Résumé : Les facteurs qui peuvent influencer à court terme les fuites à travers les étanchéités composites sont examinés. On démontre que les fuites à travers ce type d'étanchéité sont moindres que celles anticipées pour une géomembrane (GM) ou une couche d'argile (CA) seule. Toutefois, les fuites calculées pour les défauts dans une GM mise en contact direct avec une CA sont typiquement beaucoup plus petites que celles observées sur le terrain. On montre que la contribution des fuites calculée en tenant compte de la longueur typique de plis raccordés entre eux explique l'ampleur des fuites observées sur le terrain pour de telles étanchéités composites (GM et CA). Lorsque l'on réduit la présence de longueurs excessives de plis raccordés, les fuites à travers les étanchéités composites peuvent s'avérer très faibles lorsque comparées à celles des GM ou CA utilizées seules. Il est aussi démontré que les fuites à travers les étanchéités composites comportant un géosynthétique bentonique (GSB) sont typiquement bien moindres que pour les étanchéités composites avec une couche d'argile compactée (CAC). Finalement, on discute des facteurs qui affectent les fuites à long terme à travers les étanchéités composites. Les travaux montrent que ces étanchéités composites se sont très bien comportés sur le terrain depuis deux décennies, et que les recherches récentes aident à comprendre les raisons qui expliquent ces bonnes performances. Les études fournissent aussi une nouvelle perception des aspects qui doivent être considérés pour assurer une excellente performance à long terme des étanchéités composites, particulièrement dans le cas où la température peut excéder 35 °C.

Mots-clés : fuites, étanchéités composites, géosynthétique bentonique, géomembrane, site d'enfouissement, déchets solides municipaux, lagons.

Introduction

Composite liners are comprised of a geomembrane (GM) over a clay liner. Typically the clay liner (CL) will be either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL). The composite liner may rest on either a permeable (e.g., drainage) layer or a subsoil that may act as an attenuation layer (AL). GMs used in landfill-related applications are usually high density polyethylene (HDPE) with a thickness typically ranging from 1.5 to 2.5 mm. GCLs (typically <10 mm thick off the roll) come in a variety of forms, but invariably involve a thin layer of bentonite clay that may be glued to a plastic carrier layer, contained between two geotextiles or, in some cases, contained between two geotextiles with a plastic coating–film on one side. The most common GCLs have a geotextile on either side of the bentonite layer and are held together by needle-punching or, in some cases, stitching. These are sometimes called reinforced GCLs because of the presence of the needle-punched or stitched fibres, which place some constraint on the swelling of the GCL as it hydrates in addition to contributing to the internal shear strength of the GCL (both positive attributes). Needle-punched GCLs with bentonite between two geotextiles are the most commonly used GCLs and consequently the discussion of leakage through GCLs in this paper is focused on this

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type of GCL. Unless otherwise noted, the bentonite in the GCLs is natural sodium bentonite. This bentonite is commonly used in North American GCLs, but not necessarily elsewhere. Cost pressures (lowest bid) may affect the quality of bentonite in GCLs unless strict quality requirements are imposed in the GCL specification, especially when good quality natural sodium bentonite is not locally available because of both material and transportation costs. The AL is a subgrade (usually already in place) that must have a hydraulic conductivity $k_A \leq 1 \times 10^{-7}$ m/s to be classified as an attenuation layer.

A composite liner is intended to minimize the migration of fluids (both liquids and gases) by the processes of diffusion and advection. There are a wide range of applications for composite liners, but this paper focuses on their use as bottom liners for municipal solid waste (MSW) landfills and leachate lagoons, although much of the material presented and discussed has a broader range of application.

To some extent, a composite liner takes advantage of the strengths of one material to offset the weaknesses of the other. For example, an intact GM is an excellent barrier to the advective and diffusive migration of fluids such as landfill leachate and many contaminants in the leachate (e.g., volatile fatty acids, sodium, chloride, ammonia, sulphate, iron, lead, zinc, mercury, arsenic, etc. see Rowe et al. 2004; Rowe 2005) — except where it has a hole. Even one relatively small hole (0.5 mm radius) per hectare can result in significant leakage for a GM if there is no hydraulic resistance adjacent to the GM. CCLs and GCLs under ideal conditions can also perform as excellent advective barriers to leachate, but may not be as effective as a diffusion barrier as the GM to the contaminants listed above. In contrast, certain contaminants found in small quantities in leachate (e.g., volatile organic compounds, such as benzene, toluene, dichloromethane, etc.) can readily diffuse through standard HDPE GMs, while a suitable clay liner and attenuation layer can provide much better resistance to their migration (Rowe 2005). Thus the combined use of a GM together with a GCL or CCL and an attenuation layer has the potential to provide excellent diffusive resistance to a wide range of chemicals found in landfill leachate by taking advantage of the better performance of the GM in preventing diffusion of some contaminants and the better performance of the clay liner and attenuation layer in minimizing the migration of other contaminants.

However, the combination of the GM and CL does more than take advantage of the benefits of the two materials — together they act as a composite liner which, as will be shown, demonstrates superior performance than one would expect simply based on the sum of its parts.

The objective of this paper is to explore the factors that can affect the performance of GMs and CLs (with emphasis on GCLs) as part of composite liners for containing MSW leachate both in landfills and leachate lagoons. The paper follows three of the author's past papers that have addressed some of these issues, namely the keynote lecture at the 6th International Conference on Geosynthetics in Atlanta (Rowe 1998), the 45th Rankine Lecture (Rowe 2005), and the 23rd Rocha Lecture (Rowe 2007). This paper will touch on some of the same issues as these three papers — but with an emphasis on highlighting what has been learned with respect to selected topics in the intervening years and addressing the issue of leakage (advective flow) in much more detail than the earlier papers. Thus this paper only deals with a few of the many issues addressed in the previous papers and, except where essential for understanding, does not repeat material in those three papers. The interested reader will find additional information in those papers that is very relevant today and which complements the material presented in this paper. The reader should be aware that each practical project is different and so while the information presented in this paper will provide a guide to issues that should be considered, specific numbers that are presented should not be used for projects without independent verification of their suitability for that particular application or project.

Holes in geomembranes

In the absence of holes, the leakage of water or leachate through a typical 1.5 mm HDPE GM used in landfill applications is negligible. However, experience has shown that it is extremely difficult to ensure no holes exist in practical situations. Holes may arise from: (*i*) manufacturing defects, (*ii*) handling of the GM rolls, (*iii*) on-site placement and seaming, (*iv*) the placement of drainage gravel over the liner system, (*v*) traffic over the liner or the overlying protection layer, (*vi*) placement of the waste in a landfill or cleaning of residue from a leachate lagoon, and (*vii*) stress cracking as the GM ages. Table 1 summarizes the hole sizes reported by Colucci and Lavagnolo (1995). Here 50% of holes had an area of less than 100 mm^2 (equivalent radius r_o < 5.64 mm). Nosko and Touze-Foltz (2000) reported 3 holes/ha following installation and 12 holes/ha following placement of the drainage layer. In principle, holes arising from sources (*i*) through (*iv*) having a radius greater than 0.5 mm should be detected by a water-lance electrical leak detection survey on bare geomembrane, as this is a calibration requirement of the American Society of Testing and Materials (ASTM) standard D7002 (ASTM 2010*a*). For up to 600 mm of soil covering a geomembrane, the suggested calibration for the di-pole survey in ASTM standard D7007 (ASTM 2009*b*), is typically a 6 mm diameter hole although other calibrations can be specified and sensitivity can be increased with tighter measurement spacing and wetter conditions. However, these surveys are not generally required and even then holes can be missed and subsequent holes can develop. Giroud and Bonaparte (2001) suggested that 2.5 to 5 holes/ha be used for design calculations of leakage for GMs installed with strict construction quality assurance.

The holes discussed above represent those present shortly after construction and placing of the waste (or filling of a lagoon with leachate). As will be discussed later, the number of holes may increase in the long term due to ageing of the GM.

Leakage through a geomembrane

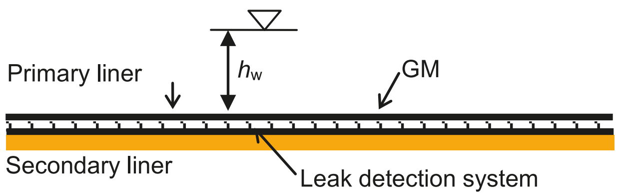
In the absence of hydraulic resistance above and below a GM, and assuming zero head below the GM as may be the case for a single primary GM liner in a double liner system such as shown in Fig. 1, the leakage through a circular hole in a GM is given by Bernoulli's equation

$$[1] \qquad Q = \pi C_B r_o^2 \sqrt{(2gh_w)}$$

Table 1. Reported size of holes in GMs (based on data reported by Colucci and Lavagnolo (1995)).

Leak area (mm^2)	Equivalent radius of circular hole, r_o (mm)	Percentage (%)	Cumulative percentage (%)
0–20	0–2.5	23.2	23.2
20–100	2.5–5.64	26.3	49.5
100–500	5.64–12.6	28.2	77.7
500–10^3	12.6–17.8	8.8	86.5
10^3–10^4	17.8–56.4	7.8	94.3
10^4–10^5	56.4–178	4.5	98.2
10^5–10^6	178–517	1.2	100

Fig. 1. Single GM primary liner over a leak detection system.



where Q is the leakage through the hole (m^3/s), C_B is the coefficient (dimensionless) related to the shape of the edges of the hole with $C_B = 0.6$ for sharp edges (Giroud and Bonaparte 1989*a*), r_o is the radius of the hole (m), g is the acceleration due to gravity (m/s^2), and h_w is the head on the GM (m).

Adopting a typical design head on the liner for landfill applications of $h_w = 0.3$ m and considering a leachate head of $h_w = 5$ m in a lagoon, the leakage through a GM liner, as calculated from eq. [1], for three different hole sizes are given in Table 2. For a landfill with 2.5 to 5 holes/ha having a radius of 0.5 mm, the leakage may range from 250 to 500 lphd (litres per hectare per day). For 2.5 to 5 holes/ha with a radius of 1 mm (area of 3.14 mm^2), the leakage is about 1000 to 2000 lphd and well within the range of values observed for operating landfills with a leak detection system (LDS). For 2.5 to 5 holes/ha with a radius of 5.6 mm (area of 100 mm^2 = 1 cm^2), the leakage is very large (32 000 to 63 000 lphd). Even for the smallest hole, the leakage is higher than is desirable when dealing with containment of contaminated fluids such as leachate. Once the leakage exceeds 1000 lphd it is certainly excessive for landfill applications. As may be inferred from eq. [1], and can be seen from Table 2, increasing the head to what one might expect in a pond just increases the leakage further for each hole size.

Leakage through clay liners

In the absence of a GM, the leakage through a clay liner is given by Darcy's law

[2] $$Q = Ak_L i$$

where Q is the leakage through the liner (m^3/s), A is the area of the liner under consideration (m^2), k_L is the hydraulic conductivity (permeability) of the clay liner (m/s), and i is the hydraulic gradient.

Factors affecting hydraulic conductivity of GCLs

The short-term hydraulic conductivity, k_L, of a GCL will depend (Rowe et al. 2004) on

- the type (e.g., sodium or calcium) and quality of the bentonite and, to some extent, the mass per unit area of bentonite;
- the method of manufacture of the GCL (e.g., whether it is reinforced or glued, the type of geotextiles used to confine the bentonite, whether it is stitch-bonded or needle-punched, if it is thermally treated or if it has a plastic film bonded to it, etc.); and
- the effective stress.

For GCLs with sodium bentonite, manufacturers' specification sheets typically define a maximum k_L of 5×10^{-11} or 3×10^{-11} m/s under standard test conditions (e.g., ASTM standard D5887 (ASTM 2009*a*) or D5084 (ASTM 2010*b*)) that commonly involve a consolidation pressure of 35 kPa, a pressure difference across the specimen of 15 kPa, and a permeant that is de-aired, deionized water (ASTM standard D5887), although de-aired tap water is also used by some manufacturers when using ASTM standard D5084.

In the short term the value of k_L of the GCL in the field will be different from that stated by the manufacturers' specification sheets if there is (Rowe 1998)

- different consolidated stress conditions than in the reference laboratory test (k_L may be slightly higher under low stress conditions such as in a lagoon application or smaller for the high stresses experienced in a typical landfill application);
- bentonite migration down-slope in either a "dry" or hydrated state; or
- lateral movement (thinning) of bentonite during and following hydration that would cause an uneven distribution of the bentonite in the GCL — for example, due to traffic on a partially hydrated GCL before it is covered or wrinkles in a GM that may create an area of reduced bentonite in an underlying GCL (Stark 1998).

In addition to the factors noted above, the long-term k_L value for a GCL in the field may be different from that in the manufacturer's literature if there is

- interaction between the leachate permeating the GCL and the bentonite in the GCL (e.g., Rad et al. 1994; Petrov et al. 1997; Petrov and Rowe 1997; Ruhl and Daniel 1997; Rowe 1998, 2007; Shackelford et al. 2000; Jo et al. 2001, 2004, 2005; Schroeder et al. 2001; Kolstad et al. 2004; Guyonnet et al. 2005, 2009; Katsumi et al. 2007; Rauen and Benson 2008; Musso and Pejon 2010);
- loss or internal erosion of bentonite into underlying subsoil or drainage layers (Rowe and Orsini 2003) — an

Table 2. Calculated leakages through a GM liner (all calculated leakages are rounded to two significant digits).

			Q (lphd)	
h_w (m)	r_o (mm)	a (mm^2)	2.5 holes/ha	5 holes/ha
0.3	0.5	0.79	250	500
	1	3.14	1000	2000
	5.64	100	32 000	63 000
5	0.5	0.79	1000	2000
	1	3.14	4000	8000
	5.64	100	130 000	260 000

additional geotextile filter may be required to avoid bentonite loss for some GCLs (Estornell and Daniel 1992); or

- cation exchange with carbonate in the bentonite as is found, for example, in some sodium-activated calcium bentonites (e.g., Egloffstein et al. 2002; Guyonnet et al. 2009) or divalent cations in the adjacent soil or pore water (e.g., James et al. 1997), especially if combined with wet–dry cycles (e.g., Melchior 1997; Lin and Benson 2000; Meer and Benson 2007; Benson et al. 2010; Scalia and Benson 2011).

Rowe (1998) tabulated data from a number of papers for eight different GCLs containing natural sodium bentonite. The hydraulic conductivity with respect to water ranged from 5×10^{-11} m/s at "low" (3 to 4 kPa) confining stress to 1×10^{-11} m/s at "intermediate" (34 to 38 kPa) confining stress and 7×10^{-12} m/s at "high" (109 to 117 kPa) confining stress.

When GCLs are permeated with salt solutions or simulated or real MSW leachates, the confining stress at the time of hydration and the hydrating fluid can have a significant effect on the final hydraulic conductivity as shown in a number of the papers cited above. For example, Petrov and Rowe (1997) showed that a GCL hydrated with de-aired, deionized water at 3 to 4 kPa and then permeated with a 0.1 mol/L NaCl solution (Na^+ ~2300 mg/L) at the same low stress level had a hydraulic conductivity of 1×10^{-10} m/s, whereas the same GCL hydrated at the same stress but permeated with a 0.1 mol/L NaCl solution at higher stress (112 kPa) had a hydraulic conductivity of 1.5×10^{-11} m/s (about one order of magnitude lower), and a sample hydrated with water and then permeated with 0.1 mol/L NaCl all at 108 kPa had a hydraulic conductivity of 0.7×10^{-11} m/s. Thus it is important to carefully consider the hydrating conditions and final stress level when selecting the hydraulic conductivity of the GCL to be used for calculating leakage on a given project. It also follows that for a given GCL, the hydraulic conductivity relevant to a liner on the bottom of a landfill may be lower than for the same GCL being used in a leachate holding or treatment pond.

The chemical composition of the permeating fluid can have a very significant effect on the hydraulic conductivity of a GCL as has been demonstrated by many of the papers cited above. A great deal has been published on the interaction of GCLs with simple salt solutions (predominantly NaCl, $CaCl_2$, and to a lesser extent KCl); relatively little work has been done on simulated MSW leachates. Rowe (1998) summarized what had been done by 1998. Most of the comparable data was at about 30 to 35 kPa, at which stress Ruhl and Daniel (1997) reported $k_L < 1 \times 10^{-12}$ m/s for a real MSW leachate (see Rowe 1998 for a discussion of this low value), but a very high $k_L = 2 \times 10^{-8}$ m/s for a very aggressive "synthetic leachate." This synthetic leachate was not based on any real landfill leachate, but rather was prepared with high cation concentrations that would greatly increase the value of k_L for the sodium bentonite being tested. At the same stress, Petrov and Rowe (1997) reported $k_L = 7 \times 10^{-11}$ m/s for a synthetic leachate based on the composition of the Keele Valley landfill leachate at that time. Shan and Lai (2002) reported tests at 35 kPa for a GCL hydrated and permeated with a simulated MSW leachate, which gave $k_L = 2.6 \times 10^{-11}$ and 3.0×10^{-11} for two different GCLs. Lange et al. (2010) reported tests at 25 kPa for a GCL hydrated with water and permeated with a simulated MSW leachate, which gave $k_L = 4 \times 10^{-11}$ m/s. Other papers addressing this issue have been published by Schroeder et al. (2001), Guyonnet et al. (2005, 2009), Katsumi et al. (2007), Rauen and Benson (2008), and Rosin-Paumier et al. (2011).

Rauen and Benson (2008) examined GCLs permeated with both real conventional and real recirculated leachate for 1 year at 70 kPa. They reported $k_L \leq 1 \times 10^{-11}$ m/s for conventional leachate and $k_L \leq 0.7 \times 10^{-11}$ m/s for recirculated leachate. Guyonnet et al. (2009) examined a number of GCLs with bentonite from different continents (North America, Europe, India, and Australia). In each case the GCL was prehydrated with a 10^{-3} mol/L NaCl solution and then permeated with synthetic or real landfill leachate at confining stresses of 25, 50, and 100 kPa. When permeated with synthetic leachate, values of $k_L \leq 4.5 \times 10^{-11}$ m/s were reported for 100 kPa for five of six GCLs with natural and activated sodium bentonite examined, but $k_L = 1 \times 10^{-10}$ m/s was reported for one case. When permeated with real leachate the values of k_L were lower than that for synthetic leachate with $k_L \leq 4.4 \times 10^{-11}$ m/s at 100 kPa or all-natural or activated sodium bentonite. They reported that in one case a GCL, which the manufacturer claimed contained natural bentonite, actually contained activated bentonite. In another case the so-called bentonite had a smectite content of less than 30% by weight and the most abundant clay mineral was kaolinite. This GCL had a cation exchange capacity of 38 meq/100g. These two examples highlight the need for vigilance in checking the bentonite delivered to a site. This is especially important in a competitive global economy where lowest bid sometimes results in the delivery of a material different to that expected, but unless one has appropriate construction quality control and assurance (CQC/CQA), one may not know until it is too late. Guyonnet et al. (2009) recommended minimum performance-based indicators for selecting GCLs for use in landfill applications. These indicators included requiring a minimum swell index (SI ≥ 24 mL/2g) and cation exchange capacity (CEC ≥ 75 meq/100g), and a maximum calcite content (≤5% by weight).

Based on a review of the available data, the "typical" or "base case" value of k_L for consideration in this paper was taken to be the typically specified $k_L = 5 \times 10^{-11}$ m/s as it represents a reasonable value for GCLs permeated with water at low (3 to 4 kPa) stress levels, but also closely approximates the values obtained for GCLs permeated with a realistic simulated MSW leachate at stresses of 25 to 35 kPa (e.g., Petrov and Rowe 1997; Shan and Lai 2002; Lange et al. 2010; as noted above) and is conservative with respect to tests using real leachate noted above. It is recognised that, especially at low confining stress, permeation with leachate having high cation concentrations (or cation exchange with cations in an adjacent soil) could result in higher hydraulic conductivities and a value of $k_L = 2 \times 10^{-10}$ m/s was selected as a second base case. To assess the effect of k_L on leakage, additional calculations were performed for $k_L = 7 \times 10^{-12}$ m/s as a lower bound, $k_L = 1 \times 10^{-10}$ m/s as an intermediate, and $k_L = 2 \times 10^{-8}$ m/s as an upper bound based on the very aggressive synthetic leachate used by Ruhl and Daniel (1997).

Given the importance of the hydration of a GCL prior to contact with leachate on its long-term hydraulic performance, it is surprising that the hydration of GCLs from the underlying subsoil has received very little attention and it is simply assumed that they will be adequately hydrated by the time they need to perform their containment function. Daniel et al. (1993) showed that, when placed on sand at 3% gravimetric moisture content, an initially air-dry GCL reached 88% moisture content after 40 to 45 days. Eberle and von Maubeuge (1998) showed that an initially air-dry GCL placed over sand with a moisture content of 8% to 10% reached a moisture content of 100% in less than 24 h and 140% after 60 days. However, Rayhani et al. (2011) showed much slower hydration for three different needle-punched GCLs on underlying sand and silty sand of up to 70 weeks. They demonstrated that the initial moisture content of the subsoil can have a large effect on the rate of hydration and the final equilibrium GCL moisture content. For example, GCLs on subsoil with initial moisture contents close to field capacity hydrated quickly and their final moisture contents were essentially the same as if the GCL had been immersed in water. In contrast, GCLs on the subsoil at an initial moisture content close to their residual moisture content (5% for the silty sand and 2% for the sand considered) only hydrated to a gravimetric moisture content of 30% to 35%, which is about one-quarter of the fully hydrated value.

Rayhani et al. (2011) also demonstrated that the method of GCL manufacturing had a significant effect on both the rate of GCL hydration and the final GCL moisture content when the subsoil had low moisture contents. This difference was related to different water retention curves for the three GCLs (Beddoe et al. 2011), the difference in confinement of the bentonite provided by different carrier geotextiles, and the presence or absence of thermal treatment of the needle-punched fibres. The best hydration performance was observed for GCLs manufactured with a scrim-reinforced and thermally treated nonwoven carrier geotextile. One of the GCLs had coarse granules (D_{60} = 1.1 mm) and two had fine granules (D_{60} = 0.35 mm). There was no apparent significant difference in hydration performance related to the granule size. The effect of having powdered versus granular bentonite was not examined in this study.

Factors affecting hydraulic conductivity of CCLs

Much has been written on compacted clay liners (see Rowe et al. 2004 for a review). The short-term hydraulic conductivity, k_L, of a CCL will depend (Rowe et al. 2004) on

- plasticity and grain-size distribution of the soil;
- moisture content at which it is compacted;
- method of compaction; and
- effective stress.

In the long term, the value of k_L will depend on (*i*) interaction between the leachate permeating the CCL and the clay minerals and (*ii*) desiccation.

Desiccation results from drying of the clay from its as-compacted state and may be especially severe for CCLs compacted near or above the plastic limit. Desiccation may occur (*i*) after construction of the clay liner and before placing the GM (Figs. 2 and 3), (*ii*) after placing the GM and before covering with the drainage layer, and (or) (*iii*) after placing the waste.

These issues have been discussed by Rowe et al. (2004) and Rowe (2005) and are elaborated further later in this paper. Based on experience (e.g., Benson et al. 1994, 1999; Daniel and Koerner 1995; Rowe et al. 2004), CCLs typically have a design $k_L = 1 \times 10^{-9}$ m/s. Well-constructed liners may achieve $k_L = 5 \times 10^{-10}$ m/s or even $k_L \leq 1 \times 10^{-10}$ m/s after consolidation (Rowe 2005); however, CCL may also have $k_L = 1 \times 10^{-8}$ m/s unless great care is taken in the selection of the soil and compaction. These values will be used to calculate leakage in some of the following sections.

Calculated leakage through clay liners

Table 3 gives the calculated leakage for a primary clay liner in a double liner system where the primary liner is underlain by a leak detection layer to collect the leakage through the primary liner (Fig. 4). Leakages are given for a typical CCL design $k_L = 1 \times 10^{-9}$ m/s and thickness H_L = 0.6 m and a typical GCL $k_L = 5 \times 10^{-11}$ m/s and H_L = 0.01 m, assuming zero head below the liner (h_a = 0 m) and no attenuation layer (H_A = 0 m). Under these circumstances, the leakage through the GCL and CCL are very similar — both about 1300 lphd. This is within the range expected for a GM alone having 2.5 to 5 holes (r_o = 1 mm) per hectare (Table 2).

If the GCL was resting on a 0.59 m thick attenuation layer (AL, $k_A = 1 \times 10^{-7}$ m/s; Fig. 5) such that the total thickness and average gradient was the same as for the CCL (Table 3), then for the landfill liner application (h_w = 0.3 m), the leakage with the GCL is almost three times the CCL leakage for the assumed hydraulic conductivities — this will be discussed later.

Considering a single clay liner resting on a subsoil (AL; Fig. 5) of thickness H_A, such that the total distance between the top of the liner and the underlying receptor aquifer is $H_L + H_A$ = 3.75 m (the minimum allowed under Ontario Regulation 232/98 (Ontario Ministry of the Environment

Fig. 2. Desiccation cracking of CCL before the GM is placed.

Fig. 3. Compacted clay liner (forming part of a composite liner) that has desiccated (photo courtesy of P. Davies).

Table 3. Calculated leakage through a single primary clay liner for typical design hydraulic conductivity (GCL k_L = 5×10^{-11} m/s, H_L = 0.01 m; CCL k_L = 1×10^{-9} m/s, H_L = 0.6 m). Refer to Figs. 4 and 5.

			Q (lphd)	
Liner	H_A (m)	h_a (m)	h_w = 0.3 m	h_w = 5 m
GCL	0	0	1300	22 000
CCL	0	0	1300	8000
GCL	0.59	0	3800	23 000
GCL	3.74	3	3800	21 000
CCL	3.15	3	1400	7900

1998)), and assuming that the potentiometric surface is 3 m above the aquifer (h_a = 3 m), the leakage can also be calculated based on Darcy's law

$$[3a] \quad Q = Ak_s i_s$$

where

$$[3b] \quad k_s = (H_L + H_A)/[(k_L/H_L) + (k_A/H_A)]$$

Fig. 4. Single primary clay liner over a LDS.

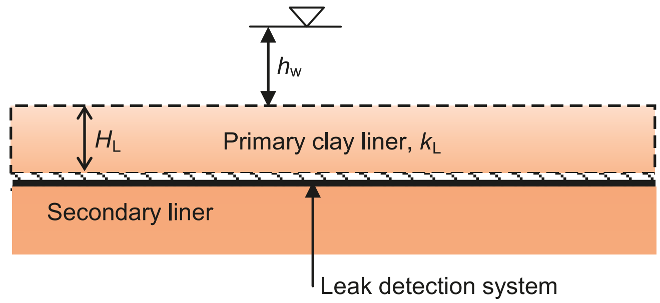
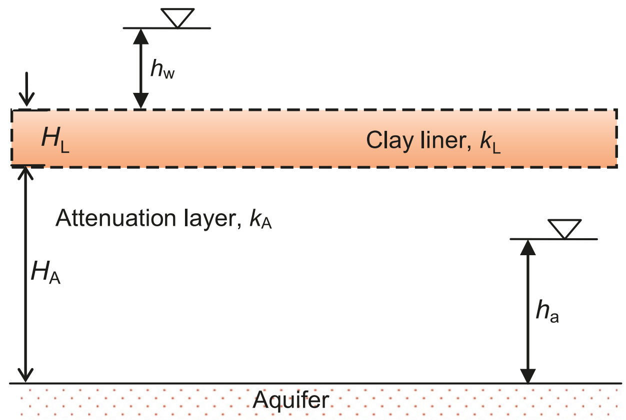


Fig. 5. Clay liner over an attenuation layer and aquifer.



is the harmonic mean hydraulic conductivity of the clay liner and attenuation layer (m/s) and

$$[3c] \quad i_s = (h_w + H_L + H_A - h_a)/(H_L + H_A)$$

is the average hydraulic gradient (dimensionless) across the CL and AL. The leakage for the GCL and CCL for this case is given in the last two rows of Table 3. Again, for these parameters, the leakage through the single GCL is greater than for the CCL.

In a lagoon application (h_w = 5 m; Table 3) the leakages are higher due to the higher gradients, but the trends are the same as discussed above except for the GCL alone, which now gives much greater leakage (due to the much higher gradient) than the CCL alone.

A key parameter in assessing the performance of a single clay liner is the hydraulic conductivity. The hydraulic conductivity of a GCL or CCL can vary depending on many factors as discussed earlier. The leakages calculated using typical upper bounds for bottom liner applications discussed in this paper (k_L = 2×10^{-10} m/s for the GCL and k_L = 1×10^{-8} m/s for the CCL — under extreme conditions higher values are possible) are given in Table 4. For the "typical" worst case conditions (Table 4), the GCL performs about the same as the CCL except for the case of a primary liner in a double lined system (rows 1 and 2 of Table 4), where the GCL performs substantially better than the CCL for the landfill liner case.

Just as the hydraulic conductivity can be worse than typical design parameters it can also be better (especially in landfill bottom liners when there is significant applied stress; see Rowe et al. 2004). The leakages calculated for the cases

Table 4. Calculated leakage through a single primary clay liner for upper bound hydraulic conductivity (GCL $k_L = 2 \times 10^{-10}$ m/s, $H_L = 0.01$ m; CCL $k_L = 1 \times 10^{-8}$ m/s, $H_L = 0.6$ m). Refer to Figs. 4 and 5.

			Q (lphd)	
Liner	H_A (m)	h_a (m)	$h_w = 0.3$ m	$h_w = 5$ m
GCL	0	0	5400	87 000
CCL	0	0	13 000	81 000
GCL	0.59	0	14 000	87 000
GCL	3.74	3	10 000	57 000
CCL	3.15	3	9900	54 000

discussed above, but using typical lower bounds of hydraulic conductivity ($k_L = 7 \times 10^{-12}$ m/s for a GCL and $k_L = 1 \times 10^{-10}$ m/s for a CCL), are given in Table 5. As might be expected, the leakages are substantially reduced compared to the typical design parameters (Table 3).

The examples discussed above serve to illustrate two points. First, when a clay liner is used as a single liner it is very important to consider the factors that can affect hydraulic conductivity and adopt a design value relevant to the expected conditions at the site, as they may be quite different to "typical" values obtained by permeating a GCL or CCL with water in the laboratory (Rowe et al. 2004). For example, hydraulic conductivity values can be significantly affected by both the permeant and stress (Petrov and Rowe 1997). Thus the hydraulic conductivity in a bottom liner application with 50 m of overlying waste may be quite different to that in a leachate lagoon application. Second, in many of the cases considered above, the leakage exceeds what would normally be considered acceptable in terms of potential impact on an underlying aquifer.

Leakage through composite liners

Except perhaps for the very best conditions, the leakages reported in the two previous sections for both a single GM and single CL generally exceed desirable values. A common means of reducing the leakage is to use the GM and CL together to form a composite liner as illustrated schematically in Figs. 6 and 7. The schematics show the GM in direct contact with the underlying CL and Fig. 8 shows a photo of this situation at the Queen's University Environmental Liner Test Site (QUELTS) located in Godfrey, Ontario. Leakage through a hole in a composite liner for this direct contact situation will be discussed in the following subsection.

Solutions for GM in direct contact with clay liner

Rowe (2005) reviewed the many methods (empirical, analytical, and numerical) for calculating leakage through a GM with a hole in direct contact with the clay liner. Probably the most commonly used of these methods are the ones using empirical equations (e.g., Giroud and Bonaparte 1989*b*; Giroud 1997) established by curve-fitting families of solutions from analytical equations for the situation shown schematically in Fig. 9. These solutions assume that there is a zone between the GM and CL with transmissivity, θ.

The transmissive zone between the GM and CL arises due to small irregularities at the interface (as discussed below) between the two materials that will allow fluid to migrate a distance called the wetted radius from the hole and then move by advection through the underlying liner. Thus the leakage, *Q*, will depend on (*i*) the size of the hole, (*ii*) the head difference across the liner, (*iii*) the hydraulic conductivity of the clay liner, and (*iv*) the transmissivity of the interface between the GM and CL. The very important new parameter here is the transmissivity of the interface.

Interface transmissivity

The irregularities at the interface between a GM and CCL may arise from many sources including small stones or clay clods on the surface, indentations made by tires or the edge of a smooth drum roller, cracks (e.g., due to desiccation) in the surface of the clay, etc. Cartaud et al. (2005) reported that the interface between 2 mm thick HDPE GM and a CCL could vary from direct contact to as much as a 10 mm gap within a 1 m^2 area. Giroud and Bonaparte (1989*b*) defined two types of GM–CCL contacts — "good" and "poor" — and Rowe (1998) related these descriptors to transmissivities of the GM–CCL interface

1. for good contact

$$\log_{10}\theta = 0.07 + 1.036(\log_{10}k_L) + 0.0180(\log_{10}k_L)^2 \quad [4]$$

2. for poor contact

$$\log_{10}\theta = 1.15 + 1.092(\log_{10}k_L) + 0.0207(\log_{10}k_L)^2 \quad [5]$$

where transmissivity, θ, is in m^2/s and CCL hydraulic conductivity, k_L, is in m/s. For a typical CCL design hydraulic conductivity $k_L = 1 \times 10^{-9}$ m/s, this corresponds to a transmissivity of 1.6×10^{-8} m^2/s for good contact and 1×10^{-7} m^2/s for poor contact. These values are used in the calculations described later. These relationships consider only minor local irregularities and do not consider major desiccation of CCLs (Figs. 2 and 3) or significant wrinkles in the GM to be discussed later.

The results for GM–GCL interface transmissivity reported by Harpur et al. (1993) at 7 kPa (a stress relevant to some lagoon applications) and 70 kPa are given in Table 6 together with values for a stress at 50 kPa reported by Barroso et al. (2008, 2010) and Mendes et al. (2010).

The method of manufacture of the GCL had some influence on the results, with the lowest transmissivity values being for a GCL with bentonite glued to a plastic carrier layer such that the bentonite was in direct contact with the GM.

Harpur et al. (1993) only examined one GCL with a nonwoven geotextile (N) in contact with the GM and obtained relatively high values of transmissivity (1×10^{-10} m^2/s at 7 kPa and 8×10^{-11} m^2/s at 70 kPa); however, many other tests indicated in Table 6 for GCLs with a similar construction gave much lower values with an average of 2.2×10^{-11} m^2/s based on five tests on four different GCLs at 50 kPa.

Harpur et al. (1993) examined three GCLs with a woven geotextile (W) in contact with the GM and obtained relatively wide-ranging values of transmissivities (3×10^{-11} to 2×10^{-10} m^2/s at 7 kPa and 6×10^{-12} to 1×10^{-11} m^2/s at 70 kPa). How-

Table 5. Calculated leakage through a single primary clay liner for lower bound hydraulic conductivity (GCL k_L = 7×10^{-12} m/s, H_L = 0.01 m; CCL k_L = 1×10^{-10} m/s, H_L = 0.6 m). Refer to Figs. 4 and 5.

			Q (lphd)	
Liner	H_A (m)	h_a (m)	h_w = 0.3 m	h_w = 5 m
GCL	0	0	190	3000
CCL	0	0	130	810
GCL	0.59	0	540	3400
GCL	3.74	3	620	3400
CCL	3.15	3	150	820

Fig. 6. Primary composite liner over a LDS.

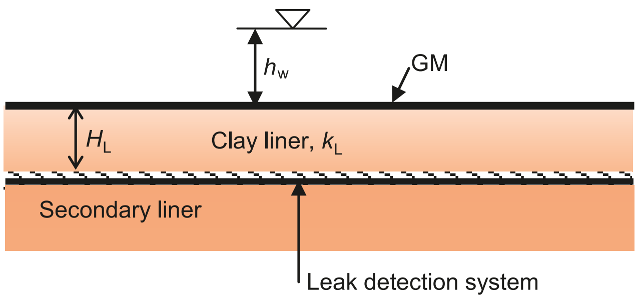
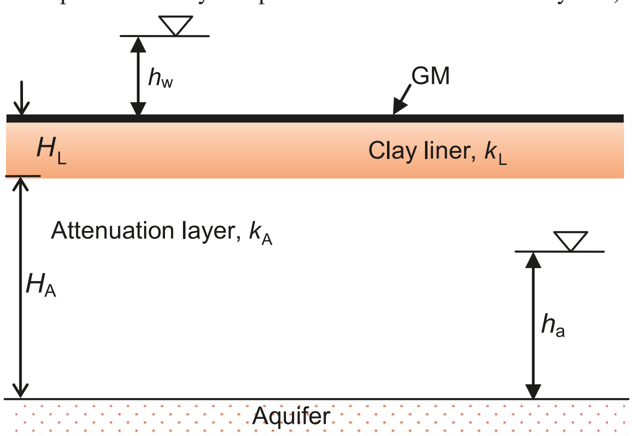


Fig. 7. Single composite liner over an attenuation layer and aquifer (also depicts secondary composite liner in a double lined system).



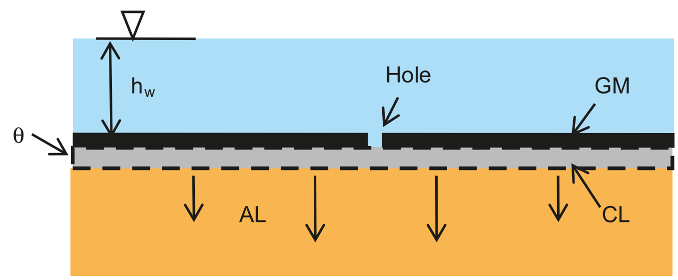
ever, four other tests summarized in Table 6 for a woven geotextile in contact with the GM gave quite consistent values, with an average of 2.3×10^{-11} m^2/s.

Barroso et al. (2008) examined the effect of the GM surface on transmissivity, examining one smooth and three different textured GMs in contact with the same GCL (N–F; Table 6) and the range of transmissivities was relatively small (1.4×10^{-11} to 3.7×10^{-11} m^2/s at 50 kPa) with an average of 2.5×10^{-11} m^2/s.

Barroso et al. (2010) studied the effect of confining stress on interface transmissivity between a smooth GM and a GCL with a nonwoven cover geotextile in contact with the GM. Based on five tests at stresses between 25 and 200 kPa, they found very little difference with the highest value of θ = 1.4×10^{-11} m^2/s at 25 kPa and values between 7.8×10^{-12} and 1.2×10^{-11} m^2/s between 50 and 200 kPa.

Fig. 8. Photo of a GM in direct contact with the underlying GCL liner at QUELTS at 0700 on a cool October morning. Note: right–left distance from toe of slope to anchor trench is about 20 m.

Fig. 9. Schematic showing leakage, Q, through a hole in a GM over a CL.



Mendes et al. (2010) examined the effect of bentonite on interface transmissivity. Two different calcium bentonite GCLs having hydraulic conductivities of 5.8×10^{-8} m/s (mass per unit area, M_A = 5730 g/m^2) and 6.9×10^{-10} m/s (M_A = 10590 g/m^2) at 50 kPa had remarkably similar transmissivities (θ = 3.0×10^{-11} and 2.8×10^{-11} m^2/s, respectively). The two other sodium bentonite GCLs, having hydraulic conductivities of 3.2×10^{-11} m/s (M_A = 5410 g/m^2) and 1.6×10^{-11} m/s (M_A = 7400 g/m^2), had an average transmissivity of 2.3×10^{-11} m^2/s. For these GCLs, a 3600-fold difference in hydraulic conductivity of the GCL increased the leakage by only 15% and a 2.5-fold increase in hole size increased the leakage by only 17%.

Based on the foregoing, it appears that the reported GM–GCL interface transmissivity for reinforced GCLs (needle-punched and stitch-bonded) may vary between a high of 2×10^{-10} m^2/s and a low of 6×10^{-12} m^2/s with an average of about 4×10^{-11} m^2/s for all the reinforced GCL data and about 2×10^{-11} m^2/s for all the sodium bentonite data at 50 kPa. Although higher stress may give slightly lower transmissivity, there was no strong trend. Likewise, the geotextile in contact with the GM and the hydraulic conductivity of the GCL had very little effect on the interface transmissivity. Finally, the recent experimental data suggest that the interface transmissivity rather than the hydraulic conductivity of the GCL controls the leakage through a composite liner with a hole in a GM in direct contact with a GCL, confirming predictions made by Rowe (1998).

Table 6. Published GM–GCL interface transmissivities (GCLs needle-punched and containing sodium bentonite unless otherwise noted).

GM–GCL contact	θ at 7 kPa (m^2/s)	θ at 50 kPa (m^2/s)	θ at 70 kPa (m^2/s)
S–Bentonite[a]	2×10^{-12}	—	2×10^{-12}
S–W–B[a]	3×10^{-11}	—	9×10^{-12}
S–W–C[a]	8×10^{-11}	—	6×10^{-12}
S–W–D[a]	2×10^{-10}	—	1×10^{-10}
S–N–E[a]	1×10^{-10}	—	8×10^{-11}
S–N–F[b]	—	2.2×10^{-11}	—
TSO–N–F[b]	—	3.7×10^{-11}	—
TEH–N–F[b]	—	1.4×10^{-11}	—
TDS–N–F[b]	—	1.8×10^{-11}	—
S–N–G[c]	—	1.1×10^{-11}	—
S–N–H[d]	—	2.4×10^{-11}	—
S–N–H[d]	—	2.1×10^{-11}	—
S–W–SB[d]	—	2.6×10^{-11}	—
S–W–SB[d]	—	1.9×10^{-11}	—
S–N–CB1[d]	—	3.0×10^{-11}	—
S–W–CB2[d]	—	2.8×10^{-11}	—
S–W–CB2[d]	—	2.7×10^{-11}	—

Note: Bentonite, bentonite glued to a plastic carrier layer with bentonite in direct contact with the GM; S, smooth GM; TDS, textured GM; TSO, textured GM with "sprayed-on" texture; TEH, textured GM with "embossed honeycomb" texture; W, woven geotextile in contact with GM; N, nonwoven geotextile in contact with GM; –B, GCL product B, etc.; SB, product is stitch-bonded; GCL–F: $k_L = 3.7 \times 10^{-11}$ m/s at 50 kPa; $M_A = 5000$ g/m^2; GCL–H: $k_L = 1.6 \times 10^{-11}$ m/s at 50 kPa, $M_A = 7400$ g/m^2; GCL–SB: $k_L = 3.2 \times 10^{-11}$ m/s at 50 kPa, $M_A = 5410$ g/m^2; GCL–CB1: calcium bentonite and $k_L = 5.8 \times 10^{-8}$ m/s at 50 kPa, $M_A = 5730$ g/m^2; GCL–CB2: calcium bentonite and $k_L = 6.9 \times 10^{-10}$ m/s at 50 kPa, $M_A = 10\,590$ g/m^2.

[a]Harpur et al. (1993).

[b]Barroso et al. (2008).

[c]Barroso et al. (2010).

[d]Mendes et al. (2010).

Calculated leakage through a hole in a GM in direct contact with clay liner

Once an estimate can be made of the interface transmissivity, the leakage through a hole in a GM liner in direct contact with an underlying clay liner forming a primary composite liner in a double lined system can be calculated and compared with the leakages calculated earlier for a GM or CL alone using the analytical solution developed by Rowe (1998). The calculated leakages are given in Tables 7 and 8 and discussed below.

Considering firstly a composite liner with a GCL over a 0.6 m thick AL for a 5.6 mm radius hole (a = 100 mm^2) in the GM, Table 7 summarizes the calculated leakage for a range of values of k_L, θ, and h_w for 2.5 and 5 holes/ha. For a typical "upper bound" GCL hydraulic conductivity of 2×10^{-10} m/s as examined in Table 4, the leakage for the extreme range of transmissivities reported in the literature (6×10^{-12} to 2×10^{-10} m^2/s; Table 6) for a typical design head on a landfill liner (h_w = 0.3 m) ranged between a low of 0.003 lphd and a high of 0.08 lphd (Table 7) as compared to 14 000 lphd for a GCL with $k_L = 2 \times 10^{-10}$ m/s on a 0.59 m AL (Table 4) and 32 000 to 63 000 lphd for the GM alone (Table 2). Similarly, considering a pond application (h_w = 5 m), the leakage ranged between a low of 0.03 lphd and a high of 0.9 lphd as compared to 87 000 lphd for a GCL with $k_L = 2 \times 10^{-10}$ m/s on a 0.59 m AL (Table 4) and 130 000 to 260 000 lphd for the GM alone.

Compared with the most optimistic value of $k_L = 7 \times 10^{-12}$ m/s for the GCL, but poor interface transmissivity (1×10^{-10} m^2/s) for the composite liner, the calculated leakages (for 5 holes/ha) of 0.02 lphd for h_w = 0.3 m and 0.3 lphd for h_w = 5 m are very small compared to about 190 lphd and 3000 lphd for a GCL alone with $k_L = 7 \times 10^{-12}$ m/s (Table 5). This demonstrates the potentially vast reduction in leakage that can be obtained with a composite liner involving a GCL compared with either a GCL or GM alone in the base liner of a landfill or leachate lagoon.

The results in Table 7 also show that for a given value of $k_L = 2 \times 10^{-10}$ m/s, a 30-fold increase in θ (6×10^{-12} to 2×10^{-10} m^2/s) increased leakage by a factor of about 14 while for a given value of $\theta = 1 \times 10^{-10}$ m^2/s, an almost 3000-fold increase in k_L, only increased leakage by a factor of about 5. Thus for a composite liner where the GM is in direct contact with the GCL, it is the interface transmissivity rather than the hydraulic conductivity of the GCL that controls leakage for typical values of transmissivity.

Considering, secondly, a composite liner with a CCL and a hole in the GM, Table 8 summarizes the calculated leakage for a typical design $k_L = 1 \times 10^{-9}$ m/s, good contact conditions, and h_w of 0.3 and 5 m for both 2.5 and 5 holes/ha. For a landfill bottom liner with h_w = 0.3 m, the leakage for a CCL alone (Table 3) was 1300 lphd and for a GM alone with 5 holes/ha was 2000 and 63 000 lphd for a small (r_o = 1 mm) and large (r_o = 5.64 mm) hole, respectively (Table 2).

Table 7. Leakage through a hole in a GM for composite liner with GCL and AL: $H_L = 0.01$ m, $H_A = 0.6$ m, $h_a = 0$ m, large hole: $r_o = 5.64$ mm, $a = 100$ mm^2.

			Q (lphd)	
k_L (m/s)	θ (m^2/s)	h_w (m)	2.5 holes/ha	5 holes/ha
2×10^{-10}	6×10^{-12}	0.3	0.003	0.006
		5.0	0.033	0.066
2×10^{-10}	2×10^{-10}	0.3	0.04	0.08
		5.0	0.47	0.94
7×10^{-12}	1×10^{-10}	0.3	0.01	0.02
		5.0	0.17	0.34
2×10^{-10}	1×10^{-10}	0.3	0.02	0.04
		5.0	0.27	0.54
2×10^{-8}	1×10^{-10}	0.3	0.09	0.18
		5.0	0.85	1.7

Table 8. Leakage through a hole in a GM for composite liner with CCL: $H_L = 0.6$ m, $h_a = 0$ m, $k_L = 1 \times 10^{-9}$ m/s, good contact: $\theta = 1.6 \times 10^{-8}$ m^2/s.

	Q (lphd): small hole, 1 mm radius, 3.14 mm^2 area		Q (lphd): large hole, 5.64 mm radius, 100 mm^2 area	
h_w (m)	2.5 holes/ha	5 holes/ha	2.5 holes/ha	5 holes/ha
0.3	1.0	2.0	1.3	2.6
5.0	14	26	18	36

In comparison, for a composite liner with a similar CCL, the calculated leakage was only 2 and 2.6 lphd for a small and large hole, respectively (Table 8).

For a leachate lagoon liner with $h_w = 5$ m, the leakage for a CCL alone (Table 3) was 8000 lphd and for a GM alone with 5 holes/ha was 8000 and 260 000 lphd for a small and large hole, respectively (Table 2). In comparison, for a composite liner with a similar CCL, the calculated leakage was only 26 and 36 lphd for a small and large hole, respectively (Table 8).

Thus, as was found with a GCL, it is also evident that with a CCL the performance of a composite liner is substantially better than a CCL or GM liner used alone.

Comparison between leakage observed and calculated through composite liners where the GM is in direct contact with clay liner

The calculations for a composite liner with a GM in direct contact with a CL presented in the previous section suggest that composite liners are remarkably good — but the question remains as to how well do these calculations compare with reality? Considering primary composite liners in a double lined landfill system (Fig. 6) where there is a LDS, the leakage can be calculated for different conditions and compared with what has actually been observed in well-documented landfills. Table 9 presents one such comparison; Rowe (2005) presents others.

For a composite liner with a 0.9 m thick CCL, calculations are presented for 5 holes/ha ($r_o = 5.64$ mm) for excellent conditions ($k_L = 1 \times 10^{-10}$ m/s and good contact with $\theta = 1.6 \times 10^{-8}$ m^2/s) and marginal conditions ($k_L = 1 \times 10^{-9}$ m/s and poor contact with $\theta = 1 \times 10^{-7}$ m^2/s), together with the range of observed average monthly flows and the peak flow for a number of similar liners (Table 9). Even the worst case calculation is well below the lowest average monthly flow for the actual landfills considered and an order of magnitude below the peak flow.

For a composite liner with a GCL, the calculated leakage for good conditions ($k_L = 5 \times 10^{-11}$ m/s; $\theta = 2 \times 10^{-12}$ m^2/s) and poor conditions ($k_L = 2 \times 10^{-10}$ m/s; $\theta = 2 \times 10^{-10}$ m^2/s) are consistent with the low end of the range, but two to four orders of magnitude below the upper end of the range and three to four orders of magnitude below the peak flows (Table 9).

The results presented here further illustrate the point made by Rowe (2005) that calculations of leakage for composite liners assuming direct contact between the GM and the CL significantly (i.e., by one or more orders of magnitude) underestimate the actual leakage in typical North American landfills. Rowe (2005) postulated that the reason for the discrepancy was that GMs in North American landfills are not generally in direct contact with the CL (i.e., at the time covered they do NOT look like the GM in Fig. 8), but rather there are wrinkles that, if coincident with a hole, would substantially increase leakage. Rowe (2005) showed theoretically that the Rowe (1998) equation for leakage through wrinkles could explain the observed leakage, but at that time there was very little data available to confirm the length of connected wrinkles that were required to explain the observed leakage; as indicated below, that data is now available.

Wrinkles in HDPE geomembranes

Although it has long been recognised that HDPE GMs experience significant thermal expansion and consequent wrinkling (waves) upon heating (e.g., Giroud and Peggs 1990; Giroud and Morel 1992; Pelte et al. 1994; Giroud 1995;

Table 9. Comparison between observed and calculated leakage (direct contact solution) during the active period for 0.9 m thick CCL and 0.01 m thick GCL in a primary liner over a geonet LDS.

				Observed leakage (lphd)[b]	
Liner	k_L (m/s)	θ (m^2/s)	Calculated leakage[a]	Range[c]	Peak[d]
CCL	1×10^{-10}	1.6×10^{-8}	6	60–160[e]	390[e]
	1×10^{-9}	1×10^{-7}	40	60–160	390
GCL	5×10^{-11}	2×10^{-12}	0.001	0–11	54
	2×10^{-10}	2×10^{-10}	0.06	0–11	54

[a]Hole $r_o = 5.6$ mm; $h_w = 0.3$ m, $h_a = 0$ m; $H_A = 0$ m, 5 holes/ha; calculations rounded to one significant figure.

[b]Bonaparte et al. (2002).

[c]Weighted average flow based on data from Bonaparte et al. (2002).

[d]Maximum peak flow.

[e]Specifically for 0.9 m CCL in Table 4 of Rowe (2005). Note that leakages up to almost 2000 lphd have been reported for other composite liners with a CCL.

Koerner et al. 1999; Touze-Foltz et al. 2001), there was a paucity of data regarding actual wrinkle dimensions on a scale larger than 40 m × 40 m that could be used to quantify leakage for realistic wrinkle geometries.

Rowe (1998) had developed a simple equation to predict leakage through a hole in a GM coincident with (or adjacent to) a wrinkle (Fig. 10) which, in its simplest form (assuming no interaction between adjacent wrinkles), can be written:

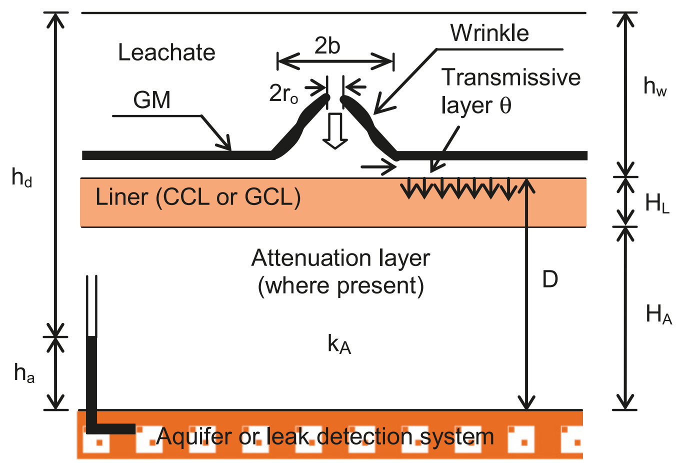
$$[6] \qquad Q = 2L[kb + (kD\theta)^{0.5}]h_d/D$$

where Q is the leakage (m^3/s); L is the length of the connected wrinkle (m); k is either the hydraulic conductivity (m/s) of the clay liner, k_L, if there is no AL or the harmonic mean of the CL and AL hydraulic conductivities, k_s, if there is an AL; $2b$ is the width of the wrinkle (m); $D = H_L + H_A$ is the thickness of the CL and AL (m); θ is the transmissivity of the GM–CL interface (m^2/s); and $h_d = (h_w + H_L + H_A - h_a)$ is the head loss across the composite liner (m). All of these parameters except the connected wrinkle length and wrinkle width are as previously discussed. What is needed to use eq. [6] is an indication of the likely values of L and $2b$. Thus, starting in 2006 an extensive study was initiated, including the construction of a full-scale test liner to provide field data regarding L and $2b$ for some North American conditions.

QUELTS was constructed at a latitude of 44.34° N and longitude of 76.39° W, 40 km north–northwest of Kingston, Ontario, Canada, in September 2006 to study the long-term performance of exposed geosynthetic composite liners (Brachman et al. 2007). The relevant portion of the test site was 80 m wide (west to east) with a 21 m long south-facing 3H:1V slope (where H represents horizontal and V represents vertical) and 19.4 m long base with a 3% grade. A 1.5 mm thick HDPE GM was placed with smooth GM on the base and mostly textured GM on the side slope (full details are given by Brachman et al. 2007). Four different GCLs were used to allow an examination of potential shrinkage of different products under similar conditions. This site provided a unique opportunity to examine a number of issues including wrinkling of GMs and shrinkage of GCLs over different times of the day, different seasons, and over a number of years.

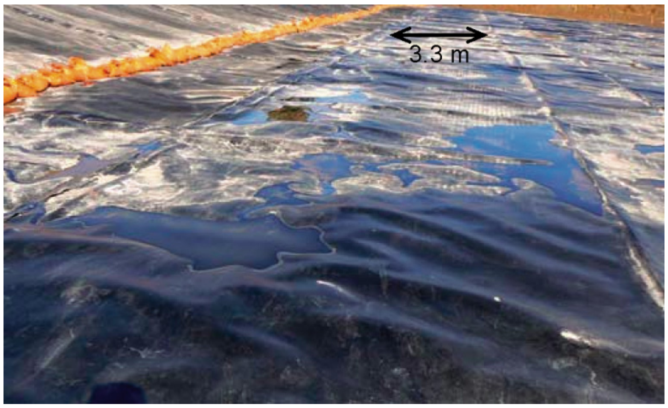
Figure 8 shows the base liner at QUELTS early on a cool October morning when there are no wrinkles — here the GM is in direct contact with the underlying GCL. If the GM was covered with the protection layer and drainage gravel in this state then there would be no wrinkles and the equations for a composite liner with direct contact would be appropriate. This situation approximates that required in Germany (e.g., Averesch and Schicketanz 1998; Müller 2007), but is not generally practised elsewhere. In fact, it does not take much exposure to the sun before significant wrinkles start to form. For example, Fig. 11 shows the same base liner at QUELTS as shown in Fig. 8 on a sunny spring morning in March when the ambient temperature was 9 °C. Despite the presence of some snow still on the liner, wrinkle development is well underway.

Fig. 10. Schematic showing leakage through a wrinkle of length L and width $2b$ with a hole of radius r_o (adapted from Rowe 1998).



To quantify wrinkle dimensions both at QUELTS and other field sites, a system was developed to obtain low-altitude aerial high-resolution photographs of the GM using a digital single lens reflex camera mounted on the underside of a 6.4 m long helium-filled blimp (Take et al. 2007). Each photograph covers an area of approximately 19 m by 28 m when taken with a 50 mm lens at a height of 60 m. A grid of ground control points at 5 m spacing along each GM seam was surveyed to provide exact locations for digital image alignment. To correct for distortion that can arise due to camera orientation (especially with respect to the side slope), the image pixel coordinates were

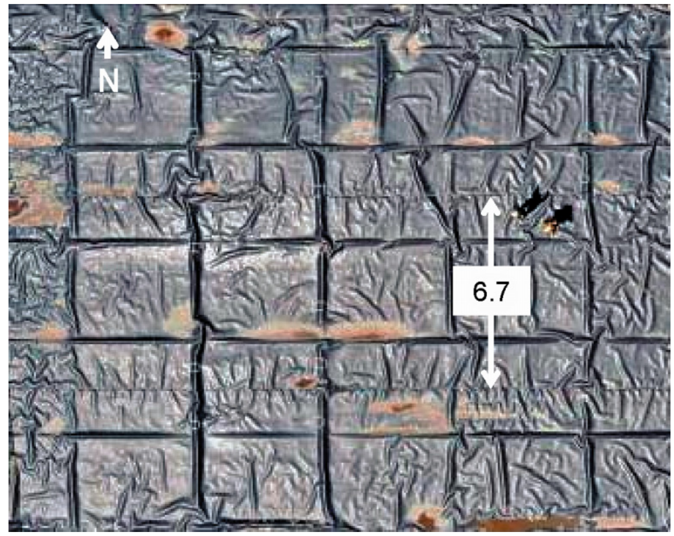
Fig. 11. Photograph of wrinkles at QUELTS (same bottom liner as shown in Fig. 8) on 23 March 2007 when ambient temperature was 9 °C. Note longitudinal wrinkles at 3.3 m spacing are beginning to form. White patches are what remain of a sprinkling of snow on liner from the previous night. Water puddles from melting snow are constrained from flowing off the base (slope 3% from left to right — north to south) by the wrinkles.



correlated to real world coordinates using the known locations of the control grid points and the image was geometrically corrected through image transformation to create a constant scale factor of 1 pixel to 0.01 m to allow accurate measurement of distance in the image (Take et al. 2007). Using the control points, the individual photographs were stitched together to create a single master image of the GM over the site. Figure 12 shows a portion of one such image for the base of the landfill at QUELTS on 28 May 2008 when the ambient temperature was 11 °C but the liner was 53 °C. Using these photos, the length, width, and area under wrinkles was quantified. In this analysis, only wrinkles with a height greater than 3 cm were quantified because smaller wrinkles have a reasonable chance of being suppressed when the GM is covered. Larger wrinkles are likely to remain after covering (Stone 1984; Soong and Koerner 1998; Gudina and Brachman 2006; Brachman and Gudina 2008).

The wrinkle pattern shown in Fig. 12 has two distinct sets of orthogonal wrinkles: one running east to west in the roll direction across the site at a spacing of about 3.3 m and the other running north to south at a spacing of about 4.1–4.4 m (GCL panel width between overlaps; range is because different products may have different roll widths). The first set corresponds to the locations of folds in the blown-film GM created during manufacture while the second set corresponds to the locations of GCL panel overlaps. There are additional smaller wrinkles, many of which connect to the longitudinal features. At the time this photo was taken, the connected wrinkle length on the approximately 80 m long and almost 20 m wide base (area of 0.14 ha) was 1400 m and the area under wrinkles represented 22% of the total area of the base. Had the GM been covered with the gravel leachate collection system at this time, then any hole aligning with any wrinkle forming part of the connected network would allow fluid to migrate laterally with no real resistance to other points below the network over a length of about 1400 m.

Fig. 12. Aerial photo showing a small portion of connected wrinkle network on the base liner at QUELTS (same bottom liner as shown in Figs. 8 and 11) (modified from Rowe et al.[2]). Photo taken on 28 May 2008 at 1300; air temperature of 11 °C; GM temperature on the base of 53 °C. Distance between GM seams is approximately 6.7 m as shown.



Monitoring at QUELTS[2] has indicated that while wrinkles may occasionally reach 0.2 m in height and 0.5 m in width, this is rare. The average wrinkle height is about 0.06 m and the width (2b) is between about 0.2 and 0.25 m over most of the day.[2] The average daily wrinkle width was 0.20 and 0.22 m on the base and slope, respectively, with a standard deviation of 0.04 m in both cases.[2] There is an approximately bi-linear relationship between the length of connected wrinkles and the area of wrinkles.[2] When wrinkles first start to form they are mostly independent; the connected wrinkle length increases slowly to about 200 m with an increasing area of wrinkles until a total of about 8% of the area is wrinkled. Once this threshold is passed the wrinkles interconnect and the connected wrinkle length grows rapidly with a further increase in area under the wrinkles, reaching over 2000 m when 30% of the site was wrinkled even for this relatively small site.[2] At this site, to keep the connected wrinkle length below 200 m during the normal construction season (May to October) the GM generally would need to be covered before 0800 or after 1600. If this was done and considering the site size (with 0.14 ha base and 0.17 ha side slope), one could infer that there would be about 6 to 7 connected wrinkles/ha with $L \leq 200$ m. Evidence that wrinkles are in fact covered is confirmed by field observations (e.g., Fig. 13).

Thus, if there were 2.5 to 5 holes/ha, there is a reasonable probability that, if covered under these conditions, there would be at least one hole in a connected wrinkle of length $L \leq 200$ m. If covered later in the day the probability of a hole in a wrinkle increases as does the length of the connected wrinkles. If the GM were covered near 1330, assuming 5 holes/ha, there would be about a 50% probability that a randomly located hole would align with a wrinkle with $L \geq$

[2]Rowe, R.K., Chappel, M.J., Take, W.A., and Brachman, R.W.I. A field study of wrinkles in a geomembrane at a composite liner test site. Submitted for publication.

Fig. 13. Photo showing wrinkles being covered.

1500 m. However, the probability is even higher because holes are not going to be purely random but, rather, are more likely at wrinkles. The rationale behind this statement is twofold. First, in the short term, field observations suggest that the risk of damage due to the placement of the overlying drainage material or ballast is high as it is closer to the bulldozer blade and tracks than the rest of the GM (Fig. 13). Second, in the longer term, the tensile strains in the GM are higher at the wrinkle than away from the wrinkle (Gudina and Brachman 2006, 2011; Brachman and Gudina 2008). Thus, wrinkles that are locked in after covering provide a potential source for holes and a conduit for transmission of flow through the hole. Because of their linear nature, they also can serve to dam up the leachate as it flows on a relatively flat slope (e.g., Figure 11) in the drainage layer on the landfill base, with leachate levels building up to the height of the wrinkles (Figs. 12 and 13), which can easily be 0.06 m and up to as much as about 0.2 m in typical situations at the time of covering.[2]

The low-altitude aerial photogrammetric system developed by Take et al. (2007) has been used to quantify wrinkles at six different sites (including QUELTS) in eastern Canada with generally similar findings. For example, Chappel et al. (2011) examined wrinkling of a smooth 1.5 mm thick HDPE GM placed over a GCL on the 55 m by 140 m base of a MSW landfill located at 44°23 N 79°43 W on 11 June 2007. As with QUELTS, the wrinkles varied over the course of the day, with the total area beneath wrinkles ranging from 3% at 0845, 20% at 1225 and 7% at 1715. The wrinkle width varied between 0.12 and 0.4 m, but the average value was quite consistent throughout the day, ranging between 0.22 and 0.24 m with an overall daily average of 0.23 m. The connected wrinkle length increased from 30 m at 0845 to 2500 m at 1345. The base of this landfill was effectively divided into four approximately equal subareas of about 0.2 ha by sandbags at about 3 m spacing. This generally isolated the subareas with respect to wrinkles and hence limited the length of the connected wrinkle. The longest wrinkle (L = 2500 m) actually broke through between two subareas where a sand bag was missing. Had the sand bag been present, the longest connected wrinkle would have been about 1550 m. This demonstrates that unless the lateral extent of wrinkling is constrained, the presence of linear wrinkle features along (and across) rolls related to linear geometric imperfections (e.g., folds in blown-film extruded GM, seams in flat die–extruded GMs, GCL overlaps, track marks on CCLs, etc.) that typically develop will likely increase the connected wrinkle length with the size of the unrestrained area (other things being equal).

Chappel et al. (2008) examined a 140 m wide by 65 m long 3H:1V slope covered with a 1.5 mm thick textured GM in July 2006. The maximum ambient temperature during monitoring was 28 °C. A statistical analysis of the wrinkle network on the slope indicated that 92% of wrinkles had a width of between 0.1 and 0.3 m with an average wrinkle width of 0.21 m (standard deviation = 0.06 m).

In summary, based on the presently available data, it can be concluded that although wrinkles may reach heights of 0.2 m or more and widths up to 0.5 m on occasion, a detailed analysis of a very large number of wrinkles at a number of sites at different times of the day and year indicate that for 1.5 mm thick (smooth or textured) HDPE GM, at least during the typical eastern Canadian construction season, wrinkles were typically about 0.06 m high and about ($2b$ =) 0.2 to 0.3 m wide. The typical width did not change significantly over most of the day. The connected length varied substantially with time of day and to some extent with the size of the unconstrained area. If the GM were covered with the leachate collection layer before 0800 in the morning or after about 1600 in the afternoon, then there would have been about 6 to 7 connected wrinkles/ha with $L \leq 200$ m. This length would increase with the time of day the GM was covered, typically peaking at around 1300, until the connected length was about 2000 m for areas unrestrained up to about 0.2 ha (and larger for larger unrestrained areas).

Evaluation of the connected wrinkle length required to explain the observed leakage through composite liners

Considering the observed leakages for the landfills with configurations examined in Table 9, eq. [6] was used to calculate the length of connected wrinkle with a hole required to explain the range of average monthly leakage and the peak leakages. In performing these calculations, it was assumed that for a new landfill, the head giving rise to the average monthly flow would be low (h_w = 0.05 m) but that the peak flow likely corresponded to an infiltration event when the head may well have reached the full design value of h_w = 0.3 m. Calculations were performed for the best case and worst case combination of k_L and θ considered in the calculations for direct contact (Table 9) as well as a number of other combinations to show the effect that these parameters have on the wrinkle length required to explain a given leakage (Table 10).

The worse (i.e., higher) the values of k_L and θ, the shorter is the connected wrinkle length (with a hole) required to explain a given leakage (Table 10). For the composite liners with a 0.9 m CCL, the different combinations of parameters and range of average monthly leakages observed for several different landfills over a period of time correspond to connected wrinkle lengths, L, of $35 \leq L \leq 730$ m, while the peak flows correspond to $180 \leq L \leq 1400$ m. The difference in lengths for average monthly flows and peak flows are not surprising given that most landfills have a base slope to the

Table 10. Calculated connected wrinkle length (with a hole) per hectare to explain observed target leakage for the assumed parameters.

		L (m)	
k_L (m/s)	θ (m²/s)	h_w = 0.05	h_w = 0.3
CCL observed target[a] Q (lphd): range[b] = 60–160[d], peak[c] = 390[d]			
1×10^{-10}	1.6×10^{-8}	270–730	1400
5×10^{-10}	1.6×10^{-8}	120–380	620
1×10^{-9}	1.6×10^{-8}	85–230	440
1×10^{-9}	1.0×10^{-7}	35–90	180
GCL observed target[a] Q (lphd): range[b] = 0–11, peak[c] = 54			
5×10^{-11}	2×10^{-12}	0–1800	1700
5×10^{-11}	2×10^{-11}	0–1300	1200
1×10^{-10}	2×10^{-11}	0–740	700
2×10^{-10}	2×10^{-11}	0–400	390
2×10^{-10}	2×10^{-10}	0–270	250

Note: Leakage calculated using eq. [6] and geometry as per schematics in Figs. 6 and 10 with H_A = 0 m, h_a = 0 m, $2b$ = 0.2 m, hole r_o = 5.6 mm; CCL H_L = 0.6 m, GCL H_L = 0.01 m. Calculated numbers have been rounded to two significant digits.

[a]Bonaparte et al. (2002).

[b]Weighted average flow based on data from Bonaparte et al. (2002).

[c]Maximum peak flow.

[d]Specifically for 0.9 m CCL in Table 4 of Rowe (2005); leakages up to almost 2000 lphd have been reported for other composite liners with a CCL.

sump and the higher leachate heads associated with a significant rainfall event have a higher probability of interconnection with more holed wrinkles than the lower heads corresponding to average flow. As there was good construction quality (CQA/CQC) at these landfills, one might expect good contact conditions ($\theta \sim 2 \times 10^{-8}$ m²/s) and after some consolidation under the weight of the waste a specified k_L = 1×10^{-9} m/s is likely to decrease to $1 \times 10^{-9} \leq k_L \leq 5 \times 10^{-10}$ m/s. For these conditions the connected wrinkle lengths required to explain average monthly flows are $85 \leq L \leq 380$ m, while the peak flows correspond to $440 \leq L \leq 620$ m.

For composite liners with a GCL, the lowest monthly leakages were very small and suggest little or no role for wrinkles; however, leakage for the upper end of the range of average monthly flows corresponds to the connected wrinkle lengths of $270 \leq L \leq 1800$ m, while the peak flows correspond to $250 \leq L \leq 1700$ m. Assuming an average transmissivity for sodium bentonite at 50 kPa (based on data in Table 6) of $\theta = 2 \times 10^{-11}$ m²/s and $2 \times 10^{-10} \leq k_L \leq 5 \times 10^{-11}$ m/s, the wrinkle lengths required to explain the peak average monthly flows are $400 \leq L \leq 1300$ m, while the peak flows correspond to $390 \leq L \leq 1200$ m with the most likely range (allowing for some interaction between the GCL and leachate in the low stress zone below the wrinkle so that $2 \times 10^{-10} \leq k_L \leq 1 \times 10^{-10}$ m/s) being about 400 to 700 m for both peak average monthly and peak leakages.

While care is needed not to overinterpret these results, it would appear that at low heads, connected wrinkle lengths (with a hole) of $85 \leq L \leq 700$ m and at higher heads $400 \leq L \leq 700$ m most likely explain the observed leakages. These lengths are consistent with what one would expect based on the field studies reported in the previous section if the GM was covered when the area of base with wrinkles was between about 3% and 15%. For the climatic conditions of southern Ontario[2] this would correspond to generally covering before about 1000 or after about 1430 (i.e., not when wrinkling is most extensive, around the middle of the day). This is also consistent with the findings that wrinkles with a height greater than about 3 cm are likely to remain after loading due to placing of the waste (Stone 1984; Soong and Koerner 1998; Gudina and Brachman 2006; Brachman and Gudina 2008).

Considering the foregoing and the findings of the previous section and assuming good CQA/CQC, it can be tentatively concluded that if care is taken not to cover the GM with the leachate collection layer during a period of massive wrinkling (i.e., when more than 15% of the area is wrinkled), that for landfill design purposes, one could assume one holed wrinkle per hectare with a connected wrinkle length $L < 700$ m. If additional care is taken to limit the area of wrinkles to less than about 10%, for design purposes one could assume one holed wrinkle per hectare with a connected wrinkle length $L < 500$ m. For 5% wrinkled area the corresponding length is $L < 150$ m and for 3% wrinkled area, $L < 100$ m. When wrinkles are eliminated (e.g., Fig. 8), the direct contact solutions become applicable.

Calculated leakage for composite liners with wrinkles

To provide insight regarding the magnitude of leakage that may be expected in landfill liners (design head h_w = 0.3 m) for a number of composite liner configurations, leakage was calculated for connected wrinkles (with a hole) of lengths 100, 200, and 700 m (based on the discussion in the previous section). As indicated in the discussion of interface transmissivity, leakage does not appear to be affected by a change from sodium to calcium bentonite and hence may not be significantly affected by interaction with leachate; thus, θ was kept constant for a given CL.

For composite primary liners (Fig. 6 but with a wrinkle) in a double liner system with a leak detection layer immediately below the liner (h_a = 0 m), the calculated leakage is given in Table 11.

Table 11. Calculated leakage, Q, through selected composite liners for a hole in one connected wrinkle of length L per hectare for $h_w = 0.3$ m.

			Q (lphd)		
Case	k_L (m/s)	θ (m²/s)	L = 100 m	L = 200 m	L = 700 m
0.6 m CCL, $H_A = 0$ m[a]	5×10^{-10}	1.6×10^{-8}	58	120	410
	1×10^{-9}	1.6×10^{-8}	83	170	580
0.01 m GCL, $H_A = 0$ m	5×10^{-11}	2×10^{-11}	3	6	21
	2×10^{-10}	2×10^{-11}	9	17	61
	*	2×10^{-11}	7	14	49
0.6 m CCL, $H_A = 3.15$ m[b]	5×10^{-10}	1.6×10^{-8}	67	130	470
	1×10^{-9}	1.6×10^{-8}	94	190	660
0.01 m GCL, $H_A = 3.74$ m[b]	5×10^{-11}	2×10^{-11}	10	20	63
	2×10^{-10}	2×10^{-11}	29	59	210
	*	2×10^{-11}	16	31	110

Note: Leakeage calculated using eq. [6] and geometry as per schematic in Fig. 10 with $2b = 0.1$ m, hole r_o = 5.6 mm; calculated leakages have been rounded to two significant digits.

[a] $h_a = 0$ m.

[b] $h_a = 3$ m, $H_A + H_L = 3.75$ m.

*Assuming $k_L = 2 \times 10^{-10}$ m/s below wrinkle and $k_L = 5 \times 10^{-11}$ m/s outside wrinkle.

For typical CCL design $k_L = 1 \times 10^{-9}$ m/s in good contact with the GM, the calculated leakage is less than 100 lphd if the connected wrinkle length is less than about 120 m, but becomes reasonably large once the connected wrinkle length approaches 200 m. Some consolidation of the liner may be expected to reduce the hydraulic conductivity. Assuming consolidation reduces k_L to 5×10^{-10} m/s there is a reduction in leakage (Table 11), but it is still desirable to keep connected wrinkles to less than 200 m. However, even with a 700 m connected wrinkle, the leakages are

- still less than for a GM alone (Table 2) for five extremely small (r_o = 0.5 mm) holes/ha;
- two orders of magnitude smaller than for a GM alone with 5 same-sized holes/ha as considered here (r_o = 5.6 mm); and
- almost three times less than for a CCL alone ($k_L = 1 \times 10^{-9}$ m/s).

For a CCL, the width of the wrinkle is small compared to the thickness of the CCL and most of the leakage occurs due to migration of fluid in the transmissive zone away from the wrinkle. Therefore, the actual width of the wrinkle has relatively little effect on the leakage (the leakage for $2b = 0.2$ m is only 1% to 2% more than that for $2b = 0.1$ m) for the CCL cases examined in Table 11 and thus, the effect of the weight of the waste on consolidation of the CCL can be considered to apply to the entire leaking area with negligible error. However, this is not the case for GCLs because

1. the thickness of the GCL is much smaller than the wrinkle width and the stress due to the weight of the waste only causes consolidation for the GCL outside the wrinkle that remains after compression due to the waste, while the GCL below the wrinkle has very little stress and will be more susceptible to clay–leachate interaction; and
2. the interface transmissivity is so low that the area under the wrinkle contributes significantly to the leakage, thus the leakage for $2b = 0.2$ m is 40% to 60% more than for $2b = 0.1$ m for the cases examined in Table 11 and hence, the hydraulic conductivity of the GCL below the wrinkle plays a more significant role in the leakage than is the case for a CCL.

As indicated in an earlier section, the typical width of a wrinkle at the time of covering is about 0.2 to 0.3 m. Brachman and Gudina (2008) demonstrated that with an applied pressure of 250 kPa this wrinkle width reduces to about half the initial value, and as Table 11 corresponds to landfill applications, a value of $2b = 0.1$ m was adopted for the calculation reported in that table.

For a GCL, a value of $k_L = 5 \times 10^{-11}$ m/s could correspond to permeation with water at a low stress (≤15 kPa) or after considering clay–leachate interaction at a high stress (≥100 kPa) as discussed earlier. For this case the leakage is very small ($Q < 10$ lphd) for $L \leq 200$ m and only 21 lphd for $L = 700$ m. This estimate may be somewhat optimistic because below the wrinkle itself the stress is quite low even if there is a substantial amount of waste and hence, below the wrinkle k_L may be 2×10^{-10} m/s. If the entire layer had this hydraulic conductivity the leakage is increased to ≤ 17 lphd for $L \leq 200$ m and 61 lphd for $L = 700$ m. However, this calculation overestimates the leakage, which would be expected to lie between that given for the two values of k_L considered. An estimate of likely leakage was obtained by assuming $k_L = 2 \times 10^{-10}$ m/s below the wrinkle and $k_L = 5 \times 10^{-11}$ m/s outside the wrinkle; this gives a leakage of ≤ 14 lphd for $L \leq 200$ m and less than 50 lphd for $L = 700$ m. These leakages are very small compared to those for a GM alone (Table 2) or a GCL alone (Table 3), demonstrating that a composite liner with a GCL can be extremely effective even with wrinkles up to 700 m long and considering an increase in hydraulic conductivity due to clay–leachate interaction.

The results for the single composite liner over an attenuation layer (Figs. 7 and 10; Table 11) show the same general trends as discussed above for the primary composite liner in a double lined system except that there is a somewhat higher leakage through the composite with a GCL because of the

Table 12. Calculated leakage, Q, through selected composite liners for a hole in a connected wrinkle of length L for $h_w = 5$ m.

Case	k_L (m/s)	θ (m^2/s)	Q (lphd) L = 100 m	L = 200 m	L = 700 m
CCL[a]	1×10^{-9}	1.6×10^{-8}	510	100	3600
	1×10^{-8}	1.0×10^{-7}	4100	8200	≥24 000
GCL[b]	5×10^{-11}	2×10^{-11}	70	140	490
	2×10^{-10}	2×10^{-11}	230	450	1600
	2×10^{-8}	2×10^{-11}	18 000	36 000	≥100 000
CCL[c]	1×10^{-9}	1.6×10^{-8}	510	1000	3600
	1×10^{-8}	1.0×10^{-7}	3400	6800	≥24 000
GCL[d]	5×10^{-11}	2×10^{-11}	70	140	490
	2×10^{-10}	2×10^{-11}	160	320	1100
	2×10^{-8}	2×10^{-11}	330	670	2300
GC–CC[e]	2×10^{-8}	2×10^{-11}	32	63	220

Note: Leakeage calculated using eq. [6] and geometry as per schematic in Fig. 10 with $2b = 0.1$ m, hole $r_o = 5.6$ mm; calculated leakages have been rounded to two significant digits.

[a]$h_a = 0$ m, $H_L = 0.6$ m.

[b]$h_a = 0$ m, $H_L = 0.01$ m.

[c]$h_a = 3$ m, $H_L = 0.6$ m; $H_A + H_L = 3.75$ m.

[d]$h_a = 3$ m, $H_L = 0.01$ m; $H_A + H_L = 3.75$ m.

[e]0.01 m GCL ($k_L = 2 \times 10^{-8}$ m/s) + 0.6m CCL ($k_L = 1 \times 10^{-9}$ m/s) + 3.14 m AL ($k = 1 \times 10^{-7}$ m/s).

much larger hydraulic gradient across the thin GCL in this case (although the leakages are still substantially smaller than for the case with a CCL). Assuming $k_L = 2 \times 10^{-10}$ m/s below the wrinkle and $k_L = 5 \times 10^{-11}$ m/s outside the wrinkle, the calculated leakage is ≤31 lphd for $L \leq 200$ m and 110 lphd for $L = 700$ m. Thus, even with a 700 m long connected wrinkle (with a hole) per hectare, the leakage is substantially less than for a GM alone (Table 2) or CL alone (Table 3).

In a leachate lagoon application it is important that the liner be covered with a suitable soil (typically about 0.3 m thick), interlocking brick, cast concrete or some other suitable protection layer to avoid damage (e.g., Rowe et al. 2003), however the stress due to this protection layer may be expected to provided very little benefit with respect to improving k_L due to consolidation. Thus, results are only shown for CCLs with $k_L = 1 \times 10^{-9}$ m/s. For the GCL, $k_L = 5 \times 10^{-11}$ m/s is possible at low stress provided that there is no significant clay–leachate interaction or cation exchange with the underlying soil, but a value around $k_L = 2 \times 10^{-10}$ m/s may be more likely with significant leachate interaction or cation exchange. Under these low stress conditions and with an aggressive leachate, $k_L = 2 \times 10^{-8}$ m/s is also possible.

The leakages for the lagoon case (Table 12) are larger than for the landfill case examined above (Table 11) due to the much larger head and corresponding gradient. The width of the wrinkle ($2b = 0.2$ m) is also greater because the applied stress is much lower in a lagoon application than in a landfill application. While the leakages are substantially smaller than what would be expected for a GM with 5 similar (r_o = 5.6 mm) holes/ha (Table 2) or a CL (Table 3) alone for similar k_L, the control of wrinkles is quite important for limiting leakage through the composite liner, especially if there is clay–leachate interaction with the GCL. The leakages with the GCL (even with clay–leachate interaction and (or) cation exchange giving $k_L = 2 \times 10^{-10}$ m/s) were less than 500 lphd for $L \leq 200$ m compared to ≤1000 lphd for a CCL with $L \leq$ 200 m. For a primary composite liner underlain by a LDS, the leakage is large if GCL–leachate interaction led to $k_L = 2 \times 10^{-8}$ m/s. With the same k_L, but the GCL in a composite liner with an attenuation layer, the leakage is substantially reduced to ≤670 lphd for $L \leq 200$ m.

For leachate lagoons where interaction between the GCL and leachate is a significant concern (i.e., where $k_L \sim 2 \times 10^{-8}$ m/s might be anticipated), the use of a composite liner with a GCL and CCL together can result in a substantial reduction in leakage as shown in the last row of Table 12. Here the GCL serves to restrict the lateral migration of leachate between the GM and the GCL due to its good interface transmissivity, while the thickness of the CCL controls the leakage in the zones beneath the wrinkle and out to where leachate can migrate between the GM and GCL. For this case the leakage was 63 lphd for $L \leq 200$ m and 220 lphd for L = 700 m. Similar values are obtained for a GM, GCL, and 0.6 m CCL in a primary liner underlain by a LDS.

Other factors influencing long-term leakage

Issues specific to ponds and lagoons

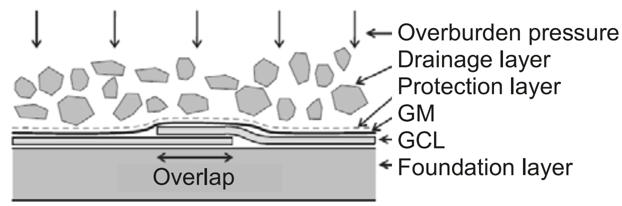
When dealing with lagoons and ponds, leakage through composite liners may be more complicated than implied by the previous discussion, especially if the GM is not covered by a suitable ballast layer. If the stresses at the hole are hydrostatic or nearly hydrostatic, the water pressure beneath the GM is only slightly less than the pressures above the GM near the hole. As HDPE has a specific gravity less than that of water, it has potential to float, reducing or eliminating the composite liner action if the weight of the ballast layer is not sufficient to adequately counter this effect. Furthermore, some liquids are biologically active and the migration of bacteria and nutrients between the GM and CL may generate gas (e.g., methane and carbon dioxide) that can lift the GM, reducing or eliminating the composite liner action if the weight of the ballast layer is not sufficient to adequately counter this effect. This situation will be aggravated by the presence of wrinkles. In addition, even if the unprotected GM was installed with no holes, it is very prone to damage unless there is an adequate protection layer. Rowe et al. (2003) describe a case where the GM was badly damaged and became ineffective within 4 years of its installation. Thus unballasted exposed geomembranes may have very limited (or no) benefit as part of a composite liner system. To realize the composite liner action discussed in this paper, there needs to be a suitable inorganic (e.g., granular soil, interlocking brick or concrete) ballast and (or) protection layer. Given the challenges of ensuring good composite liner action in pond and lagoon applications, an argument can be made that the only dependable leakage control for an important pond (e.g., one containing fluids that should not escape to the underlying groundwater system) is to have a double liner with leakage control, monitoring, and maintenance (Thiel and Giroud 2011).

GCL overlaps

In addition to considering the factors that influence the hydraulic conductivity of the GCL and hence leakage through the GCL (especially when there are wrinkles), it is also important to consider the factors that could influence the potential for leakage between GCL rolls. To provide a hydraulic barrier at the edges of the GCL rolls, they are typically physically overlapped by between 150 and 300 mm (Fig. 14), with the amount varying from one manufacturer's recommendation to another. Depending on the manufacturer, it may or may not be recommended that supplemental powdered bentonite be placed between the GCL panels at the overlap to reduce the risk of preferential flow at this location.

Several investigators have examined the hydraulic performance of GCL overlaps under uniform vertical stress (e.g., Estornell and Daniel 1992; Cooley and Daniel 1995; Daniel et al. 1997; Benson et al. 2004). These studies showed that the effectiveness of overlaps was, to some extent, dependent on the method of GCL manufacture and, most critically, on the amount and consistency of the placement of bentonite between the overlapped GCL panels. Generally, provided that there was adequate overlap (150 mm) and adequate and consistent supplemental bentonite between the panels, good performance was observed such that the overlap was not a weak point (i.e., leakage would be controlled by the GCL away from the overlap rather than the overlap itself). Application of a uniform vertical stress generally improved overlap performance. However, Dickinson and Brachman (2006) demonstrated that wrinkles can give rise to nonuniform stresses on an underlying GCL when subjected to vertical overburden pressure. Although they were not considering overlaps in their experiments, this work does raise the question as to what effect nonuniform vertical stresses could have on GCL overlap performance. Two potentially significant scenarios can be envisaged where (*i*) the GCL overlap runs parallel to and below a wrinkle (e.g., see Fig. 12 where the long north–south wrinkles all align with GCL panel overlaps) and (*ii*) the panel overlap is perpendicular to longitudinal wrinkles (as is the case where the north–south panel overlaps in Fig. 12 intersect the east–west wrinkles). In both cases, there is potential for the nonuniform stresses to cause opening of the overlap if the overlap is not sufficient. Brachman et al. (2011) reported the results from the first tests conducted to examine whether GM wrinkle deformations and stress conditions can have an adverse effect on the GCL overlap. Their initial tests with a 150 mm overlap parallel to the wrinkle indicated no adverse impact; however, additional testing is required to identify if there are conditions where there could be an adverse impact.

Fig. 14. Schematic of a GCL panel overlap (adapted from Brachman et al. 2011).



GCL panel shrinkage

The overlap of GCL panels may vary with time if the GCL or composite liner is not covered quickly with the drainage layer or another suitable layer that will minimize thermal cycles, as the high GM temperatures that cause wrinkling of GMs may also cause moisture loss from partially (or fully) hydrated GCLs. Thiel and Richardson (2005) were the first to publicly document shrinkage of reinforced GCLs covered by a GM and left exposed (i.e., with no overlying cover soil). Koerner and Koerner (2005*a*, 2005*b*) reported additional cases where GCL panels had either lost a portion of their original overlap or had completely separated. Thiel et al. (2006) summarized six cases where GCL panels reported to have originally been overlapped by 0.15 m had separated, leaving a gap between panels of between 0.20 and 1.20 m after periods of exposure of between 2 and 60 months. The loss of panel overlap has occurred both on side slopes and on relatively gently sloping bases (Table 13). In cases where separation occurs, the composite action is lost. If separation were to occur at a location where there is a wrinkle (as it has for some, but not all, GCL products tested at QUELTS — future publication forthcoming), the leakage would be controlled by the size of the hole in the GM at the wrinkle and the head and would be given by eq. [1]. Thus, avoiding the loss of panel overlap is critical to ensuring composite liner performance.

Extensive laboratory studies (e.g., Thiel et al. 2006; Bostwick et al. 2007, 2008, 2010; Rowe et al. 2009*a*, 2010*a*, 2011*a*, 2011*b*; Brachman et al. 2010; Thiel and Rowe 2010; Joshi et al. 2011) have been conducted to help understand the factors affecting panel shrinkage and some potential solutions. The research has highlighted the complexity of this issue. Based on the research reported in the references cited above, GCL panel shrinkage appears to be influenced by

- *Method of GCL manufacture* — When subjected to the same wet–dry cycling (e.g., in pan tests reported by Thiel et

Table 13. Summary of reported GCL panel separation (gap) (data based on Koerner and Koerner 2005*b* and Thiel et al. 2006).

GCL[a]	Slope (°)	Maximum gap (mm)	Shrinkage (%)[d]	Exposure (months)
W–W[b]	22	300	10	60
N–W[c]	18	200	8	15
	4	300	10	2
N–N[c]	34	1200	31	36
	18	300	10	5
	4	450	14	2
	2–4	150	7	2

Note: GCLs were to have been initially overlapped by 150 mm and hence shrinkage is 150 mm greater than the gap indicated in the table. GTX, geotextile; W, woven GTX; N, nonwoven GTX.

[a]Cover GTX – carrier GTX.

[b]Unreinforced GCL.

[c]Reinforced GCL with an as-manufactured water content reported to be 20%–44%.

[d]Calculated for initial overlap of 150 mm and roll width of 4.4 m.

al. 2006; Bostwick et al. 2010; Rowe et al. 2011*a*), all GCLs experience significant shrinkage (with some shrinking more than others depending on the method of manufacture). However, in the field the shrinkage depends on the moisture cycles the GCL experiences and it has been found that the method of manufacture can significantly affect a number of factors influencing the magnitude of the moisture cycles in a given environment, including the water retention curve (Beddoe et al. 2011) and the uptake and loss of moisture both under isothermal conditions (Rayhani et al. 2011) and when subjected to thermal cycles (e.g., Rowe et al. 2011*b*). As a consequence, the method of GCL manufacture does affect the actual shrinkage observed both in the laboratory and especially in the field under nominally identical conditions with some GCLs being much more prone to shrinkage than others (even from the same manufacturer).

- *Variability in the distribution of bentonite mass within a specimen* — The greater the nonuniformity of bentonite mass distribution, the greater the shrinkage. Variability was most evident in GCLs having lower average bentonite mass per unit area.
- *Initial moisture content* — The greater the initial (e.g., off the roll) moisture content, the greater the initial and accumulated shrinkage during the first five wet–dry cycles, but this did not notably affect the final equilibrium shrinkage after many cycles.
- *Moisture content to which the GCL can hydrate between drying cycles* — Wet–dry cycles that only allowed the GCL to hydrate to a moisture content of about 60% took much longer (many more cycles) to reach (almost the same) final equilibrium shrinkage than specimens allowed to hydrate to about 100% moisture content between drying cycles.
- *Change in moisture content due to daily thermal cycles* — This is highly dependent on the initial moisture content and the water retention curve of the foundation soil.
- *Daily and seasonal thermal cycles to which the GCL is subjected* — It would appear that variable weather conditions that give rise to many overcast days followed by a sunny day may have more effect on shrinkage than consistent sunny (or overcast) days, as this allows more moisture uptake by the GCL before it experiences a severe drying cycle.
- *Bonding between GCL panels* — This may occur fortuitously (and hence cannot be relied on in design) due to hydration followed by drying of supplemental bentonite between overlapped panels (Brachman et al. 2010) or intentionally by heat-tacking the overlaps (Thiel and Thiel 2009; Rowe et al. 2010*a*; Joshi et al. 2011).

Factors that appear to have relatively minor to no influence on the percent shrinkage include

- Size and aspect ratio of the GCL panel.
- Dry mass per unit area of the product provided that the bentonite is evenly distributed.

The shrinkage strain required to cause the loss of 150 to 300 mm panel overlap could be mobilized in about five wet–dry cycles of the magnitude examined by Thiel et al. (2006), Bostwick et al. (2010) or Rowe et al. (2011*a*). Thus shrinkage could occur relatively quickly under some circumstances.

There is evidence that in field applications, panel separation can occur in less than 2 months in some situations, while under other circumstances a composite liner with a different GCL product can be exposed for up to 5 years without any significant shrinkage. These differences are likely a result of a combination of the factors noted above.

There are ways of minimizing potential GCL shrinkage and hence panel separation. The best mitigative measure is to place panels with 300 mm of overlap and then place the drainage layer (or other cover soil) over the composite liner as quickly as possible after placement of the GM over the GCL. In cases where it may not be practical to cover the composite liner quickly, other options for composite liners with GCLs include (*i*) using a GCL that has demonstrated relatively low shrinkage in the field (e.g., a scrim-reinforced needle-punched GCL with thermal treatment) and (or) (*ii*) mechanically bonding the overlaps (e.g., by sewing or heat-tacking). The available data would suggest that both approaches may substantially reduce the risk of panel separation; however, at this time there is no assurance that either approach will prevent panel separation under worst-case conditions —

one should still cover the composite liner as quickly as possible.

Desiccation of CCLs in exposed composite liners

To achieve low hydraulic conductivity, CCLs are typically compacted at 2% to 4% above standard Proctor optimum water content. This is often close to the plastic limit. If the CCL is left exposed to the sun and wind or if a GM over a CCL is left exposed to the sun, drying of the clay from its as-compacted state will quickly result in desiccation cracking of the CCL (Basset and Bruner 1993; Bowders et al. 1997). Even if this cracking only extends to a depth of a few centimetres (Fig. 3), it can still significantly affect leakage as the desiccation crack substantially increases the transmissivity of the GM–CCL interface. If left too long (and this could be as little as 1 day in some cases), the cracking can be sufficient to cause composite liner action to be effectively lost. The leakage will then be controlled by either eq. [1] and the size of the hole and head (e.g., Table 2) or by Darcy's law (eq. [3]) and the hydraulic gradient and hydraulic conductivity of the CCL (Tables 3, 4, and 5). Thus quick covering is critical for composite liners with CCLs to minimize construction-related desiccation cracking of the CCL. The potential desiccation that can occur while waiting for the results of quality assurance tests on GM seams must be carefully considered when constructing composite liners with CCLs.

Waste-generated liner temperature

Rowe and Islam (2009) updated the catalogue of observed temperatures in different landfills reported by Rowe (2005). Figure 15 shows even more recent data for the Keele Valley Landfill, which received 28 million tonnes of MSW from the greater Toronto area between the first acceptance of waste in 1984 and closure in December 2002. In the oldest cell of the landfill (1984), the annual average liner temperature increased to 34 °C over the first 14 years and has remained at an average of 35.5 °C over the past 14 years. At a location where waste was first placed in 1990, the annual average liner temperature increased to 39 °C over the first 13 years and peaked at 42 °C in year 14. Over the past 10 years the average temperature has been 39.4 °C. At a third location where waste was first placed in 1991, the annual average temperature increased to 35 °C over the first 12 years and has averaged 35.1 °C for the last 10 years.

Other investigators (e.g., Needham and Knox 2008) have also reported liner temperatures of 32 to 40 °C across the base of "normal" MSW landfills. Substantially higher liner temperatures (50 to 60 °C) have been observed for cases where there has been significant moisture augmentation. Although there are no explicit liner temperature measurements, waste temperatures of 60 to 80 °C at locations only a few metres above the liner have been observed in some unusual MSW landfills with leachate temperatures of 50 to 60 °C (the reason for these higher than expected temperatures are unknown at the time of writing). For ashfills, temperatures of 50 to 90 °C have been observed 3 m above the liner and leachate temperatures of 65 to 70 °C have been recorded. Most recently, Calder and Stark (2010) reported that landfills containing reactive wastes, such as aluminum production wastes, have been observed to generate waste temperatures in the landfill greater than 100 °C and in some cases in excess of 143 °C, and temperatures in excess of 85 °C in leachate collection systems near the geomembrane (Stark et al. 2011). Table 14 summarizes temperature ranges for a number of different environments.

More data on long-term liner temperatures is required; however, it is clear that significant temperatures can be generated in landfills and on landfill liners and in other applications for composite liners. As yet there is a paucity of data regarding how long peak temperatures will be maintained, but the available data does show that it is certainly more than a decade.

Desiccation due to waste-generated temperature

When a composite landfill liner is heated to a temperature higher than the soil at depth, heat flows downward toward the cooler area. This causes a downward migration of water vapour from the GCL and the underlying subsoil to a cooler depth where it condenses. The consequent decrease in moisture content of warmer areas causes liquid water to move upward along the capillary potential gradient. Moisture migration increases the soil's permeability to water vapour, making it easier for the downward movement of water vapour, but at the same time reducing the unsaturated hydraulic conductivity in the underlying soil nearest to the liner, making upward movement of water more difficult. Thus a point is reached where the upward liquid flux cannot balance the downward flux of water vapour. This can cause drying and possibly desiccation cracking in both CCLs and GCLs (Collins 1993; Rowe 2005; Southen and Rowe 2005; Azad et al. 2011). Zhou and Rowe (2003) developed a model that can be used to indentify when tension and desiccation is likely to be initiated in situations where there is applied external vertical stress, but does not to simulate the cracking after it is initiated. As the objective of design is to ensure that desiccation is not initiated, this limitation is of no practical significance. Approaches that model desiccation once initiated (e.g., Amarasiri et al. 2011) are not suitable for modelling the case of a buried composite liner (but may, subject to verification, be appropriate for exposed composite liners). The Zhou and Rowe (2003) model was used to examine compacted clay liners by Zhou and Rowe (2005).

Southen and Rowe (2005) reported an experimental study of single composite liners subjected to thermal gradients of between 25 and 29 °C/m. The temperature at the GM was kept at approximately 55 °C and overburden stresses of 15 to 95 kPa were examined. They found that when the silty sand subsoil they examined had an initial moisture content of around 12% to 13% there was no desiccation. In many cases where the initial moisture content of the subsoil was 4% to 7%, however, significant desiccation was observed even with a surcharge of 70 to 80 kPa. Thus for a given temperature gradient, the initial moisture content of the subsoil below the GCL greatly affects the potential for GCL desiccation, with the risk increasing with lower initial subsoil moisture contents. These results were for one specific subsoil and the moisture content at which desiccation occurs may vary with the soil grain-size distribution and water retention curve of the subsoil; this requires more investigation. Southen and Rowe (2005) also reported that the nature of the GCL product may influence the potential for desiccation, with one of the GCLs examined being less prone to

Fig. 15. Most recent available data for liner temperatures at three locations at the Keele Valley Landfill, Toronto, and the idealized temperature time history used by Rowe and Islam (2009) to generate the first case in Table 15 (data courtesy of the City of Toronto and Golder Associates).

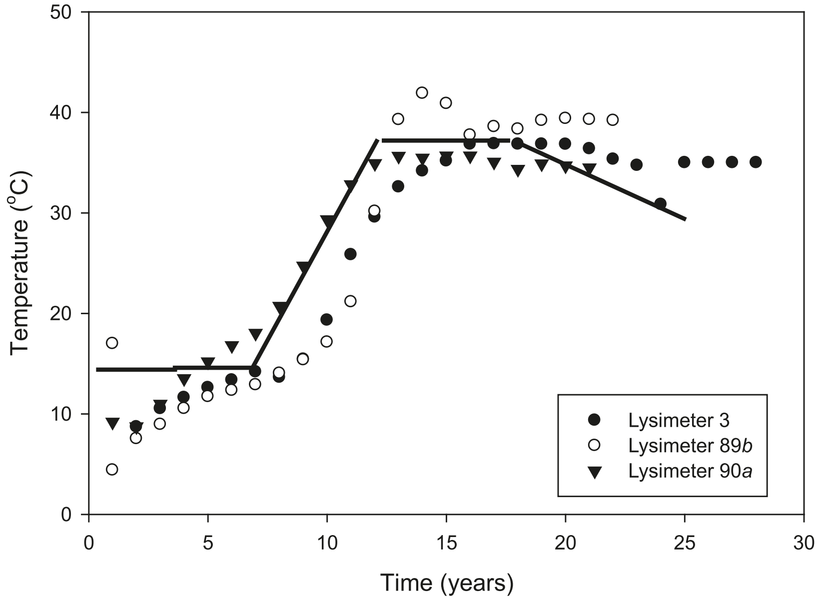


Table 14. Temperature on (or near) liners for different environments.

Environment	Temperatures (°C)	Reference
Normal MSW landfills (limited moisture addition)	30–40	Brune et al. (1991), Rowe (2005), Koerner and Koerner (2006), Needham and Knox (2008), author's files
Wet landfills (e.g., bioreactor landfills) where there is a significant amount of moisture	40–60	Yoshida and Rowe (2003), Koerner et al. (2008), author's files
Unusual MSW landfills[a]	60–80[a]; 50–60[b]	Author's files
Ash monofills	46; 50–90[a]; 65–70[b]	Klein et al. (2001), author's files
MSW with aluminum production waste and leachate recirculation	85[c]; >143[d]	Stark et al. (2011)
Nickel heap leach pad	70	Abdelaal et al. (2011)
Ponds for highly saline fluid	70–93	Lichtwardt and Comer (1997)

[a]No monitors on liner so liner temperature is unknown; temperature given is in waste about 3 m above liner.
[b]Leachate temperature.
[c]Temperature in leachate collection pipes.
[d]Temperature in waste.

desiccation under otherwise similar conditions than others. Higher bentonite mass per unit area and greater carrier geotextile thickness appeared to reduce desiccation potential for the conditions examined. The greater the temperature gradient, the greater was the potential for desiccation cracking.

Azad et al. (2011) followed the experimental work by Southen and Rowe (2005) on single composite liners by considering GCLs in double composite liners. This study showed that for GCLs underlain by a silty sand in both primary and secondary liners in the double liner systems examined, there was no GCL desiccation for initial subsoil moisture content ≥ 10% and primary GM temperature < 40 °C. For a primary composite liner, desiccation cracking did occur on a foundation layer at 10% to 11% initial moisture content and a GM temperature of 45 °C. For a secondary composite liner, desiccation was observed when the subsoil below the GCL had an initial moisture content of about 5% and the primary GM temperature was 40 °C. Thus, unless care is taken to ensure that the subsoil has an appropriate initial moisture content, desiccation cracking may occur even at the upper end of the temperature range for a normal MSW landfill.

For GCLs in a primary composite liner resting directly on a geonet drainage layer, it was found that the risk of desiccation was greatest for GCLs at low initial moisture content. Thus in these situations it is desirable for the GCL to hydrate before a significant thermal gradient is applied.

Both Southen and Rowe (2005) and Azad et al. (2011) conducted hydraulic conductivity tests on desiccated GCL samples. They found that for all three products tested (one Canadian, one European, and one Australian), the desiccated GCL self-healed during permeation and the hydraulic conductivity decreased from a desiccated k_L of 1×10^{-9} to 1×10^{-8} m/s to the healed $k_L \leq 2 \times 10^{-11}$ m/s when permeated with clean water. This situation may not have been as good had the desiccated GCL been permeated with a leachate.

The experiments reported by Southen and Rowe (2005) and Azad et al. (2011) have been modelled using the Zhou and Rowe (2003) model (Southen and Rowe 2011 and Azad et al. 2012, respectively) and the model was found to give very encouraging agreement with the experimental observations.

In summary, there is potential for desiccation of GCLs even at traditional MSW landfill liner temperatures (35 to 40 °C) under conditions of low stress and where the foundation soil has low initial moisture content. Thus, placement of a GCL over relatively dry subsoil (<10% initial moisture content) should be avoided for landfill applications. Increasing stress was shown to reduce the potential for desiccation (other things being equal). As the liner temperature increases, the risk of desiccation increases and thus special care is required for waste that can generate heat in excess of about 30 to 40 °C on the liner (e.g., MSW incinerator ash containing aluminum, reactive wastes, and MSW waste when the landfill is operated as a bioreactor; see Table 14).

Geomembrane service life

As demonstrated in previous sections, a composite liner can be extremely effective at controlling leakage from a landfill or lagoon. This is only the case as long as the GM remains relatively intact (i.e., with only the holes that occur in the short term as discussed earlier). GMs do, however, have a finite service life. The likely failure scenario for GM liners involves (*i*) stage I: depletion of protective antioxidants from the GM (monitored in terms of an index quantity called the "oxidative induction time" (OIT)); (*ii*) stage II: a period between depletion of antioxidants and measurable physical degradation of the GM (e.g., environmental stress crack resistance, SCR, or tensile properties); (*iii*) stage III: oxidative degradation of the HDPE that decreases properties such as the strength at break or the stress crack resistance; and (*iv*) failure**:** cracking in the GM due to low stress crack resistance combined with tensile stresses. Traditionally the nominal service life is said to have been reached when the physical property of interest (in this case SCR) has decreased to 50% of its original value (Hsuan and Koerner 1998). However, many GMs have an initial SCR much higher (600 h to over 5000 h) than the usually specified value (which is typically 300 h). Since it does not seem appropriate to judge the GM to have reached nominal failure when its SCR is still above the specified value, an alternative definition of nominal service life of the GM is proposed as the time from installation to when the physical property of interest (e.g., SCR) has decreased to 50% of the specified value. The actual service life of the GM (i.e., the time to actual failure) may be taken to be the time to when it no longer acts as an effective barrier to fluids in a liner.

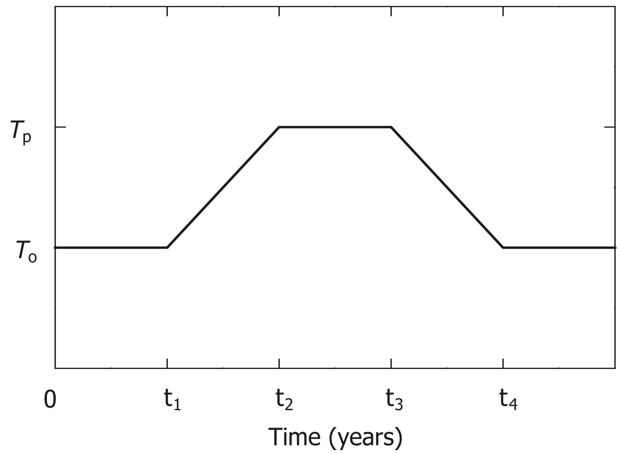
Rowe (2005) provided a detailed discussion of the information available up to early 2005 with respect to the service life of HDPE GMs. Since that time, considerable research has been conducted to further address questions regarding the service life of HDPE GMs (Rowe and Rimal 2008*a*, 2008*b*; Rowe et al. 2008, 2009*b*, 2010*b*, 2010*c*). The key findings from the work reported in these papers for the HDPE GMs and conditions examined can be summarized as follows:

- The service life of an HDPE GM is dependent on the polyethylene resin, carbon black, and antioxidant package in the specific GM. Even for a given manufacturer these may vary from time to time and the service life predictions in the cited publications are only for GMs with properties similar to or better than those tested; they do not apply to all HDPE GMs.
- The antioxidant depletion time (stage I) was shorter for GMs immersed in simulated MSW leachate than for GMs immersed in water. The longest depletion time (stage I) was measured for GMs in air.
- When immersed in water and leachate, antioxidant depletion was primarily associated with outward diffusion of antioxidants to the adjacent liquid.
- Using Arrhenius modeling for the GM tested, the predicted antioxidant depletion time (stage I) at a typical MSW liner temperature of 35 °C was about 10 years in leachate, 35 years in water, and 65 years in air.
- The key component of MSW leachate with respect to depletion of antioxidants (stage I) is surfactant (soaps). Even a relatively small amount of surfactant can substantially increase the rate of antioxidant depletion.
- GM thickness has a significant effect on the depletion of antioxidants (stage I). A 2.5 mm GM had an approximately 50% longer time to antioxidant depletion than a 1.5 mm GM.
- Using Arrhenius modelling for the GM tested, the antioxidant depletion time for a GM at a typical MSW landfill liner temperature of 35 °C was estimated to be 10 years for the GM immersed in leachate, 40 years for the GM in a composite liner with a traditional geotextile (GTX) protection layer, 50 years with a 15 mm thick sand protection layer above the GTX, and 65 years when the GM was separated from the leachate by an overlying GCL.
- There was no significant effect of 250 kPa of applied stress on the depletion of antioxidants (stage I).

Rowe and Islam (2009) developed a technique for estimating the service life of HDPE GMs based on the landfill liner temperature–time history and the data available in 2008 for five GMs. Figure 16 shows a schematic of the temperature–time history they examined, where T_o is the temperature of the liner in the absence of any heat generated by the waste. It was assumed that the liner temperature started at this temperature and remained approximately constant until a time t_1 (which was zero in some cases), after which the temperature increased linearly with time to an average peak temperature T_p at time t_2. The average peak temperature was assumed to remain constant at this value until time t_3 after which it decreased linearly, returning to T_o at time t_4. They considered a wide range of temperature–time histories. Table 15 summarizes two of the temperature–time histories examined and the range of estimated service lives for the five GMs for these cases.

The first temperature–time history was based, to the extent that data was available in 2008, on an idealization of the data from the Keele Valley Landfill. As can be seen from Fig. 15, what appeared to be a decrease in temperature at year 24 (when the Rowe and Islam (2009) paper was written) was an aberration and subsequently the temperature has remained at about 35 °C. For the first case considered by Rowe and Islam (Table 15), the estimated GM service lives, while quite variable, were all very long. This is good news for designers of landfills with GMs similar to or better than the five GMs examined and temperature–time histories similar to that exam-

Fig. 16. Schematic of a temperature–time history for a landfill liner (modified from Rowe and Islam 2009). T_o, initial and final temperature; T_p, peak liner temperature.



ined. However, they also demonstrated that for the same GMs, a change in temperature–time history as considered in the second case (based, to the extent that data is available, on data for a bioreactor landfill with a peak temperature of 60 °C) has a profound effect on the estimated GM service life. In this case the range of uncertainty is quite small and the projected service lives of 20 to 30 years are likely to be inadequate for providing the required environmental protection. While recognizing that there is uncertainty associated with the properties of the GMs and especially the assumed temperature–time histories, the difference in estimated service lives for the two cases very clearly demonstrates the critical role that the temperature–time history, and especially the peak temperature, can play in the GM service life. More research is needed into this issue.

Recent (as yet unpublished) studies at Queen's University using geosynthetic landfill liner simulators (see Brachman et al. 2008 and Rowe et al. 2010*c* for simulator details) has shown conclusively that when GMs reach the end of their service life they experience extensive stress-cracking and the number of holes goes from a few holes/ha to 30 to 100 holes/m^2. At this point the liner can no longer be considered a composite liner and leakage will be controlled by the clay liner component. Under these circumstances, leakage up to that discussed in the section titled "Leakage through clay liners" (e.g., see Tables 3 to 5) can be anticipated.

The discussion above was focused on GMs in primary liners. Rowe and Hoor (2009) considered GMs in secondary liners. They examined a number of different liner configurations and modes of landfill operation. This modeling took account of the less severe exposure conditions associated with a secondary GM (using data from Rowe and Rimal 2008*b*) and the thermal properties of the barrier system. The service life of the secondary GM was shortest for an all-geosynthetic system where the primary composite liner was comprised of a GM–GCL over a geosynthetic drainage layer. Under these conditions, the service life of the secondary GM would be ample for a temperature–time history that did not involve excessive temperatures on the primary liner (e.g., the first case in Table 15), but would not be sufficiently greater than that of the primary GM to provide adequate environmental protection in situations like the second case in Table 15. Rowe and Hoor (2009) showed that the thicker the primary liner (i.e., the larger H_L in Fig. 6), the lower the temperature of the secondary GM and hence the longer the service life of the secondary GM. However, even this may not be sufficient to provide an adequate service life if liner temperatures in excess of 40 °C are going to be encountered.

The work summarized above shows that it is important to consider the effects of the temperature–time history on both the primary and secondary composite liners when designing landfills. This includes consideration of the effect of temperature on desiccation of clay liners (both CCL and GCL) and on the service life of the GMs. The research has also highlighted the need for long-term monitoring of landfill liner temperature and the need for long-term GM ageing studies that will provide improved data for assessing the likely long-term performance of GMs in MSW landfills.

For applications where the estimated GM or GCL service life (based on the primary liner temperature that may reasonably be expected) is not sufficient, options include (*i*) changing the barrier system design (e.g., thickening the primary liner) and (or) the choice of materials (e.g., some GMs will have a much longer service life than others), (*ii*) changing the method of landfill operation so as to reduce heat generation (e.g., avoiding reactive wastes, not operating the landfill as a bioreactor, etc.), (*iii*) cooling the primary liner (e.g., Rowe et al. 2010*d*) or (*iv*) insulating the secondary liner from the full effect of the primary liner temperature (e.g., Hoor and Rowe 2011).

Summary and conclusions

This paper has explored factors that can affect the performance of geomembranes (GMs) and clay liners (CLs) with emphasis on geosynthetic clay liners (GCLs) as part of composite liners for containing MSW leachate both in landfills and leachate lagoons. Based on the new analyses presented and data examined herein, the following conclusions have been reached.

Based on the typically assumed 2.5 to 5 holes/ha used for design calculations of leakage through GMs installed with strict CQA/CQC, even very small holes (radius = 0.5 mm) in a GM used as a single liner would cause leakage of 250 to 500 lphd for a 0.3 m design head in a landfill and 1000 to 2000 lphd for a lagoon with 5 m head. For a typical design hole with an area of 1 cm^2 (radius = 5.6 mm), the corresponding leakages are 32 000 to 63 000 lphd for a 0.3 m head and 130 000 to 260 000 lphd for a 5 m head.

For a single clay liner as part of the primary liner in a double liner system, the leakages assuming typical design hydraulic conductivities are about 1300 lphd for both a GCL ($k_L = 5 \times 10^{-11}$ m/s, $H_L = 0.01$ m) and CCL ($k_L = 1 \times 10^{-9}$ m/s, $H_L = 0.6$ m) for a landfill application with a head of 0.3 m and about 22 000 lphd for a GCL and 8000 lphd for a CCL in a lagoon application ($h_w = 5$ m).

Provided that there is sufficient ballast above the GM to ensure composite liner action (e.g., to avoid GM uplift from the underlying CL), then for 5 holes/ha (each with an area, $a = 1$ cm^2) in the GM component of a composite liner in a double liner system where the GM is in direct contact with the CL (i.e., there are no wrinkles), the calculated leakage

Table 15. Estimated service life of a 1.5–2 mm HDPE GM based on two temperature–time histories (modified from Rowe and Islam 2009).

t_1 (year)	t_2 (year)	t_3 (year)	t_4 (year)	T_o (°C)	T_p (°C)	Estimated service life (years)
8	14	20	40	10	37	1900–3300
0	8	30	40	20	60	20–30

for a GCL is less than 0.2 lphd even for a hydraulic conductivity as high as 2×10^{-8} m/s and less than 3 lphd for a CCL ($k_L = 1 \times 10^{-9}$ m/s, $H_L = 0.6$ m) for a typical landfill design head ($h_w = 0.3$ m), and less than 2 lphd for a GCL and 36 lphd for a CCL in a lagoon application ($h_w = 5$ m). Thus a well-constructed composite liner where the GM is in direct contact with the CL can result in leakages many orders of magnitude less than that which might be expected for a single GM or CL.

When a clay liner is used as a single liner it is very important to consider the factors that can affect hydraulic conductivity and to adopt a design value relevant to the expected conditions at the site as they may be quite different from "typical" values obtained by permeating a GCL or CCL with water in the laboratory. For a GCL, the typically specified $k_L = 5 \times 10^{-11}$ m/s may be a reasonable value for GCLs permeated with water at low (3 to 4 kPa) stress levels and can also closely approximate the values obtained for GCLs permeated with a realistic simulated MSW leachate at stresses of 25 to 35 kPa. However, permeation of a GCL with leachate at low confining stress (e.g., in leachate lagoon applications) could result in a value of $k_L = 2 \times 10^{-10}$ m/s or, in a very extreme case, $k_L = 2 \times 10^{-8}$ m/s. On the other hand, at higher stresses applicable to landfill applications, much lower hydraulic conductivities of 7×10^{-12} m/s may be achieved. For CCLs a typical design k_L is 1×10^{-9} m/s. Well-constructed CCLs may achieve $k_L = 5 \times 10^{-10}$ m/s or even $k_L \leq 1 \times 10^{-10}$ m/s after consolidation; however, a CCL could also have $k_L = 1 \times 10^{-8}$ m/s unless care is taken in the selection of the soil and compaction procedures.

The leakage through a single CL is linearly proportional to k_L; however, this is not the case for composite liners where the GM is in direct contact with the CL. In this case, it is the interface transmissivity rather than the hydraulic conductivity of the CL that controls leakage.

The reported GM–GCL interface transmissivity for a reinforced GCL (needle-punched and stitch-bonded) may vary between a high of 2×10^{-10} m^2/s and a low of 6×10^{-12} m^2/s with an average of about 4×10^{-11} m^2/s for all the reinforced GCL data and about 2×10^{-11} m^2/s for all the GCLs containing sodium bentonite at 50 kPa. Although higher stress may give slightly lower transmissivity, there was no strong trend. Likewise the geotextile in contact with the GM and the hydraulic conductivity of the GCL had very little effect on the interface transmissivity. Based on presently available data, a typical design transmissivity for a GM–CCL assuming good construction practice appears to be about 2×10^{-8} m^2/s.

Although wrinkles can be avoided, this is expensive and is not typical outside of Germany. New calculations presented in this paper further illustrate the point raised by Rowe (2005) that calculations of leakage for composite liners assuming direct contact (i.e., no linear features like wrinkles) between the GM and the CL significantly underestimate (i.e., by one or more orders of magnitude) the actual leakage in typical North American landfills.

The Rowe (1998) equation for leakage through wrinkles (eq. [6]) can explain the observed leakage in North American landfills for heads and connected wrinkle lengths typical of that observed in landfills during construction.

Based on the presently available data, it can be concluded that although wrinkles may reach heights of 0.2 m or more and widths up to 0.5 m on occasion, for 1.5 mm thick HDPE GM (smooth or textured), at least during the typical eastern Canadian construction season, wrinkles were typically about 0.06 m high and about ($2b =$) 0.2 to 0.3 m wide. The average width did not change significantly over most of the day. The length of connected wrinkles varied substantially with the time of day and to some extent with the size of the unconstrained area. If the GMs were covered with the leachate collection layer before 0800 or after 1600, there would have been about 6 to 7 connected wrinkles/ha with connected length $L \leq 200$ m. This length would increase with the time of day the GM was covered, typically peaking at around 1300 with an connected length of about 2000 m for an unrestrained area of up to about 0.2 ha (and larger for larger unrestrained areas).

It would appear that at low heads, connected wrinkle lengths (with a hole) of $85 \leq L \leq 700$ m and at higher heads of $400 \leq L \leq 700$ m most likely explain the leakages typically observed through a primary composite liner in double lined landfills in North America. These lengths are consistent with what one would expect based on the field studies reported by Chappel et al. (2011) and Rowe et al.[2] if the GM was covered when the area of the base with wrinkles was between about 3% and 15%.

Allowing for typical wrinkles, the leakage through composite liners can still be very small compared to a single GM or CL alone for a landfill application ($h_w = 0.3$ m). For a GCL with $k_L = 2 \times 10^{-10}$ m/s below the wrinkle and $k_L = 5 \times 10^{-11}$ m/s outside the wrinkle, the calculated leakage is less than about 14 lphd for $L \leq 200$ m and less than 50 lphd for $L \leq 700$ m. For a 0.6 m thick CCL ($k_L = 1 \times 10^{-9}$ m/s), the corresponding calculated leakages were less than about 83 lphd for $L \leq 200$ m and less than 580 lphd for $L \leq 700$ m.

For leachate lagoons where interaction between the GCL and leachate is a significant concern (i.e., where $k_L \sim 2 \times 10^{-8}$ m/s might be anticipated in some cases), the use of a composite liner with a GCL and CCL together can result in a substantial reduction in leakage provided that there is sufficient ballast above the GM to ensure composite liner action (e.g., to avoid GM uplift from the underlying CL). Here the GCL serves to restrict the lateral migration of leachate between the GM and the GCL due to its good interface transmissivity, while the thickness of the CCL controls the leakage in the zones beneath the wrinkle and out to where leachate can migrate between the GM and GCL. For this case ($h_w = 5$ m) the leakage was 65 lphd for $L = 200$ m and 220 lphd for $L = 700$ m. Designers should be wary of the effectiveness of composite liner action when the GM is exposed and there is potential for the GM to lift (even very slightly) from the underlying CL; in these cases a leakage control layer and secondary liner may be required to control leakage.

To ensure good composite liner action, it is important that (*i*) CCLs below the GM not be allowed to desiccate (even desiccation of the upper few centimetres of liner will substantially increase the GM–CCL interface transmissivity and hence leakage) and (*ii*) GCL panels not be allowed to shrink to the point where overlap integrity is lost. The best way of protecting the integrity of both the CCL and GCL is to cover the composite liner with the drainage or other soil protective layer quickly after placement of the GM. CCLs can significantly desiccate after only a few hours of exposure given that GM temperatures can easily reach 50 to 70 °C on a sunny day. GCL panel separation is not as urgent a problem as CCL desiccation, but panel separation can occur in less than 2 months in some situations, while in other circumstances the composite liner can be exposed for up to 5 years without separation. These differences are likely a result of a combination of the factors discussed in this paper. The shrinkage strain required to cause the loss of 150 to 300 mm of panel overlap could be mobilized in about five wet–dry cycles of the magnitude examined in several studies discussed in this paper.

The potential for loss of GCL panel overlap can be minimized by placing panels with 300 mm of overlap and then placing the drainage layer (or other cover soil) as quickly as possible after placement of the GM over the GCL as noted above. In cases where this may not be practical, other options include (*i*) using a GCL that has demonstrated relatively low shrinkage in the field and (or) (*ii*) mechanically bonding the overlaps (e.g., by sewing or heat-tacking). However, while both these latter approaches may substantially reduce the risk of panel separation, there is no assurance that they will prevent panel separation under worst-case conditions; the best solution is to cover the composite liner quickly.

Heat generated in a landfill may result in landfill liner temperatures of 30 to 40 °C for "normal" MSW landfills. Substantially higher liner temperatures (50 to 60 °C) have been observed for cases where there has been significant moisture augmentation. Although there are no explicit liner temperature measurements, waste temperatures of 60 to 80 °C at locations only a few metres above the liner have been observed in some unusual MSW landfills with leachate temperatures of 50 to 60 °C. For ashfills, temperatures of 50 to 90 °C have been observed 3 m above the liner and leachate temperatures of 65 to 70 °C have been recorded. Landfills containing reactive wastes, such as aluminum production wastes, have been observed to generate waste temperatures in the landfill in excess of 143 °C.

CCLs are particularly prone to desiccation, especially when compacted near (or above) the plastic limit as is often done to achieve a low hydraulic conductivity. Desiccation may occur (*i*) after construction of the clay liner and before placing the drainage layer or geomembrane, (*ii*) after placing the geomembrane and before covering with the drainage layer, and (or) (*iii*) after placement of waste. In the first two cases the heat is generated by the sun, while in the last case the heat is generated by the waste.

There is also potential for desiccation of GCLs even at traditional MSW landfill liner temperatures (35 to 40 °C) under conditions of low stress and where the foundation soil has low initial moisture content. As the liner temperature increases, the risk of desiccation increases and thus special care is required for waste that can generate heat in excess of about 35 to 40 °C on the liner (e.g., MSW incinerator ash containing aluminum, reactive waste, and when aggressively operating a MSW landfill as a bioreactor).

The presently available data suggest that for landfill liners with maximum temperatures of 30 to 40 °C, the service life of a 1.5 mm HDPE GM with a good resin and antioxidant package may be very long (thousands of years). However, the same data suggests that for liners subjected to temperatures of 60 °C the service life can be reduced to decades (and even less at higher temperatures).

It is important to consider the effects of the temperature–time history on both the primary and secondary composite liners when designing MSW landfills. This includes consideration of the effect of temperature on desiccation of clay liners (both CCL and GCL) and on the service life of the GMs. Recent research has highlighted the need for long-term monitoring of landfill liner temperature and the need for long-term GM ageing studies that will provide improved data for assessing the likely long-term performance of GMs in MSW landfills.

For applications where the estimated GM or GCL service life based on the primary liner temperature that may reasonably be expected is not sufficient, options include (*i*) changing the barrier system design (e.g., thickening the primary liner) and (or) the choice of materials (e.g., some GMs will have a much longer service life than others), (*ii*) changing the method of landfill operation so as to reduce heat generation (e.g., avoiding reactive wastes, not operating as a bioreactor, etc.), (*iii*) cooling the primary liner or (*iv*) cooling the secondary liner.

To minimize leakage through composite liners, it would appear that future design guidelines need to pay more attention to issues such as (*i*) wrinkles in GMs, (*ii*) the hydraulic conductivity of GCLs used in low stress applications (e.g., leachate lagoons) where there are wrinkles and potential for interaction with leachate, (*iii*) selection of the best GCL for a given application (they are not all the same), (*iv*) temperatures to which the liner may be subjected during its design life, (*v*) potential for desiccation of clay liners when the waste or fluid to be contained will be at temperatures of 35 °C or higher, and (*vi*) tensile strains in the GM. Also, installation guidelines and construction specifications need to pay more attention to issues such as (*i*) when to cover GMs to control wrinkles to an acceptable level, (*ii*) avoiding desiccation of CCLs before they are covered with a GM, (*iii*) covering the GM above a CCL quickly so that it does not desiccate when the GM is exposed to sunlight, (*iv*) moisture content of the subgrade upon which a GCL is placed, (*v*) placing GCLs with a 300 mm overlap or mechanically bonding the panels, and (*vi*) covering the composite liner as quickly as practicable (the longer it is exposed to the sun the greater the potential problems that can arise).

Based on the available data, it can be concluded that composite liners have performed extremely well in field applications for a couple of decades. The recent findings reported and examined in this paper aid in understanding why they have worked so well, but also provides new insight into issues that need to be considered to ensure excellent long-term liner performance of composite liners — especially for applications where the liner temperature can exceed about 35 °C.

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List of symbols

A area of liner under consideration (m^2)
a area of a hole in GM (m^2 or mm^2)
b half-width of a wrinkle (m)
C_B coefficient related to the shape of the edges of the hole in GM
CEC cation exchange capacity
D thickness of the CL and AL ($= H_L + H_A$) (m)
D_{60} soil particle diameter at which 60% of the mass of the soil specimen is finer
g acceleration due to gravity (m/s^2)
H_A thickness of attenuation layer (m)
H_L thickness of clay liner (m)
h_a height of potentiometric surface above aquifer (m)
h_d head loss across the composite liner ($= h_w + H_L + H_A - h_a$) (m)
h_w leachate head on liner (m)
i hydraulic gradient
i_s hydraulic gradient across CL and AL
k hydraulic conductivity/permeability (m/s)
k_A hydraulic conductivity of AL (m/s)
k_L hydraulic conductivity of clay liner (m/s)
k_s harmonic mean hydraulic conductivity of CL and AL (m/s)
L length of connected wrinkle (m)
M_A mass per unit area of GCL (g/m^2)
Q leakage (m^3/s or lphd)
r_o radius of a hole in a GM (m)
SCR stress crack resistance
SI swell index
T_0 liner temperature in the absence of any waste-generated heat
T_p peak liner temperature
θ GM–CL interface transmissivity (m^2/s)