

Assessment of equivalence of composite liners

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ABSTRACT: The equivalence of composite liners involving a geomembrane (GM) and a compacted clay liner (CCL) to alternative composite liners with a geomembrane, geosynthetic clay liner (GCL) and attenuation layer (AL) is assessed in terms of the contaminant impact occurring in a receptor aquifer. Calculations of contaminant impact of dichloromethane, benzene and chloride through GM/CCL/AL and GM/GCL/AL composite liners are reported for a hypothetical municipal solid waste landfill. The geomembrane in conjunction with either the CCL or GCL is very effective at controlling leakage such that diffusion essentially dominates the impact on the aquifer for the service life of the geomembrane. The geomembrane itself offers little resistance to diffusion of dichloromethane and benzene, and consequently the CCL or GCL and AL (of suitable thickness) are required to protect the aquifer. In contrast, the geomembrane acts as an excellent diffusion barrier to chloride over its service life. For the cases and parameters examined, the GM/GCL/AL liners were found to provide the same or even greater environmental protection to the underlying aquifer relative to GM/CCL/AL liners provided the total thickness of the liner system with the GCL was the same as that with the CCL. This can be achieved by having a thicker attenuation layer with the GM/GCL liners. Chloride impacted on the aquifer only after the service life of the geomembrane had been reached, after which contaminant transport was controlled by advection through the soil component of the liner for the cases examined.

KEYWORDS: Geosynthetics, Composite liners, Equivalence, Geomembranes, Geosynthetic clay liners, Landfills

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1. INTRODUCTION

1.1. Composite liners

Composite liners consisting of either a geomembrane (GM) and a compacted clay liner (CCL) or a geomembrane and a geosynthetic clay liner (GCL) are intended to minimise the migration of contaminants from municipal solid waste (MSW) landfills. Possible composite liners for different regulatory jurisdictions are illustrated in Figure 1.

Contaminant transport through the geomembrane is limited to leakage through small holes or defects in the geomembrane and diffusion through the intact geomembrane for many non-polar, volatile organic compounds. The clay component of the composite liner systems reduces the leakage through holes in the geomembrane and resists diffusive migration of contaminants. The base upon which the liner is constructed also serves as an attenuation layer (AL) between the waste and a potential

receptor aquifer, thereby acting as a partial diffusion barrier and providing a greater opportunity for a decrease in the concentration of many organic contaminants due to biodegradation (and possibly sorption).

Designs that are in accordance with the United States, Subtitle D of the Resource Conservation and Recovery Act typically involve a composite liner composed of a minimum of a 1.5 mm-thick HDPE geomembrane and a 0.6 m compacted clay liner with hydraulic conductivity, k , of 1×10^{-9} m/s or equivalent (e.g. the system shown in Figure 1a is compliant with these minimum requirements). The general requirements of the European Communities (EN 16.7.1999) for non-hazardous waste landfills require a minimum of an artificial sealing layer and a mineral liner with a thickness greater than or equal to 1 m with a hydraulic conductivity of at least 1×10^{-9} m/s. A schematic of a composite liner compliant with the European minimum requirements is

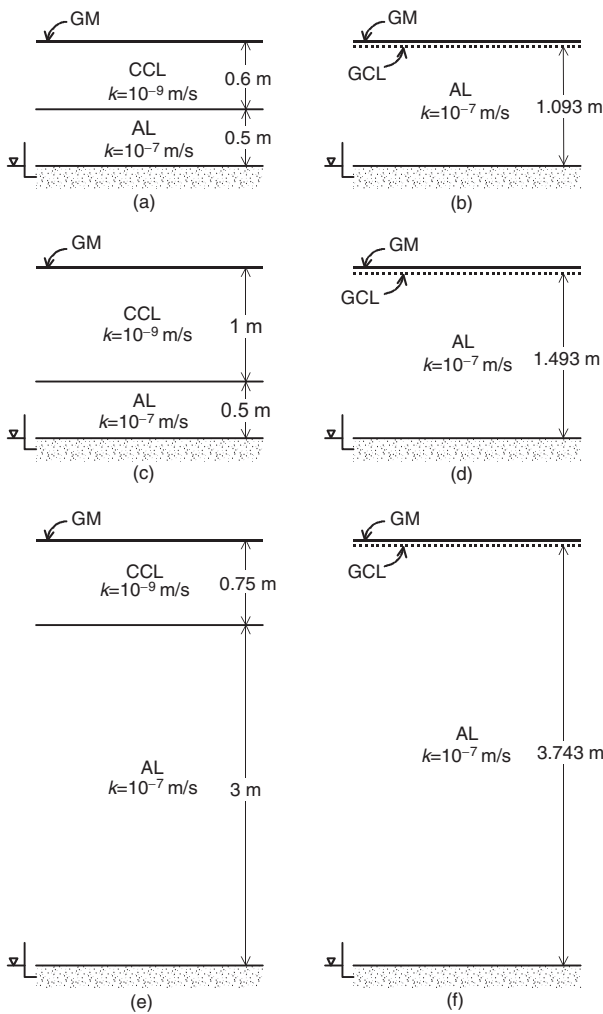


Figure 1. Schematic of the composite barrier systems examined

shown in Figure 1c. Neither the minimum US nor European regulations stipulate the presence of an attenuation layer (i.e. a layer of soil that separates the liner from the underlying aquifer or water resource that needs to be protected). However, there will often be a layer between the composite liner and an underlying aquifer that provides a firm base for construction of the composite liner, and this will serve as an attenuation layer. An arbitrary thickness of attenuation layer of 0.5 m is adopted for the composite liners shown in Figures 1a and 1c, which are referred to as cases a and c respectively. In some cases the attenuation will be less (e.g. for liner systems constructed in old quarries where there is a high water table), but in many situations the attenuation layer will be thicker than that considered here. The influence of the thickness of the attenuation layer on the potential contaminant impact on the aquifer is examined later in the paper.

In the province of Ontario, Canada, Ontario Regulation 232/98 (MoE 1998) requires either a single or a double composite liner, depending on the maximum waste loading and background groundwater chemistry in the receptor aquifer. Under this regulation the minimum default single composite liner system, referred to as case e and shown in Figure 1e, must consist of a 1.5 mm-thick

HDPE geomembrane, 0.75 m-thick clay liner with a hydraulic conductivity no greater than 1×10^{-9} m/s, and 3 m-thick natural or engineered attenuation layer (AL) with a hydraulic conductivity less than 1×10^{-7} m/s. The attenuation layer may be greater than 3 m.

1.2. Equivalence of composite liners

Most regulations allow alternative liner designs provided one can demonstrate ‘equivalence’. Of practical interest in this paper is the question as to whether a GM/GCL composite liner is equivalent to the standard GM/CCL composite liner. However, assessment of equivalence may depend on what is being compared and how it is being compared. Thus the assessment of equivalence of different composite liners may involve considerations of practical issues related to construction, the hydraulic performance, and potential contaminant impact through the composite liners.

1.2.1. Practical considerations

In addition to the contaminant transport considerations that are the focus of this paper, the evaluation of a GCL as an alternative to a CCL may involve consideration of a number of practical factors such as:

- the availability of suitable clay for constructing a CCL;
- the ease of construction of a GM/GCL relative to a GM/CCL composite liner;
- the potential to ensure field quality control;
- ensuring that the GCL is not compromised by internal erosion of bentonite under large hydraulic gradients (this requires attention to the nature of the subgrade material and the choice of GCL; see Rowe and Orsini 2003); and
- slope stability.

As not all GCL products are the same, equivalence must be assessed on a case-by-case basis.

For composite liners with a geomembrane it is important that there is adequate protection of the geomembrane from indentation of gravel to prevent puncture and limit the tensile strains. Limiting the indentations in the geomembrane will also provide protection of the GCL from differential pressure and clay movement from the irregular gravel contacts above the geomembrane. It is also important to minimise the wrinkles in the geomembrane to reduce the effect of holes on leakage through the liner and to limit the tensile strains in the geomembrane (Rowe 1998a). In this assessment of equivalence it is assumed that the geomembrane is adequately protected and free of wrinkles.

1.2.2. Hydraulic equivalence of composite liners

The hydraulic performance of the composite liner is one criterion that may permit comparison of different liner systems. For example, Giroud *et al.* (1997) compared the leakage through composite GM/CCL and GM/CCL liners and the steady-state travel time, neglecting the effects of clay consolidation and diffusion on the time to

first arrival of a conservative contaminant. Similarly, Richardson (1997) considered the leakage and steady-state travel time as well as chemical absorption capacity and dilution potential between composite liners with a CCL and GCL.

Giroud *et al.* (1997) reported that the leakage through a composite liner of a geomembrane and a 0.6 m clay liner with $k = 1 \times 10^{-9}$ m/s was seven times larger than through a composite liner of a geomembrane on top of a 7 mm-thick GCL with $k = 1 \times 10^{-11}$ m/s (with pressure heads of 0.3 m above the GM and zero at the base of either the CCL or GCL). However, their calculations of leakage through composite liners neglected the presence of a soil layer beneath the GCL and assumed that the interface conditions between a GM and GCL are the same for a GM and CCL. The hydraulic equivalence of the different composite liners shown in Figure 1 will be assessed in Section 2.3.3 of this paper including consideration of leakage through the geomembrane and all the soil materials of the barrier system.

1.2.3. Equivalence of contaminant transport through composite liners

Another criterion that may be used to assess the equivalence of composite liners is the calculated contaminant impact on a receptor aquifer beneath a landfill. In this approach the advection–dispersion equation is solved subject to appropriate boundary conditions (Rowe *et al.* 2004). Rowe (1998a) provided a framework to model the contaminant transport through GM/CCL and GM/GCL composite liners considering:

- the source concentration and the decay characteristics of contaminants in landfill;
- the advective flux of contaminants flowing through the barrier system;
- the combined thickness of clay liners and any attenuation layer between the waste and any receptor aquifer;
- the diffusive flux of contaminants migrating through the barrier system;
- sorption or retardation of contaminants in the liner and underlying soil;
- biodegradation of organic contaminants in the liner and underlying soil;
- dilution in the aquifer (if appropriate);
- the finite service life of engineered components of the landfill; and
- the manner in which the landfill is operated.

Rowe (1998a) showed that the peak chloride and dichloromethane concentrations in an underlying aquifer were smaller for a GM/GCL composite liner similar to that in shown Figure 1f than for a GM/CCL composite liner similar to the one shown in Figure 1e.

Foose *et al.* (2002) also modelled the contaminant transport through composite liners for simplified boundary conditions. They reported that the steady-state mass flux of toluene through a GM and a 6.5 mm-thick GCL composite liner was 40 times larger than through a liner with a GM and a 0.61 m-thick CCL (a constant source

concentration on top of the GM and zero concentration at the base of the composite liner were assumed). As they calculated much smaller leakage through the GM/GCL liner than that for the GM/CCL liner they concluded that the equivalence of alternative liner designs should be based on contaminant transport rather than leakage rate, which is consistent with the recommendation of Rowe (1998a). Foose *et al.* (2001b) also considered 1D diffusive and advective flux through a layer of finite depth (assuming zero concentration at the base), where they approximated the flow through a hole by an approximately equivalent 1D flow. As part of this analysis they used approximate means to consider the case of a GCL located on an attenuation layer. They confirmed the earlier finding by Rowe (1998a) that consideration of this attenuation layer makes a significant difference to the mass flux through the composite liner system, and needs to be considered when assessing equivalence.

1.3. Assessment of equivalence of environmental protection of composite liners

The objective of this paper is to assess the equivalence of the environmental protection provided by composite liners involving a geomembrane and geosynthetic clay liner compared with that of composite liners with a geomembrane and a compacted clay liner. The approach of Rowe (1998a) is adopted, and extended to account for recent findings regarding factors that may influence this assessment. These factors include clay–leachate interaction, leakage through geomembranes, diffusion through geomembranes and geosynthetic clay liners, and the service life of geomembranes. Calculations of contaminant impact for composite liners compliant with the regulatory requirements of the United States, European Community and Ontario Canada and possible alternative GM/GCL composite liners are examined for a hypothetical landfill.

2. FACTORS INFLUENCING THE ASSESSMENT OF EQUIVALENCE OF COMPOSITE LINERS

2.1. Clay–leachate interaction

The hydraulic conductivity of a GCL for a given permeant depends on the bulk void ratio of the GCL. This in turn depends on the applied stress, during both hydration and permeation, and the method of manufacture of the GCL. The clay–chemical interaction with groundwater and the type and concentration of permeant will also influence the final bulk hydraulic conductivity of the GCL. The hydraulic conductivity of a GCL to water is very low, and typically may range between 7×10^{-12} and 7×10^{-11} m/s, depending on the bulk void ratio (Rowe 2001).

Shackelford *et al.* (2000) provide a discussion on the factors influencing the hydraulic conductivity of GCLs when permeated with liquids other than water. There is a potential for the hydraulic conductivity to increase

because of interaction between the clay and leachate. For example, three samples of the same GCL (granular bentonite needle-punched between nonwoven cover and carrier geotextiles) tested by Petrov and Rowe (1997) had hydraulic conductivities of: 1.3×10^{-11} m/s when hydrated and permeated with water at 35–37 kPa and 8.7×10^{-11} m/s when hydrated with water but permeated with a particular synthetic leachate at 31 kPa. Even larger increases were measured for lower effective stresses. However, these increases in hydraulic conductivity need not be a problem provided the barrier system has been designed based on the higher hydraulic conductivity of the GCL upon exposure to the leachate. Selection of hydraulic conductivity for landfill design therefore depends on the specific GCL product to be used and the leachate that it is likely to encounter. In this assessment of equivalence of composite barriers using a hypothetical landfill a hydraulic conductivity to leachate of 2×10^{-10} m/s is adopted, based on Rowe (1998a).

2.2. Diffusion through geosynthetic clay liners

Contaminants can migrate through a GCL under a concentration gradient by the process of molecular diffusion. Diffusion through a GCL is essentially the same process as diffusion through a porous medium, although it is possible that there may be some interaction between certain organic species and the geotextile component of the GCL (Lake and Rowe 2004). It is important to consider this interaction when interpreting results from laboratory diffusion tests on GCLs, but it can be shown that it has little effect on the contaminant impact through the composite liners shown in Figure 1, and can be conservatively neglected.

Similar to the hydraulic conductivity of GCLs, the diffusion coefficient depends predominantly on the bulk void ratio. Lake and Rowe (2000) conducted diffusion tests on GCLs with 3–5 g/l solutions of sodium chloride and found a lower diffusion coefficient for lower bulk void ratio ($1.0 < e_B < 3.5$). For a GCL with a bulk ratio of approximately 2 (corresponding to hydration of the GCL with water under a stress of 150 kPa) they reported a diffusion coefficient for chloride of $0.005 \text{ m}^2/\text{a}$ and porosity of 0.7.

Lake and Rowe (2004) also conducted tests that measured the diffusion of volatile organic compounds through GCLs. They reported diffusion coefficients of about $0.009 \text{ m}^2/\text{a}$ and $0.006 \text{ m}^2/\text{a}$ (3×10^{-10} and $2 \times 10^{-10} \text{ m}^2/\text{s}$) for dichloromethane and benzene respectively. These experiments were conducted under effective stresses of 5–10 kPa representing conditions where the GCL hydrates under only 0.25–0.5 m of cover material. The diffusion coefficient is expected to be smaller if hydrated under an effective stress of 150 kPa, as there would be a decrease in bulk void ratio of the GCL. The results of Lake and Rowe (2004) probably represent an upper bound on the diffusion coefficients for dichloromethane and benzene in an actual landfill application (with vertical stresses well above 510 kPa) and are conservatively used in this assessment of equivalence of composite liners.

2.3. Leakage through geomembranes

2.3.1. Leakage and interface conditions

Contaminant migration through a geomembrane can occur by advective flow (often referred to as leakage) through holes or defects in the geomembrane, and by diffusion through the geomembrane. The amount of leakage depends on the number and size of holes, the hydraulic head acting above and below the composite barrier, the hydraulic conductivity and thickness of any underlying soil, and the transmissivity of the interface between the geomembrane and the underlying material.

The quantity of leakage is strongly influenced by the nature of the contact between the geomembrane and the underlying soil. Gaps along this interface may arise from (Rowe 1998a):

- protrusions related to particle size distributions;
- small indentations left in the underlying soil from construction equipment; and
- wrinkles in the geomembrane that do not disappear following placement of the waste.

Experiments measuring leakage through composite liners over an area of about 50 m^2 by Touze-Foltz (2001) showed substantial lateral flow along the interface and highly variable leakage rates for a geomembrane on a compacted clay liner.

Even in the absence of these gaps, one would expect (for the same geomembrane and overburden stresses) that different underlying materials (i.e. CCL compared with GCL) would have different interface transmissivities, as discussed by Rowe (1998a). Based on field leakage measurements for composite liner systems with both CCLs and GCLs (Bonaparte *et al.* 2002), the available evidence shows that the leakage through GM/CCL systems is much greater than that through GM/GCL systems, and suggests that the interface transmissivity for a GM/CCL is much greater than that for a GM/GCL (Rowe *et al.* 2004).

Recognising the importance of interface conditions with respect to leakage, Giroud (1997) proposed simple equations to estimate leakage for what was defined as good and poor contact conditions between the geomembrane and an underlying compacted clay liner. Based on these equations, Rowe (1998a) inferred transmissivities of $1.6 \times 10^{-8} \text{ m}^2/\text{s}$ and $1 \times 10^{-7} \text{ m}^2/\text{s}$ for good and poor contact between a geomembrane and 0.6 m clay liner with hydraulic conductivity equal to $1 \times 10^{-9} \text{ m/s}$, respectively. Until more data are published, these values represent the best available estimate of GM/CCL interface transmissivity. A lowest value of $1.6 \times 10^{-8} \text{ m}^2/\text{s}$ is used in this assessment of the equivalence of composite liners to estimate leakage for a GM and CCL.

The transmissivity of the interface between a geomembrane and a geosynthetic clay liner may be expected to be even smaller than for the interface with a CCL, particularly if the cover geotextile of the GCL is impregnated with bentonite. Harpur *et al.* (1993) reported transmissivities of 6×10^{-12} to $2 \times 10^{-10} \text{ m}^2/\text{s}$ for the interface between a geomembrane and different

GCLs with cover and carrier geotextiles. In this paper the highest transmissivity reported by Harpur *et al.* (1993), $2 \times 10^{-10} \text{ m}^2/\text{s}$, is used for the interface transmissivity between a GM and a GCL.

The choice of the lower bound transmissivity for the GM/CCL ($1.6 \times 10^{-8} \text{ m}^2/\text{s}$) and upper bound transmissivity for the GM/GCL ($6 \times 10^{-12} \text{ m}^2/\text{s}$) provides a 'worst case' comparison for assessing the equivalence of a GM/GCL system to a GM/CCL system based on available published information. If the GM/GCL system is as good as, or better than, the GM/CCL system for this set of parameters, it logically follows (as confirmed by analysis) that it would also be as good as, or better than, the GM/CCL system (i.e. 'equivalent') for other combinations of transmissivity values within the likely range for the two systems.

2.3.2. Calculating leakage rates through composite liners

Rowe (1998a) presented a theoretical solution for leakage through composite liners that considers flow through a circular hole in a geomembrane and the low-permeability soil beneath the geomembrane within the zone defined by the wetted radius. One-dimensional vertical flow through the clay and lateral flow along the interface between the geomembrane and the underlying soil with transmissivity θ was considered. Foose *et al.* (2001a) showed that there is negligible difference between this approach and the modelling of three-dimensional flow in the underlying soil, provided the transmissivity is greater than $2 \times 10^{-10} \text{ m}^2/\text{s}$ for a GM/CCL composite liner (with $k = 1 \times 10^{-9} \text{ m/s}$) and greater than $8 \times 10^{-13} \text{ m}^2/\text{s}$ for a GM/GCL composite liner (with $k = 2 \times 10^{-10} \text{ m/s}$). The solution of Rowe (1998a) can therefore be used to estimate leakage through composite liners for expected ranges of transmissivity.

The solution of Rowe (1998a) does underestimate the leakage for 'perfect' contact between the GM and the underlying soil by a factor of 2. For the case of 'perfect' contact, the semi-analytical solution of Rowe and Booker (2001) or the numerical solution of Foose *et al.*

(2001a) can be used, although it is likely that 'perfect' contact rarely, if ever, governs the flow in a landfill.

2.3.3. Comparison of leakage rates for GM/CCL and GM/GCL composite liners

Calculations of leakage rates using the solution of Rowe (1998a) through the different composite barriers shown in Figure 1 are given in Table 1. These results are for a 'large' circular defect as defined by Giroud (1997) with radius 0.00564 m and frequency of 2.5 holes/ha, and assume that the hole does not coincide with a wrinkle in the geomembrane. Results are given for three different hydraulic heads acting on top of the GM: 0.3 m head corresponds to an operational leachate collection system, and larger heads of 6 and 12 m represent the mounding of leachate when the effectiveness of leachate collection is reduced (e.g. by biologically induced clogging of the leachate collection system). The piezometric head in the underlying aquifer was taken as the elevation of the top of the aquifer, as shown in Figure 1.

The leakage rates for GM/CCL composite barriers are compared with alternative composite barrier systems with a GM, a GCL and an attenuation layer (AL), with the thickness of the AL such that the total thickness between the GM and the top of the aquifer is the same for a given regulatory design. For example, the combined thickness of the GCL (thickness of 7 mm) and attenuation layer in Figure 1b is the same as the combined thickness of the CCL and the AL in Figure 1a.

The hydraulic conductivity of the CCL was taken to be $1 \times 10^{-9} \text{ m/s}$. The hydraulic conductivity of the GCL was taken to be $2 \times 10^{-10} \text{ m/s}$ to account for exposure to leachate. The hydraulic conductivity of the attenuation layer was taken to be $1 \times 10^{-7} \text{ m/s}$, recognising that this layer may be sandy silt.

In all cases, the calculated leakage through the GM/CCL/AL composite liners is larger than the leakage through the GM/GCL/AL alternatives. For example, the leakage through the GM + 0.6 m CCL + 0.5 m AL liner in Figure 1a is 30 times greater than that for the GM + GCL + 1.093 m AL system in Figure 1b, with a

Table 1. Calculated leakage rates through composite liners shown in Figure 1 for different leachate mounds (h_w) acting on the geomembrane. The geomembrane is assumed to have 2.5 undetected circular holes of radius 5.64 mm per hectare

Fig.	Liner system	Leakage rate						
		$0 - T_1: h_w = 0.3 \text{ m}$		$T_1 - T_2: h_w = 6 \text{ m}$		$T_2 - T_3: h_w = 12 \text{ m}$		$> T_3$
		(lphd)*	(m/a)	(lphd)*	(m/a)	(lphd)*	(m/a)	(m/a)
1a	GM + 0.6 m CCL + 0.5 m AL	1.4	5.0×10^{-5}	22	8.1×10^{-4}	43	1.6×10^{-3}	0.15
1b	GM + GCL + 1.093 m AL	0.047	1.7×10^{-6}	0.62	2.3×10^{-5}	1.2	4.3×10^{-5}	0.15
1c	GM + 1 m CCL + 1 m AL	1.4	4.9×10^{-5}	22	7.9×10^{-4}	42	1.5×10^{-3}	0.15
1d	GM + GCL + 1.493 m AL	0.049	1.8×10^{-6}	0.62	2.3×10^{-5}	1.2	4.3×10^{-5}	0.15
1e	GM + 0.75 m CCL + 3 m AL	1.5	5.5×10^{-5}	23	8.5×10^{-4}	45	1.7×10^{-3}	0.15
1f	GM + GCL + 3.743 m AL	0.056	2.0×10^{-6}	0.65	2.4×10^{-5}	1.2	4.4×10^{-5}	0.15

*Litres per hectare per day.

Table 2. Properties of HDPE geomembrane used in contaminant transport analyses

Property	Value	Units
Thickness	0.0015	m
Diffusion coefficient chloride, D_g	1.3×10^{-6}	m^2/a
Diffusion coefficient dichloromethane, D_g	2.0×10^{-5}	m^2/a
Diffusion coefficient benzene, D_g	1.1×10^{-5}	m^2/a
Partitioning coefficient chloride, S_{gr}	8×10^{-4}	
Partitioning coefficient dichloromethane, S_{gr}	6	
Partitioning coefficient benzene, S_{gr}	30	
Number of holes	2.5	holes/ha
Hole radius	0.00564	m
Service life at 20°C	120	years
Service life at 33°C	70	years

head of 0.3 m on top of the GM. Although the harmonic mean hydraulic conductivity of the GCL and attenuation layer are greater than the hydraulic conductivity of the CCL they are replacing, less leakage occurs for the GM/GCL/AL systems because of the much lower transmissivity between the GM and GCL compared with the GM and CCL.

Leakage increases as the head on the liner system increases. However, both GM/CCL and GM/GCL liners are very effective at controlling leakage, with the GM/GCL allowing just over 1 lphd of leakage for a head of 12 m acting on the top of the geomembrane.

Similar leakage rates were calculated for the GM/CCL liners shown in Figures 1a, 1c and 1e. The calculated leakage rates for the different GM/GCL/AL liner systems (Figures 1b, 1d and 1f) are nearly the same. This indicates that the thickness of the attenuation layer has no substantial effect on the leakage rate. It will be shown in Section 3.3, however, that the attenuation layer does have an important effect on the diffusion of contaminants and hence on contaminant impact through the barrier system.

2.4. Diffusion through geomembranes

In addition to leakage through holes, contaminants can migrate by diffusion through the intact portion of the geomembrane. This process involves:

- adsorption at the interface between the medium containing the permeant and the inner surface of the geomembrane;
- diffusion of the permeant through the polymeric structure of the geomembrane; and
- desorption at the interface between the outer surface of the geomembrane and the outer medium (e.g. Park and Nibras 1993).

Partitioning at the geomembrane interface can be characterised by the coefficient S_{gr} , and diffusion in the geomembrane is characterised by D_g .

For HDPE geomembranes commonly used as liners in municipal solid waste landfills, the geomembrane is an excellent diffusive barrier to water and hydrated ions (e.g. Na^+ , Cl^- , Zn^{2+} , Ni^{2+} , Mn^{2+} , Cu^{2+} , Cd^{2+} and Pb^{2+}), but is not a good diffusion barrier for organic compounds such as toluene and dichloromethane. Rowe *et al.* (2004) inferred a diffusion coefficient for chloride of

$D_g = 1.3 \times 10^{-6} m^2/a$ using the partition coefficient for water of $S_{gr} = 8 \times 10^{-4}$ based on a permeation diffusion test with over 10 years of data. These values are used in this paper. For dilute organic contaminants Sangam and Rowe (2001a) reported partition and diffusion coefficients obtained from permeation tests on a 2 mm-thick HDPE geomembrane at a temperature of $22 \pm 2^\circ C$. Values for dichloromethane and benzene obtained from these studies and used in this paper are given in Table 2.

2.5. Service life of geomembranes

Even a well-designed and properly constructed geomembrane is expected to have a finite service life. Quantifying the service life of a geomembrane, however, is difficult given the complex chemical and physical conditions and possibly high temperatures that it is likely to experience in a landfill.

It is possible to obtain estimates of service life using elevated antioxidant depletion tests. As oxidation is the primary degradation mechanism that may limit the service life of HDPE geomembranes, and oxidation of the polymer is retarded by the presence of antioxidants, the chemical ageing of an HDPE geomembrane may be considered as the sum of (Hsuan and Koerner 1998):

- the time to deplete the antioxidants by consumption and/or extraction;
- the induction time to the onset of polymer degradation; and
- the time for degradation of the polymer to decrease some property (or properties) to an arbitrary level (e.g. to 50% of the original value).

Sangam and Rowe (2002) reported the depletion times of antioxidants in samples of HDPE geomembranes measured by the oxidative inductance time (OIT). Tests were conducted at temperatures between 22 and 85°C, and predictions were extrapolated to lower temperatures using Arrhenius modelling. They found that depletion times were longest for samples immersed in air and shortest for samples in leachate, and decreased with increased temperature. Estimates of antioxidant depletion time for a geomembrane exposed to leachate on one side and 'unsaturated soil' on the other side (likely conditions for a primary geomembrane liner) were also

given by Sangam and Rowe (2002) to be 140 years at 15°C and 40 years at 33°C.

The service life of a geomembrane can then be estimated for a given temperature and exposure conditions using: these antioxidant depletion times, inferred from accelerated immersion tests of Sangam and Rowe (2002); the induction time reported by Viebke *et al.* (1994) for an unstabilised HDPE; and an assumed degradation time of 25 years (Rowe 1998a). Using this approach, the service life for a primary HDPE geomembrane liner is estimated to be greater than 200 years provided the landfill is well maintained such that the temperature is not higher than 15°C. The service life is estimated to be reduced to 120 years if the temperature at the base of the landfill is 20°C, and 70 years if the temperature is 33°C. These values are used in the assessment of equivalence of composite liners in this paper, and are considered to be conservative (i.e. err on the low side) based on currently available information.

3. ASSESSMENT OF CONTAMINANT IMPACT THROUGH COMPOSITE LINERS

3.1. Description of contaminant transport model

Contaminant impact for GM/CCL composite barriers is now compared with that for alternative composite barrier systems with a GM, a GCL and an attenuation layer (AL) to assess the equivalence of the environmental protection provided by each composite barrier system. Concentrations in the receptor aquifer located beneath the barrier systems were calculated for the six composite barrier systems shown in Figure 1 using the one-dimensional finite layer contaminant transport model for multilayered systems, POLLUTE v. 6 (Rowe and Booker 1997). Contaminant impact analyses were conducted for chlorinated organic solvent dichloromethane (DCM) and aromatic hydrocarbon benzene, both often found in low but significant concentrations in MSW leachate. The migration of chloride was also examined, as it is representative of conservative inorganic contaminants.

The details of the numerical model and its validation by comparison to experimental results have been published for the diffusion of chloride through HDPE geomembranes (Rowe 1998a; Rowe *et al.* 2004), the migration of volatile organic compounds through HDPE geomembranes (Sangam and Rowe 2001a), the migration of chloride and DCM through geosynthetic clay liners (Lake and Rowe 2000, 2004), and the migration of DCM and TCE through composite liners (Sangam and Rowe 2001b). The model has also been successfully used to predict the field performance of a GM/CCL composite liner (Rowe *et al.* 2003). Rowe *et al.* (2004) provide a summary of this work together with full details of the modelling methodology.

The Darcy flux through the composite liner was obtained by dividing the total leakage rate through the 2.5 circular holes (with radius of 5.64 mm, area 1 cm²)

per hectare in the geomembrane by the entire footprint of the landfill. Although this approach underestimates the seepage velocity immediately beneath the defect, the error introduced in the calculated peak impact in the aquifer is expected to be negligible for the cases examined in this paper. This is because the calculated leakage rates are so small that diffusion (which is 1D) controls the peak impact for volatile organic compounds, and failure of the geomembrane (which reduces the problem to a 1D problem) controls for chloride. A comparison between results obtained from a full 3D analysis with those from this simplified approach is currently in progress (Abdel-Atty, personal communication), but is beyond the scope of this paper.

3.2. Description of barrier systems

All composite liners were modelled with a 1.5 mm-thick HDPE geomembrane. The properties of the geomembrane used in the analysis are summarised in Table 2. It is assumed that a leak detection survey was conducted and that all holes detected were repaired. However, it is recognised that not all holes will be detected, and so it was assumed that the geomembrane had 2.5 undetected 'large' circular defects with radius 0.00564 m per hectare. For the current comparison, it was also assumed that the holes did not coincide with wrinkles in the geomembrane.

The properties of the compacted clay liner, geosynthetic clay liner and attenuation layer used in the analyses are given in Table 3. The compacted clay liner was 0.6, 1.0 and 0.75 m thick for the cases shown in Figures 1a, 1c and 1e respectively. The compacted clay liner was assumed to have a diffusion coefficient of 0.02 m²/a and a porosity of 0.4.

For the cases involving a 7 mm-thick GCL (Figures 1b, 1d and 1f) the thickness of the attenuation layer was selected such that the total thickness between the GM and the top of the aquifer was the same for a given regulatory design. To recognise that this layer may be composed of natural or engineered soils that are more permeable than the compacted clay liner, the attenuation layer was modelled with typical parameters for sandy silt using a hydraulic conductivity of 1×10^{-7} m/s, diffusion coefficient of 0.022 m²/a (Rowe *et al.* 2004), and porosity of 0.3.

No sorption of volatile organic compounds (VOCs) was modelled in the materials beneath the geomembrane as sorption is highly dependent on the organic carbon content of the clay and attenuation layers, and cannot be relied on for generic comparisons (as per MoE 1998). As sorption tends to reduce the peak impact when there is a finite mass of contaminants in the landfill, neglecting sorption is a conservative and equal basis on which to compare the alternative barrier systems. Biodegradation of VOCs in the soil below the geomembrane was considered with a half-life of 50 years for dichloromethane and 125 years for benzene, based on a review of data relating to the biodegradation of contaminants in soil (Hrapovic 2001) and recognising that, unlike typical cases where leachate is migrating through soil, when

Table 3. Properties of compacted clay liner (CCL), geosynthetic clay liner (GCL) and attenuation layer (AL) used in contaminant transport analysis

Property	CCL	GCL	AL	Units
Thickness				
United States ^(d)	0.6 ^(d)	0.007	0.5, 0.593	m
Europe ^(d)	1.0 ^(d)	0.007	0.5, 0.993	m
Ontario ^(d)	0.75 ^(d)	0.007	3 ^(d) , 3.743	m
Hydraulic conductivity to leachate	1×10^{-9}	2×10^{-10}	1×10^{-7}	m/s
Diffusion coefficient	0.02	0.005 ^(a) , 0.009 ^(b) , 0.006 ^(c)	0.022	m ² /a
Sorption	0	0	0	
Porosity	0.4	0.7	0.3	
Transmissivity of geomembrane/clay interface	1.6×10^{-8}	2×10^{-10}		m ² /s
Half-life in soil				
Chloride	∞	∞	∞	year
Dichloromethane	50	50	50	year
Benzene	125	125	125	year

^(a) Chloride^(b) Dichloromethane.^(c) Benzene.^(d) Values specified in regulation.

VOCs diffuse through a geomembrane (the dominant transport mechanism for VOCs) the other soluble substrates (e.g. volatile fatty acids, nitrogen and phosphorus) are held back by the geomembrane and cannot readily migrate through the geomembrane owing to the very low diffusion and partitioning coefficients for polar compounds and ions. Thus the rate of degradation in the soil below the geomembrane can be expected to be substantially lower than that in the waste, where other substrates are readily available and the temperature is higher (Rowe *et al.* 2004).

3.3. Description of landfill

A landfill with a mass of waste of 250 000 t/ha was considered. The boundary condition in the landfill was modelled considering the finite mass of contaminants available for transport through the liner system. The source concentration in the landfill is allowed to decrease as leachate is collected and removed, contaminants degrade, and/or migrate through the liner system, as described by Rowe and Booker (1997). Initial concentrations, half-lives and proportion of contaminants within the waste for chloride, dichloromethane and benzene used in the analyses are summarised in Table 4 (based on MoE 1998 unless otherwise noted).

The boundary condition beneath the barrier system was modelled as a 3 m-thick aquifer with a porosity of 0.3. Dilution of contaminants within the aquifer was considered assuming a horizontal Darcy flux of 1 m/a.

The time frame of events during the operation and post-closure of the landfill modelled is illustrated in Figure 2. The landfill was assumed to operate for a 20 year period. All time is expressed relative to the middle of this period. To express time relative to closure of the landfill, one can subtract 10 years from all reported times.

For the time period between 0 and T_1 the landfill was assumed to have a low-permeability cover limiting infiltration to 3×10^{-4} m³/m²/a, and an operational leachate collection system limiting the hydraulic head on

top of the GM to 0.3 m. It is unknown as to how long society will maintain low-permeability covers, but it is not unreasonable to assume that it is between one and three generations. The available data suggest that the service life of leachate collection systems could be as low as one generation (or less) for systems without a coarse drainage layer (Rowe 1998b), but projections indicate it could well be of the order of 100 years for well-designed systems (MoE 1998; Rowe and Fleming 1998). Recognising the uncertainties, a sensitivity analysis was performed and two values of 40 and 110 years were examined for T_1 (i.e. 30 and 100 years post-closure).

Following the approach of Rowe (1998a), the cover was no longer maintained after time T_1 , and the infiltration was assumed to increase to 0.15 m³/m²/a (MoE 1998). The operation of the leachate collection system was also terminated after T_1 , allowing the leachate head on the GM to increase. It was assumed that the leachate head reached a maximum of 12 m at a time, T_2 , 20 years following termination of leachate

Table 4. Properties of the landfill used in the contaminant transport

Property	Value	Units
Landfill width	1000	m
Mass of waste per unit area	250 000	t/ha
Proportion of chloride in waste ^(a)	1800	mg/kg
Proportion of DCM in waste ^(a)	2.3	mg/kg
Proportion of benzene in waste ^(a)	0.014	mg/kg
Initial concentration in waste ^(a)		
Chloride	2500	mg/l
DCM	3300	µg/l
Benzene	20	µg/l
Half-life in landfill		
Chloride ^(a)	∞	year
DCM	2 ^(b) , 5 and 10 ^(a)	year
Benzene ^(a)	25	year

^(a) Based on MoE (1998).^(b) Default value (used unless otherwise noted); other values used in sensitivity studies.

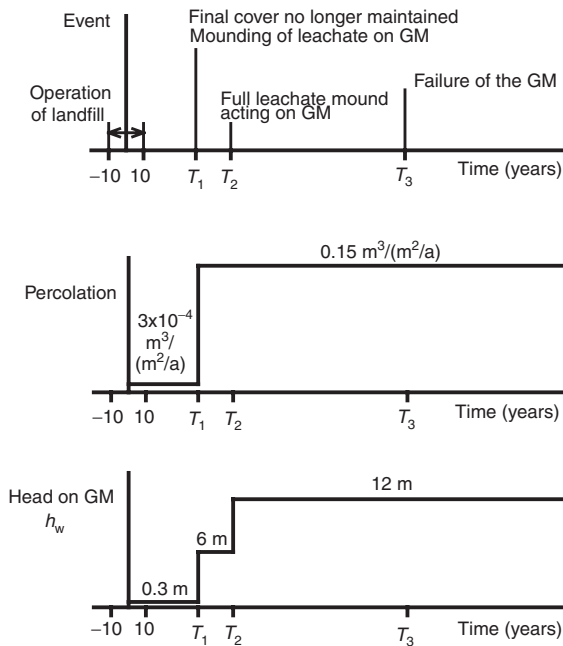


Figure 2. Major events considered in the contaminant transport analyses

collection (i.e. $T_2 = T_1 + 20$ years). The actual maximum mounding of leachate and the time to reach the maximum mound will depend on a number of factors including the porosity of the waste, the water content of the waste at the time of failure of the cover, the thickness and hydraulic conductivity of the waste, and the landfill geometry. Between times T_1 and T_2 it was assumed that an average head of 6 m acts on the liner. It is possible to model a gradual build-up of leachate; however, more detailed analyses (Rowe and Nadarajah 1995) indicate that a stepped approach, such as that adopted herein, is sufficient to provide a reasonable representation of the transport processes without the need for a full transient analysis and hence is sufficient for the comparison of the different composite barrier systems examined herein. For all stages of the analysis the percolation through the waste was equal to the leakage through underlying composite liner and any volume of leachate collected.

The geomembrane was assumed to fail at time T_3 . In order to model the finite service life of the GM consideration must be given to temperatures expected in the landfill, as the service life of the GM depends on temperature, with a shorter service life expected at higher temperatures. The temperature at the base of the landfill depends on many factors including (Rowe 1998a) the nature of the waste, landfilling practices, the geographic location of the landfill, the water content of the waste, and the level of leachate mounding. The temperature in the landfill is not expected to be constant, and will vary depending on the nature of the waste and the nature and level of biological activity in the waste. The temperature on the liner will also increase with leachate mounding on the base. For example, Barone *et al.* (1997) reported average temperatures of 14°C for an average leachate head of 0.4 m, and increasing to 33°C for a head of 4 to

6 m at the Keele Valley Landfill in Toronto, Ontario, Canada.

The estimates of geomembrane service life from Sangam and Rowe (2002) were obtained from tests conducted at constant elevated temperatures. These values are used to provide an estimate of service life of the GM, and are assumed to apply once the liner temperature starts to increase in response to leachate mounding. Thus the failure of the GM was modelled at time T_3 , which is equal to time T_1 plus the life estimates of 120 and 70 years corresponding to 20 and 33°C respectively.

Leakage rates for the different time periods corresponding to different heads acting on the GM are given in Table 1, as discussed in Section 2.3.3.

3.4. Concentrations of DCM and benzene in the aquifer

The calculated impact of DCM on the aquifer underlying the composite barrier is plotted in Figure 3. Results are given for the six composite liner systems shown in Figure 1. For these cases it was assumed that the low-permeability cover was maintained for $T_1 = 40$ years, and the geomembrane was assumed to fail at $T_3 = 160$ years (corresponding to a service life of 120 years at 20°C).

The concentrations of DCM increase rapidly for cases a and c, reaching a peak impact at times of 25 and 40 years (15 and 30 years post-closure) respectively as DCM diffuses through the composite liner. Concentrations then decrease owing to the finite mass of DCM available for transport through the liner and biodegradation of DCM.

For the cases shown in Figure 3 the impact for the GM/CCL composite liners is slightly greater than for the

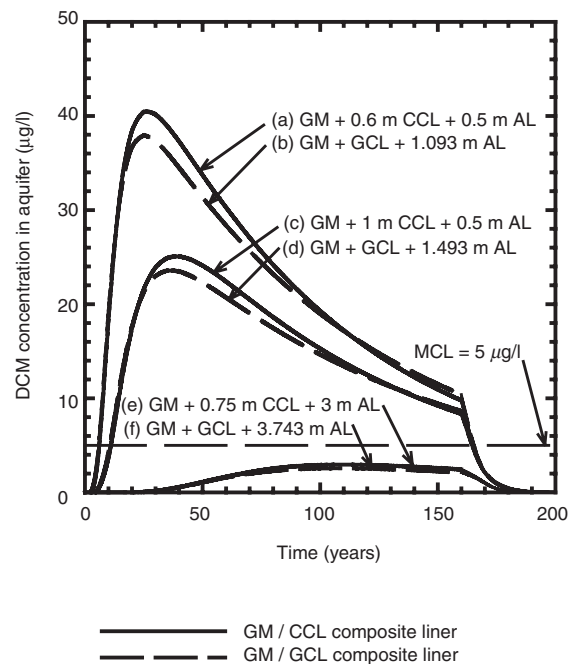


Figure 3. Calculated concentrations of dichloromethane in aquifer for cases a-f. $T_1 = 40$ years, $T_2 = 60$ years, $T_3 = 160$ years

GM/GCL/AL alternatives. For example, for the composite liners in compliance with the minimum US regulations the peak impact is 7% greater for the GM/CCL composite liner (Figure 1a) than for the GM/GCL/AL composite liner (Figure 1b). Although they are contributing factors, neither the smaller leakage rates for the GM/GCL/AL liner nor the lower diffusion coefficient of the GCL relative to the GM/CCL/AL case are sufficient to account for the lower peak DCM impact. Rather the DCM impact for the GM/GCL/AL case is less than for the GM/CCL/AL case largely because the total distance between the GM and the aquifer is the same in both cases, and here the attenuation layer acts as a better diffusive barrier than the compacted clay liner. Thus, although compaction of clay wet of optimum moisture content provides low hydraulic conductivity, it also results in a higher porosity than would be realised if the soil were in a denser state. This is important, because the diffusive flux through a porous material is controlled by the product of the porosity and the diffusion coefficient. As the porosity of compacted clay liner liners is often higher than the porosity of attenuation layers, the product of the diffusion coefficient and the porosity of the attenuation layer is often smaller than that for a clay liner. Under these circumstances the use of the GM/GCL composite to control leakage and the attenuation layer to control diffusion of organic compounds proves to be quite effective, and the GM/GCL/AL systems provide greater environmental protection than the GM/CCL/AL system. Thus the GM/GCL/AL composite liner systems examined are certainly equivalent to (and indeed a little better than) the GM/CCL/AL systems in terms of minimising the impact of DCM on the aquifer.

The effect of the total thickness of the soil beneath the geomembrane on DCM impact can also be observed from Figure 3. As the total thickness of the soil barrier increases, the peak impact on the aquifer decreases. The effect of total barrier thickness is quantified in Figure 4 for the particular case involving the GM and 0.6 m CCL (and its GM/GCL alternative). With a total thickness of $H = 0.6$ m beneath the geomembrane, the peak impact is nearly double that for cases a and b (with $H = 1.1$ m). If the total thickness is increased to 3.75 m, the peak impact is less than one-tenth of that with $H = 1.1$ m. Lower impact occurs for a thicker attenuation layer because the greater thickness of soil beneath the geomembrane increases the time it takes for DCM to diffuse through the barrier system and thus allows more time for the organic contaminants to biodegrade, thereby giving a lower impact on the aquifer.

The results in Figure 4 clearly show that the attenuation layer has a significant effect on the calculated DCM concentration in the aquifer. In fact, for the GM and 0.6 m CCL cases (and their GM/GCL alternative) the peak concentration is only less than the maximum concentration level (MCL) of $5 \mu\text{g/L}$ for DCM provided the total thickness beneath the geomembrane is at least 3.75 m thick (for the assumed initial source concentration and decay parameters). Thus, although the assumed thickness of the attenuation layer of 0.5 m for cases a

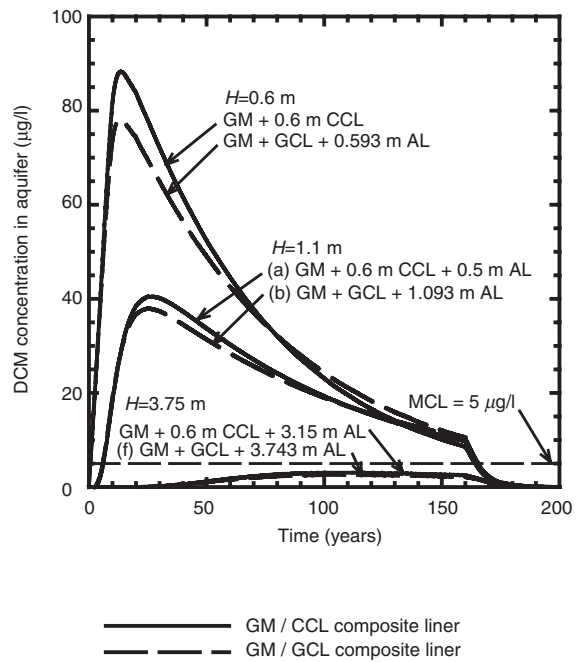


Figure 4. Calculated concentrations of dichloromethane in aquifer for composite liners with GM and 0.6 m CCL and their GCL/AL alternatives with different total thickness of liner system. $T_1 = 40$ years, $T_2 = 60$ years, $T_3 = 160$ years

and c does not change the conclusions about the equivalence of GM/GCL/AL systems compared with GM/CCL/AL, it does greatly influence the calculated DCM impact on the aquifer.

The half-life of VOCs, both in the landfill and in the soil beneath the geomembrane, greatly influences the calculated contaminant impact but not the equivalence of the different composite liner systems. Results for case e (GM + 0.75 m CCL + 3 m AL) are plotted in Figure

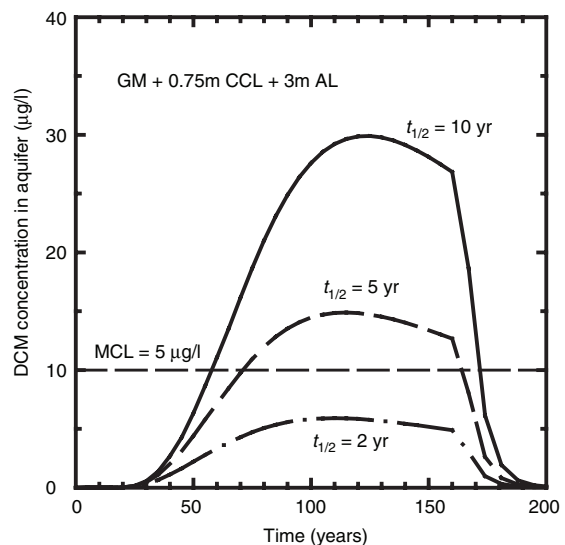


Figure 5. Calculated concentrations of dichloromethane in aquifer for case e with different assumed half-lives in landfill. $T_1 = 40$ years, $T_2 = 60$ years, $T_3 = 160$ years

5 with different half-lives of DCM in the landfill. Based on currently available evidence, the half-life of DCM in a municipal solid waste landfill is less than 10 years (MoE 1998), and there are data to support a half-life as small as 2 years (Rowe 1995; Rowe *et al.* 1997). The peak DCM impact is below the MCL for the case where the half-life in the landfill is 2 years. There is a paucity of data on the biodegradation of DCM in the soil beneath a geomembrane liner. It is likely that the half-life of DCM in the soil beneath the geomembrane is longer than that in the landfill, as the geomembrane acts as a selective barrier by severely limiting the diffusion of volatile fatty acids (VFAs) to negligible levels while allowing diffusion of volatile organic compounds such as DCM and benzene. The very low levels of VFAs in the soil below the geomembrane will slow the biodegradation processes that degrade DCM and benzene (Hrapovic 2001). In all of the cases reported in this paper, the half-life of DCM in the soil beneath the geomembrane was taken as 50 years. Lower values would result in lower impacts but would not change the conclusions regarding equivalence.

Calculated concentrations of benzene in the aquifer are plotted in Figure 6. Similar to the results for DCM, the peak impact in each case is less for the GM/GCL/AL composite liner system than for a GM/CCL/AL system. Cases e and f have a smaller peak impact than cases a to d, again because of the thicker attenuation layer. All of the results plotted in Figure 6 are below the maximum concentration level of 5 µg/L for benzene.

Analyses for DCM and benzene assuming a shorter service life of the geomembrane (to account for higher temperatures at the base of the landfill after leachate mounding) had no effect on the peak impact for DCM or

benzene provided the service life of the geomembrane was greater than 100 years.

3.5. Concentrations of chloride in the aquifer

The calculated concentration of chloride in the aquifer is plotted in Figure 7 for the six composite barriers shown in Figure 1. The results are shown for three combinations of the time for which the low-permeability cover was maintained (T_1) and time to failure of the geomembrane (T_3). For all cases shown in Figure 7 the geomembrane provides an excellent diffusive barrier to chloride, as there is essentially no arrival of chloride prior to failure of the geomembrane at time T_3 . For times greater than T_3 contaminant transport is controlled by advection through the soil, and the concentration in the aquifer increases rapidly, reaches a peak value, and then decreases because of the finite mass of chloride available for transport.

For all cases shown in Figure 7 there is negligible difference (no greater than 1%) between the peak impacts for the GM/CCL/AL and GM/GCL/AL systems. Thus, for the parameters examined, the GM/GCL/AL composite liner system provides protection against chloride for the underlying aquifer equivalent to that of the GM/CCL composite liner system.

There is no difference (to the accuracy of plotting) between chloride impact for cases a and c (or their alternatives b and d). Cases e and f have a very similar peak impact with a slightly delayed arrival relative to cases a and b. Unlike the results for DCM, thicker soil in the barrier does not decrease the magnitude of the chloride impact, as chloride is a conservative contaminant and does not degrade.

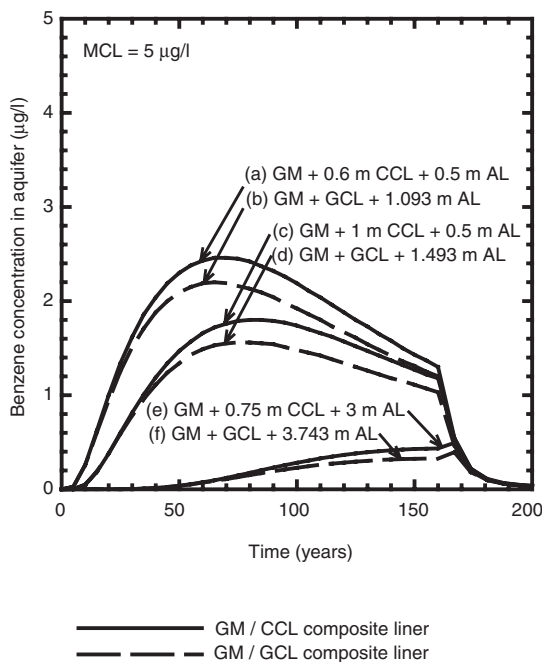


Figure 6. Calculated concentrations of benzene in aquifer for cases a–f. $T_1 = 40$ years, $T_2 = 60$ years, $T_3 = 160$ years

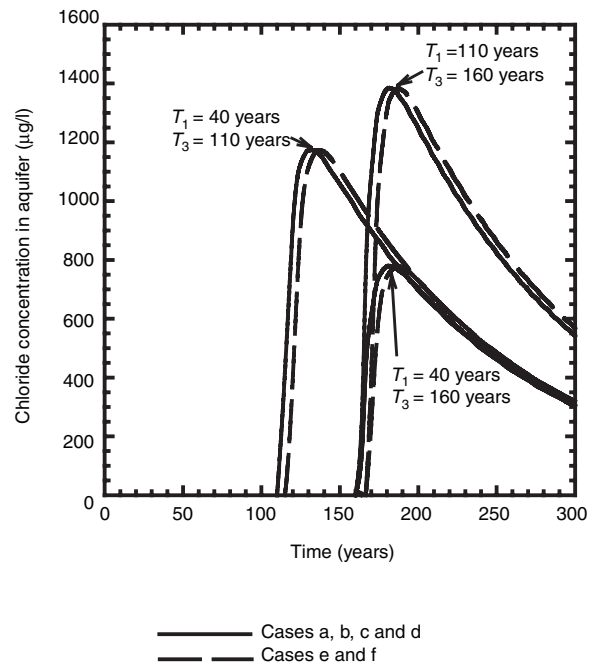


Figure 7. Calculated concentrations of chloride in aquifer for cases a–f

The effect of a shorter service life of the geomembrane can be observed by comparing the results for T_3 equal to 160 and 110 years ($T_1 = 40$ years) in Figure 7. In this comparison the service life of the geomembrane is reduced from 120 years to 70 years (corresponding to an increase in temperature from 20 to 33°C). The concentrations of chloride in the aquifer are larger for the shorter service life of $T_3 = 110$ years relative to $T_3 = 160$ years. Once the geomembrane fails, essentially all the chloride is available for transport through the barrier. As removal of mass from the landfill (via the leachate collection system) is the only way to reduce the concentrations of chloride in the landfill, if the geomembrane fails sooner there is less opportunity for the concentration of chloride to be reduced.

Increasing the time for which the low-permeability cover is maintained from $T_1 = 40$ years to $T_1 = 110$ years (both with $T_3 = 160$ years to permit comparison of the effect of increased T_1) results in larger concentrations of chloride in the aquifer. Although this may initially seem counter-intuitive, operation of the low-permeability cover for a greater period of time results in less infiltration, less chloride removal by leachate collection, and hence a larger chloride impact.

4. SUMMARY AND CONCLUSIONS

The equivalence of composite liners with a geomembrane and geosynthetic clay liner to traditional composite liners involving a geomembrane and a compacted clay liner was assessed in terms of the potential contaminant impact on a receptor aquifer. Factors that influence the contaminant transport through a composite liner were reviewed, considering recent findings on clay-leachate interaction, potential for internal erosion, contact conditions and leakage through geomembranes, diffusion through geomembranes and geosynthetic clay liners, and the service life of geomembranes.

A one-dimensional contaminant transport model was used to calculate the concentration of dichloromethane, benzene and chloride in a receptor aquifer beneath composite liners that are compliant with the minimum regulatory requirements in the United States, Europe and Ontario Canada and possible alternative GM/GCL composite liners for a hypothetical municipal solid waste landfill.

The calculated leakage through the GM/CCL/AL composite liners was found to be about 30 times larger than the leakage through the GM/GCL/AL alternatives, for the specific conditions examined. The leakage was small, however, in all cases where there was an operating leachate collection system. Although the harmonic mean hydraulic conductivity of the GCL and attenuation layer is greater than the hydraulic conductivity of the CCL they are replacing, less leakage occurs for the GM/GCL/AL systems because of the much lower transmissivity between the GM and GCL compared with the GM and CCL. This highlights the importance of obtaining as

good contact as possible between the GM and the underlying material, whether a GCL or CCL. Appropriate construction quality control will play an essential role in attaining low transmissivity in the field (e.g. preparation of a smooth base, limiting the number and size of wrinkles in the geomembrane). For the specific conditions examined, both the GM/CCL and GM/GCL liners are very effective at controlling leakage rates, to the point where contaminant transport through the composite liner is dominated by diffusion (for the number and size of holes in the geomembrane examined).

The calculated concentrations of DCM and benzene in the receptor aquifer for the GM/CCL/AL composite liners were found to be slightly greater (less than 10%) than those for the GM/GCL/AL alternatives, for the specific conditions examined. As the geomembrane offers little diffusive resistance to DCM and benzene, the CCL or GCL and the attenuation layer are required to serve as a diffusion barrier. Although the smaller leakage rates for the GM/GCL/AL liner and the lower diffusion coefficient of the GCL relative to the CCL contribute to this difference, the impact for the GM/GCL/AL alternatives was less than for the GM/CCL/AL cases, predominantly because: (a) the total distance between the GM and aquifer was selected to be the same in both cases; and (b) the sandy silt attenuation layer as modelled acts as a better diffusive barrier than the compacted clay liner. Thus the GM/GCL/AL composite liner systems examined were found to be equivalent to (and indeed a little better than) the GM/CCL/AL systems in terms of minimising the impact of DCM and benzene on the aquifer.

The choice of attenuation layer thickness did not affect the conclusions regarding equivalence between the GM/CCL/AL systems and GM/GCL/AL alternatives. However, the peak DCM impact was substantially reduced as the thickness of the attenuation layer was increased, as this increased the time for DCM to diffuse through the barrier system, provided more time for DCM to degrade, and thereby resulted in less impact on the aquifer.

The calculated concentrations of chloride in the receptor aquifer were found to be essentially the same (no greater than 1% difference) for the GM/CCL/AL and GM/GCL/AL systems examined. Given the very low leakage rates through both the GM/CCL/AL and GM/GCL/AL systems, and the fact that the GM provides an excellent diffusive barrier to chloride, practically no chloride passes through the liner over the service life of the geomembrane. After the failure of the geomembrane, chloride migrates towards the aquifer by advection at essentially the same rate for both the GM/CCL/AL and GM/GCL/AL cases (with the rate being controlled by the infiltration rate through the cover). Thus for the parameters examined, the GM/GCL/AL composite liner system provides protection against chloride to the underlying aquifer that is equivalent to that provided by the GM/CCL composite liner system.

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NOTATIONS

Basic SI units are given in parentheses.

D_g	geomembrane diffusion coefficient (m^2/s)
e_B	bulk void ratio of geosynthetic clay liner (dimensionless)
h_w	depth of leachate acting on top of geomembrane (m)
H	total thickness of soil between underside of geomembrane and top of aquifer (m)
k	hydraulic conductivity (m/s)
S_{gf}	geomembrane partition coefficient (dimensionless)
T_1	time to mounding of leachate on geomembrane and final cover no longer maintained (s)
T_2	time to full leachate mound acting on geomembrane (s)
T_3	time to failure of geomembrane (s)
$t_{1/2}$	half-life of dichloromethane in landfill (s)
θ	transmissivity between geomembrane and underlying layer (m^2/s)

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