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# Evaluation of a four-component composite landfill liner system

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**The performance of four different municipal solid waste landfill liner systems common in the United States, that is, USEPA Subtitle D prescribed composite liner system, composite liner system consisting of a geomembrane (GM) overlying a geosynthetic clay liner (GCL), Wisconsin NR500 liner system, and a proposed four-component composite liner system that is a combination of the GCL composite liner and Subtitle D liner system (with a 61-cm or 91·5-cm thick low hydraulic conductivity compacted soil), were evaluated in terms of leakage rate, solute mass flux, and cumulative solute mass transport. Leakage rates through circular and non-circular GM defects were analysed using both analytical and numerical methods. For the mass flux evaluation, solute transport analyses using GM defects and diffusion of volatile organic compounds through intact liners were conducted using one- and three-dimensional numerical models. Cadmium and toluene were used as typical inorganic and organic substances, respectively, in the analyses. The comparison shows that for the limited set of conditions considered, the four-component composite liner system outperforms the Subtitle D and Wisconsin NR500 liner systems based on leakage rate and mass flux and provides similar results to the GM/GCL liner system. Based on the analyses presented herein the four-component liner system is a viable choice for a protective Subtitle D composite liner system and provides some added protection to the GCL.**

## Notation

| | |
|---|---|
| $c$ | concentration of toluene in soil liner |
| $c_{\mathrm{m}}$ | normalised concentration of toluene in geomembrane |
| $C$ | concentration of solute |
| $\bar{c}$ | concentration of toluene sorbed on the soil liners |
| $D^*$ | effective diffusion coefficient of soil liner |
| $D_{\mathrm{gm}}$ | diffusion coefficient of toluene through geomembrane |
| $D_{\mathrm{o}}$ | free solution diffusion coefficient of toluene |
| $h_{\mathrm{p}}$ | depth of leachate |
| $h_{\mathrm{t}}$ | total head or potentiometric head |
| $K_{\mathrm{d}}$ | partition coefficient for soil liner and toluene |
| $K_{\mathrm{d,gm}}$ | partition coefficient for geomembrane and toluene |
| $K_{\mathrm{s}}$ | saturated hydraulic conductivity of soil liner |
| $L$ | distance from top of liner to depth at which concentration equals zero |
| $L_{\mathrm{s}}$ | thickness of compacted soil liner |
| $L_{\mathrm{s1}}$ | thickness of geosynthetic clay liner layer |
| $L_{\mathrm{s2}}$ | thickness of compacted soil liner |
| $n$ | porosity |
| $Q$ | leakage rate |
| $r$ | radius of defect |
| $R_d$ | retardation factor |
| $R_n$ | chemical reaction term |
| $t$ | time |
| $t_{\mathrm{gm}}$ | thickness of geomembrane |
| $w$ | width of defect |
| $x$ | lateral orthogonal direction |
| $y$ | lateral orthogonal direction |
| $z$ | vertical direction or depth from top of liner |
| $z_{\mathrm{m}}$ | normalised coordinate in z-direction in geomembrane |
| $\lambda$ | rate of constant of first-order rate reaction |
| $\rho_{\mathrm{b}}$ | bulk density of compacted soil liner |
| $\tau_{\mathrm{a}}$ | apparent tortuosity |

## Introduction

Leakage rate is commonly used to evaluate the performance of municipal solid waste (MSW) landfill liner systems. A liner system that allows the lowest leakage rate is usually deemed to exhibit the best performance (Richardson, 1997). However, several studies suggest the criterion of only leakage rate might not be sufficient for assessing the performance of composite liner systems (Crooks and Quigley, 1984; Foose *et al*., 2002; Park and Nibras, 1993; Rowe, 1987; Shackelford, 1989; Shackelford and Daniel 1991a, 1991b) because advective flow is not the only mechanism of mass transport. Instead, solute transport should also be considered so the importance of volatile organic compound (VOC) migration is also assessed (Foose *et al*., 2002). In this study, advective leakage rates and contaminant mass fluxes through four composite liner systems are estimated and compared to evaluate the relative performance of each liner system.

The following three types of composite liner systems are commonly used in MSW landfills in the United States: the Subtitle D liner system (prescribed in Subtitle D of the Resource

Conservation and Recovery Act, US EPA; 40 CFR 258.40), geosynthetic clay liner (GCL) composite system (a popular alternative liner system to the Subtitle D system), and Wisconsin NR500 liner system (prescribed in Wisconsin Administrative Code Section NR500). The Subtitle D and the Wisconsin NR500 liner systems consist of a geomembrane (GM) underlain by low hydraulic conductivity compacted soil with thicknesses of 0·6 and 1·2 m, respectively. The GCL composite liner system consists of a GM underlain by a GCL. Foose *et al*. (2002) analysed the performance of these three composite liners based on leakage rate and mass flux. The results indicate the GCL composite liner system exhibits the lowest leakage rate and lowest mass flux of the inorganic substances, such as cadmium. However, the mass flux of organic substances, such as toluene, through the GCL composite liner, is two to three orders of magnitude greater than through the intact Subtitle D or Wisconsin NR500 liner systems owing to the small thickness of the GCL and thus smaller attenuation volume.

## Effectiveness and benefits of four-component composite liner system

This study sought a more protective composite liner system that possessed a low leakage rate and also a low mass flux for both organic and inorganic substances. These criteria were desired because proposed landfills would be located in river floodplains with a shallow groundwater system. A four-component liner system composed of a GM/GCL liner and a GM/low hydraulic conductivity ($<10^{-9}$ m/s) compacted soil liner (CSL) (0·6 or 0·9 m thick) was proposed for these landfills or landfill expansions to protect important groundwater resources and facilitate permitting. This liner system is described in more detail below and provides better performance than the GCL composite, Subtitle D, and Wisconsin NR500 liner systems because it combines the benefits of these liner systems, e.g. a GCL to reduce advective flow and a thick layer of low hydraulic conductivity ($<10^{-9}$ m/s) compacted soil to reduce diffusive flow. This study was undertaken to compare the performance of this four-component composite liner system with the GCL composite, Subtitle D liner, and Wisconsin NR500 liner systems.

There are a number of potential benefits of the proposed four-component composite liner system that are discussed in this paragraph. In this system, the GCL is installed in an unhydrated condition between the two GMs and thus should remain in the unhydrated state because it is encapsulated. Hydration may occur at locations of defects in the upper or lower GM if leachate or groundwater is present, respectively. If this occurs, the GCL will hydrate at the defect location and slow or eliminate the leachate flow. In addition, the area that will be hydrated will be small because the GCL will hydrate and seal the defect area with the normal stress applied by the overlying waste. The small area of hydration is beneficial for slope stability purposes because a large amount of the bentonite will remain unhydrated so a large area of reduced shear resistance will not occur within or outside of the GCL. This should result in the critical interface being at the GM/CSL interface instead of within the GCL or a GCL interface. Daniel *et al*. (1993), Estornell and Daniel (1992), Giroud and Daniel (2004), Thiel and Erickson (2001) and Thiel *et al*. (2001) show that the amount of GCL hydration is negligible if the GCL is properly installed and protected/encapsulated by GMs, which means a low frequency of small GM holes (i.e. 1–2 per acre) occur. Even using conservative hydration scenarios, that is, using a greater than commonly assumed number of holes in the overlying GM, Thiel and Erickson (2001) estimate less than 5% of the GCL will hydrate. In the unhydrated state, the GCL also will exhibit better durability and less bentonite migration (Stark *et al*., 2004).

There are also no major construction-related issues with the proposed four-component composite liner system because the compacted soil subgrade is placed first and then the first GM. However, the first GM is usually textured on both sides so a slip sheet may be needed to place the GCL over the first GM. The GM overlying the GCL should be placed and seamed as soon as possible after the GCL is placed so the GCL does not prematurely hydrate.

This paper compares the performance of the proposed four-component composite liner system (from top to bottom, GM, 6·5-mm-thick GCL, GM, and 0·6- or 0·9-m-thick low hydraulic conductivity ($<10^{-9}$ m/s) CSL to the Subtitle D liner system which consists of either 0·6- or 0·9-m-thick low hydraulic conductivity ($<10^{-9}$ m/s) CSL overlain by a GM (see Figure 1), Wisconsin NR500 liner system which consists of a GM underlain

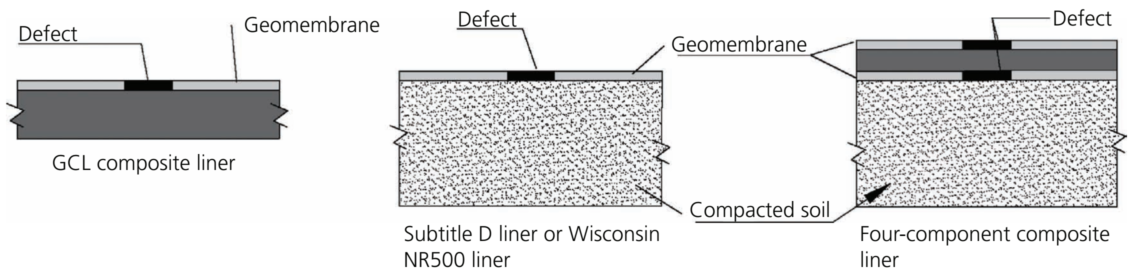


**Figure 1.** Profile of GCL composite, Subtitle D, Wisconsin NR500, and proposed four-component composite liner systems

by a 1·2-m-thick low hydraulic conductivity ($<10^{-9}$ m/s) CSL, and GCL composite liner system, which consists of a GM underlain by a 6·5-mm-thick GCL. The comparison is based on the following two performance criteria: (1) steady-state leakage rate and (2) mass flux from the base of the liner system. Analysis of leakage rate is estimated assuming defects in the GM as described below. A solute transport analysis is performed to estimate the mass flux through the four-component composite liner system assuming a GM with and without defects.

## Leakage rate estimation

### Review of existing analyses

Occurrence of defects in installed GMs has been reported, for example, Giroud and Bonaparte (1989a, 1989b), Giroud and Morel (1992), Needham *et al*. (2004), Nosko and Touze-Foltz (2000) and Rollin *et al*. (2002). Such defects are simulated herein as circular or longitudinal with a size ranging from a small hole to a long defective seam (e.g. Giroud and Bonaparte, 1989a, 1989b). Properties of the GM interface or contact between the GM and the underlying low hydraulic conductivity compacted soil are important factors in the leakage rate analysis. The quality of the GM/compacted soil contact has been defined using the following three terms: perfect (Chai *et al*., 2005; Foose *et al*., 2001; Giroud and Bonaparte, 1989a, 1989b), excellent (Giroud and Bonaparte, 1989a, 1989b; Touze-Foltz and Giroud, 2003), good, and poor (Giroud, 1997). The leakage rate analyses for the defects with imperfect contact in composite liners are presented by Foose *et al*. (2001), Giroud and Touze-Foltz (2005), Touze-Foltz and Barroso (2006), Touze-Foltz and Giroud (2003, 2005) and Touze-Foltz *et al*. (1999). In this study, the GM/compacted soil contact is assumed to be perfect to facilitate the solute transport simulations described in subsequent sections.

For perfect GM/compacted soil contact, there are several analytical solutions available for estimating leakage rate through a defect. Walton and Sagar (1990) use Forchheimer's (1930) equation for deriving the leakage rate through a small circular GM defect in perfect contact with the CSL. Forchheimer (1930) equation has been verified by Foose (1997), Walton and Sagar (1990) and Walton *et al*. (1997). Walton *et al*. (1997) developed graphical and empirical solutions for leakage rates through a composite liner system with perfect contact and a circular defect in the GM with a radius equal to one-tenth (1/10) of the thickness of the CSL. For the case of long defects, Walton and Sagar (1990) suggest a graphical solution for longitudinal defects with widths less than 1/10 of the thickness of the CSL.

For perfect GM/GCL contact, there are several analytical solutions available for estimating leakage rate through a defect. Barroso *et al*. (2008) presents a laboratory study of flow through composite liner systems that utilise a GCL. Barroso *et al*. (2008) show the influence of geomembrane texturing on flow through GM/GCL composite liner systems. Mendes *et al*. (2010) present a model of interface flow along the GM/GCL interface in a composite liner system. These studies of flow for GM/GCL composite liner systems facilitated development of the numerical simulation described below.

Harr (1962) and Walton and Seitz (1992) provide analytical solutions for leakage rate through a long defect (widths less than 1/10 of the thickness of the CSL) in a composite liner with perfect GM/compacted soil contact. More recently, Foose *et al*. (2001) recommend empirical equations for predicting leakage rates through long and circular defects with perfect GM contact based on their numerical analyses. These empirical equations were verified by comparison to analytical solutions (Harr, 1962; Walton and Seitz, 1992) and numerical evaluations (Walton and Sagar, 1990; Walton *et al*., 1997).

### Leakage rate simulation

In this study, MODFLOW 2000 (Harbaugh *et al*., 2000) was used to solve the three-dimensional (3D) governing equation for flow through the proposed four-component composite liner system assuming a saturated steady-state flow condition. The conceptual flow simulation through two vertically coaxial circular defects in the GMs of a double composite liner system is presented in Figure 2(a) and the corresponding finite difference mesh is shown in Figure 2(b).

Only one quadrant of a circular defect is simulated in the mesh due to the axisymmetric geometry. Two layers of no-flow cells are used for simulating the two layers of GM. To simulate the worst flow situation, the two GM defects are assumed to be vertically coaxial. The authors assume co-axial defects to yield an upper bound of leakage rate. The four-component composite liner system still yields a lower leakage rate than other liner systems even with co-axial defects, which indicates the effectiveness of the entire system. The upper defect is simulated using constant head cells. The constant total head ($h_t$) assigned to these cells is

$$h_t = 2*t_{gm} + L_{s1} + L_{s2} + h_p, \quad (1)$$

where

$t_{gm}$ = thickness of the geomembrane

$L_{s1}$ and $L_{s2}$ = thicknesses of the GCL and the CSL, respectively (see Figure 2(a))

$h_p$ = depth of leachate in the landfill.

It is conservatively assumed that the depth of leachate is constant with time due to a lack of data about the variation of leachate depth with time, but some data indicate temporal variations of leachate collection system flow rates in operating landfills (Bonaparte *et al*., 2002) with time. The defect in the lower GM is simulated as an active rectangular cell with hydraulic conductivity three orders of magnitude higher than the underlying low

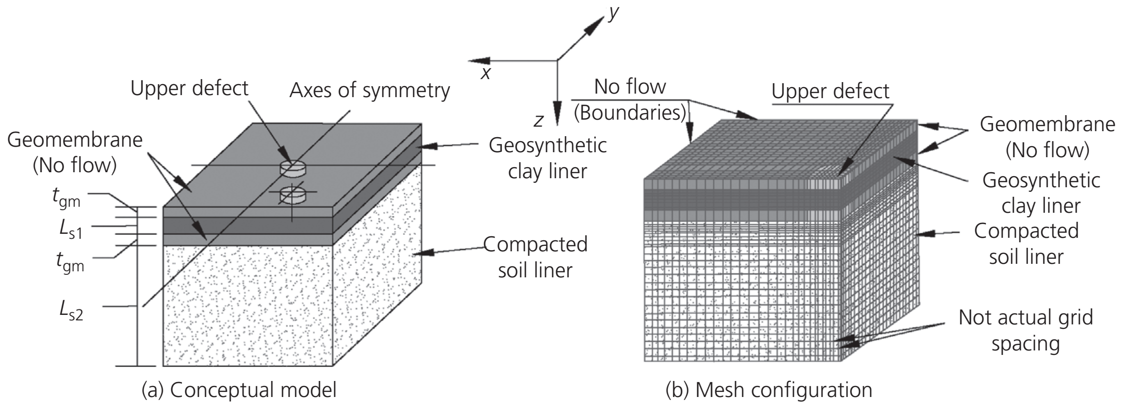


**Figure 2.** (a) Schematic view of flow through a circular defect in proposed four-component composite liner system and (b) corresponding finite difference mesh

hydraulic conductivity CSL. The side boundaries are simulated as no-flux boundaries. The bottom boundary is simulated as a fully draining boundary with a constant head of zero. The GM and CSL are assumed to be saturated, homogeneous and isotropic. The width of the mesh domain is 100 cm ($L_x = L_y = 100$ cm), which is large enough for simulation of flow through defects (Foose *et al.*, 1998).

Two numerical simulations were performed for the cases of infinitely and finitely long defects (see Figure 3). A two-dimensional (2D) numerical simulation with a unit length in the y direction is used to evaluate the leakage rate through an infinitely long GM defect. Only half of the defect width is simulated due to the symmetric geometry of the defect. The mesh size in the x- and z-directions is identical to that of the 3D simulation for circular defects. The boundaries in the y direction are considered as no-flux boundaries to simulate the infinite length of the defect in the y-direction. A 3D numerical simulation was performed to estimate the leakage rates through finitely long defects in the four-component composite liners. Only one quadrant of a long defect is also simulated due to the symmetric geometry. The dimension of the defect is large enough for simulation of flow. Other conditions and parameters are the same as the 3D simulation for a circular defect.

In this analysis, the authors assume intimate contact between the liner components even though substantial leakage could occur around damaged wrinkles (Brachman and Gudina, 2008; Chappel *et al.*, 2007, 2008, 2012a, 2012b; Giroud and Morel, 1992; Gudina and Brachman, 2006; Rowe, 2012; Rowe *et al.*, 2012a, 2012b; Take *et al.*, 2007, 2012). The size, percentage area and connectivity of wrinkles on landfill leakage are the focus of a current study. This is a simplifying assumption used for purposes of comparing the four composite liner systems. The simulation is

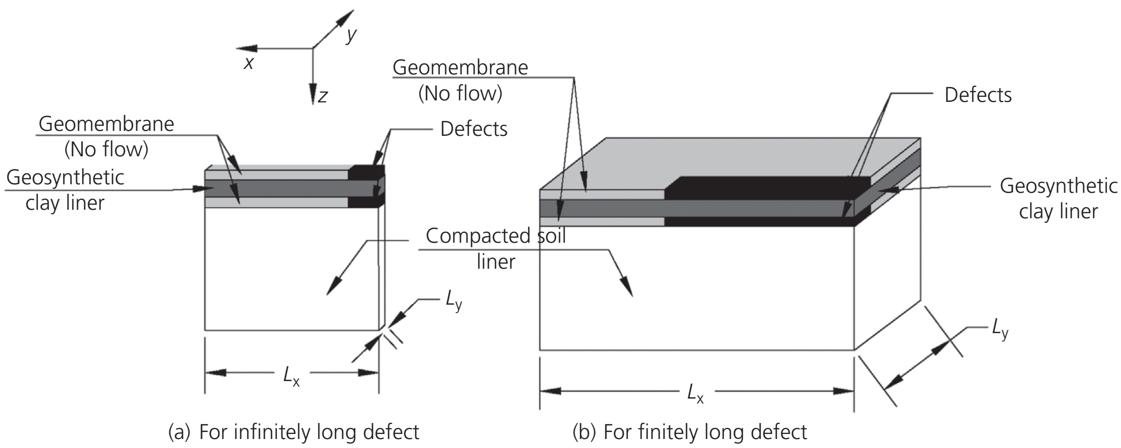


**Figure 3.** Numerical models for flow through (a) infinitely and (b) finitely long defects in the proposed four-component composite liner system

based on the requirement of small mass balance errors and convergence to the analytical solution for a simple geometry. The hydraulic conductivities of the GCL and CSL were selected as $1 \times 10^{-11}$ and $1 \times 10^{-9}$ m/s, respectively. These values represent common regulatory values and data from studies on CSLs (Foose *et al*., 1996; Giroud, 1997; Giroud and Bonaparte, 1989a, 1989b; Giroud *et al*., 1989, 1997a, 1997b; Wilson-Fahmy and Koerner, 1995). The height of leachate above the bottom of the upper GM was assumed to be 0·3 m. This is the maximum value allowed by many landfill regulations in the US.

## Leakage rate simulation results

### Circular GM defects

Leakage rates through circular defects with a varying radius ($r_{\text{defect}}$) in the GM of the four composite liner systems considered herein were estimated using MODFLOW 2000 and are shown in Figure 4(a). In each analysis, the mass balance errors are less than 1%. The results obtained using Forchheimer (1930) equation are also shown in Figure 4(a) and were used to validate the performed simulation using the MODFLOW 2000 software herein. The comparison shows excellent agreement between MODFLOW 2000 and Forchheimer (1930) equation for leakage rates through the Subtitle D liner system. Both solutions show the leakage rate through the defect increases slightly with an increase in the thickness of the CSL. The unexpectedly higher leakage rates for the case of thicker CSLs seem to be illogical. Because the simulations were performed for the steady-state solution, the larger area of outflow at the bottom of the thicker liner could be the reason for the higher leakage rate of the thicker liner. Foose *et al*. (2002) report similar results for the Subtitle D and Wisconsin NR500 liner systems, with the leakage rate for the thicker Wisconsin NR500 liner also being higher. For the GCL composite liner, the numerical simulation (MODFLOW 2000) yields marginally higher leakage rates than the Forchheimer (1930) equation.

Figure 4(b) compares the leakage rates through circular defects in the four composite liner systems considered using the validated MODFLOW 2000 code for these cases. The four-component composite liner system with a 0·6- or 0·9-m-thick CSL ($<10^{-9}$ m/s) yields significantly lower leakage rates than the Subtitle D liner system. The leakage rates for the proposed four-component composite liner system range from 0·86 to 11·94 mL/defect/year for a defect radius of 1–6 mm. These leakage rates are comparable to those of the GCL composite liner system. Interestingly, increasing the thickness of the low hydraulic conductivity compacted soil in the proposed four-component and Subtitle D composite liner systems increased the leakage rate.

For comparison purposes only, a 0·6- and 0·9-m-thick attenuation layer ($<10^{-7}$ m/s) is assumed below the GCL composite liner system to reduce diffusive flow through this composite liner system. The attenuation layer is included because the GCL composite liner system is usually constructed on a prepared subgrade to protect the geosynthetics. However, the other three

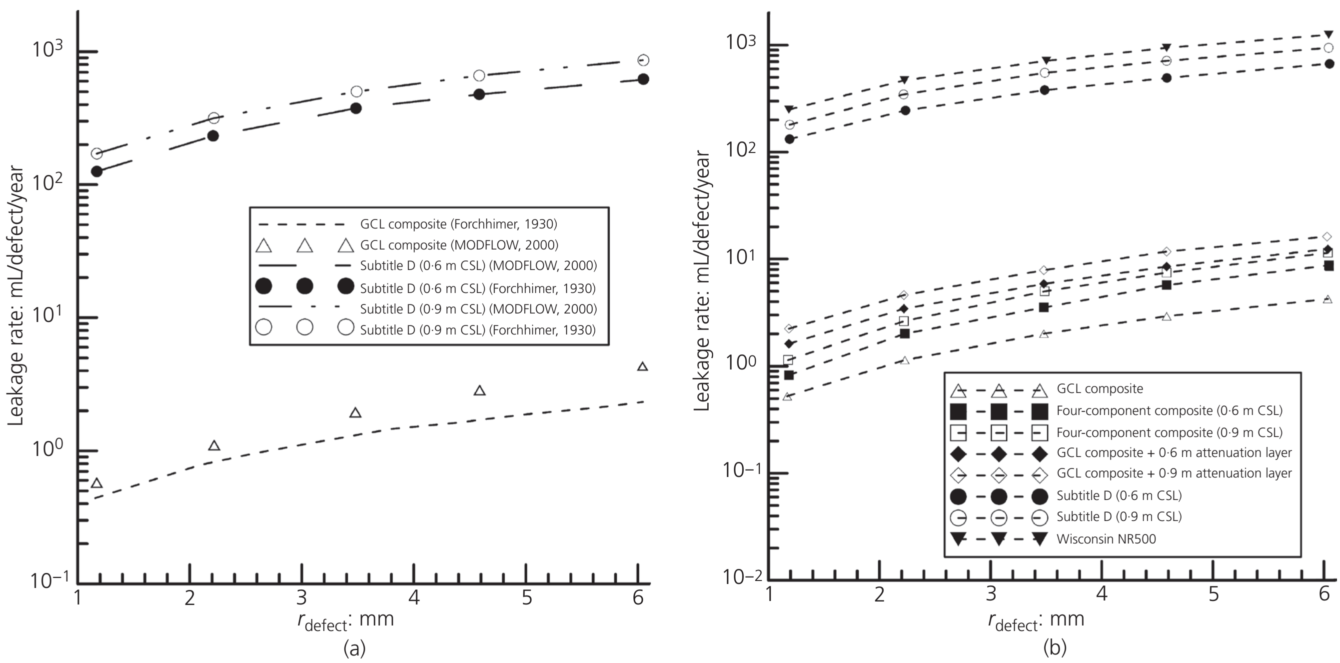


**Figure 4.** Leakage rates through circular defects in composite liner systems with perfect GM contact: (a) comparison with existing analytical solutions for verification and (b) leakage rate comparison for various composite liner systems

liner systems being considered are also constructed on a prepared subgrade but an attenuation layer is not included in their evaluation. The attenuation layer is assumed to have a hydraulic conductivity of $1 \times 10^{-7}$ m/s (Rowe, 1998).

Figure 4(b) shows the leakage rates through the GCL liner system with 0·6- and 0·9-m-thick attenuation layers are slightly higher than the proposed four-component composite liner, which shows that the proposed four-component composite liner system provides better leakage rate performance than the other three composite liner systems. Figure 4(b) also shows that the GCL composite liner system without an attenuation layer yields better, that is, lower leakage rates, than the four-component composite liner system because of the low hydraulic conductivity of the GCL. It may seem illogical that the steady-state leakage rate increases as the compacted soil layer thickness increases from 0·6 to 0·9 m unless it is remembered that this is a steady-state analysis. Under steady-state conditions, a larger area of outflow develops at the bottom of the thicker attenuation layer because a steady-state condition, that is, infinite time for a given leachate level, is applied. This increased outflow area explains the higher leakage rate for the thicker attenuation layer. These calculated leakage rates are the result of simplifying assumptions used in the simulation, which leads to values below the level of environmental consequence. However, in practice, other defects can occur that yield leakage rates that exceed the level of environmental consequence.

## Long GM defects

Figure 5(a) shows calculated leakage rates per unit length of a long defect through the Subtitle D and GCL composite liner systems using MODFLOW 2000 and limiting mass balance errors to less than 1%. Figure 5(a) also presents the solutions proposed by Harr (1962) and Walton and Seitz (1992) to validate the MODFLOW 2000 analyses. The leakage rates for the Subtitle D liner system calculated using analytical solutions proposed by Harr (1962) and Walton and Seitz (1992) are in excellent agreement with the MODFLOW 2000 results, which validates the MODFLOW 2000 model. Similar to the case of a circular defect, leakage rates for the Subtitle D liner with 0·9 m of low hydraulic conductivity compacted soil are higher than those with a 0·6-m-thick CSL. The leakage rates for the GCL composite liner calculated using analytical solutions proposed by Harr (1962) are also in excellent agreement with the MODFLOW 2000 results, but the Walton and Seitz (1992)-based leakage rates are lower but in reasonable agreement with the MODFLOW 2000 results.

Figure 5(b) compares leakage rates through infinitely long defects in the four composite liner systems considered herein estimated using the validated MODFLOW 2000 model. Leakage rates through infinitely long defects in the four-component composite liner system are 30–40 times lower than those for the Subtitle D liner. Leakage rates for the four-component composite liner are slightly higher than the GCL composite liner, which is similar to

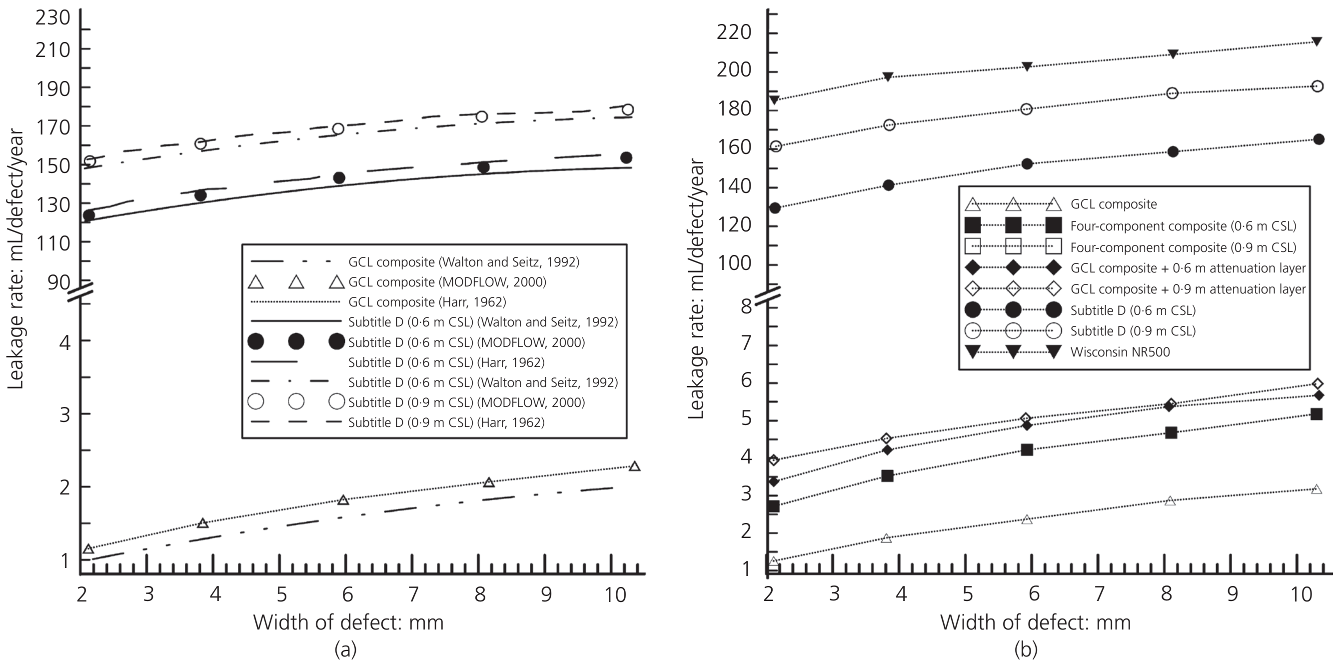


**Figure 5.** Leakage rates through infinitely long defects with perfect GM contact: (a) numerical simulation verification with Subtitle D and GCL liner systems and (b) leakage rate comparison for various composite liner systems

the results for circular defects. A GCL composite liner system underlain by an additional attenuation layer of 0·6 or 0·9 m thickness, required to control diffusion, also shows slightly higher leakage rates than the proposed four-component composite liner. Consequently, the proposed four-component composite liner system provides the lowest leakage rate for long GM defects except for the GCL composite liner system which is slightly lower on the log-scale.

A series of parametric studies were performed to investigate the relationship between leakage rate and defect length for constant defect widths of 2, 6 and 10 mm. The leakage rate of the GCL composite liner system is higher than the proposed four-component composite liner system when the defect length is relatively small and there is a transitional defect length at which the GCL composite liner system leakage rate becomes smaller than the proposed four-component composite liner (see Figure 6).

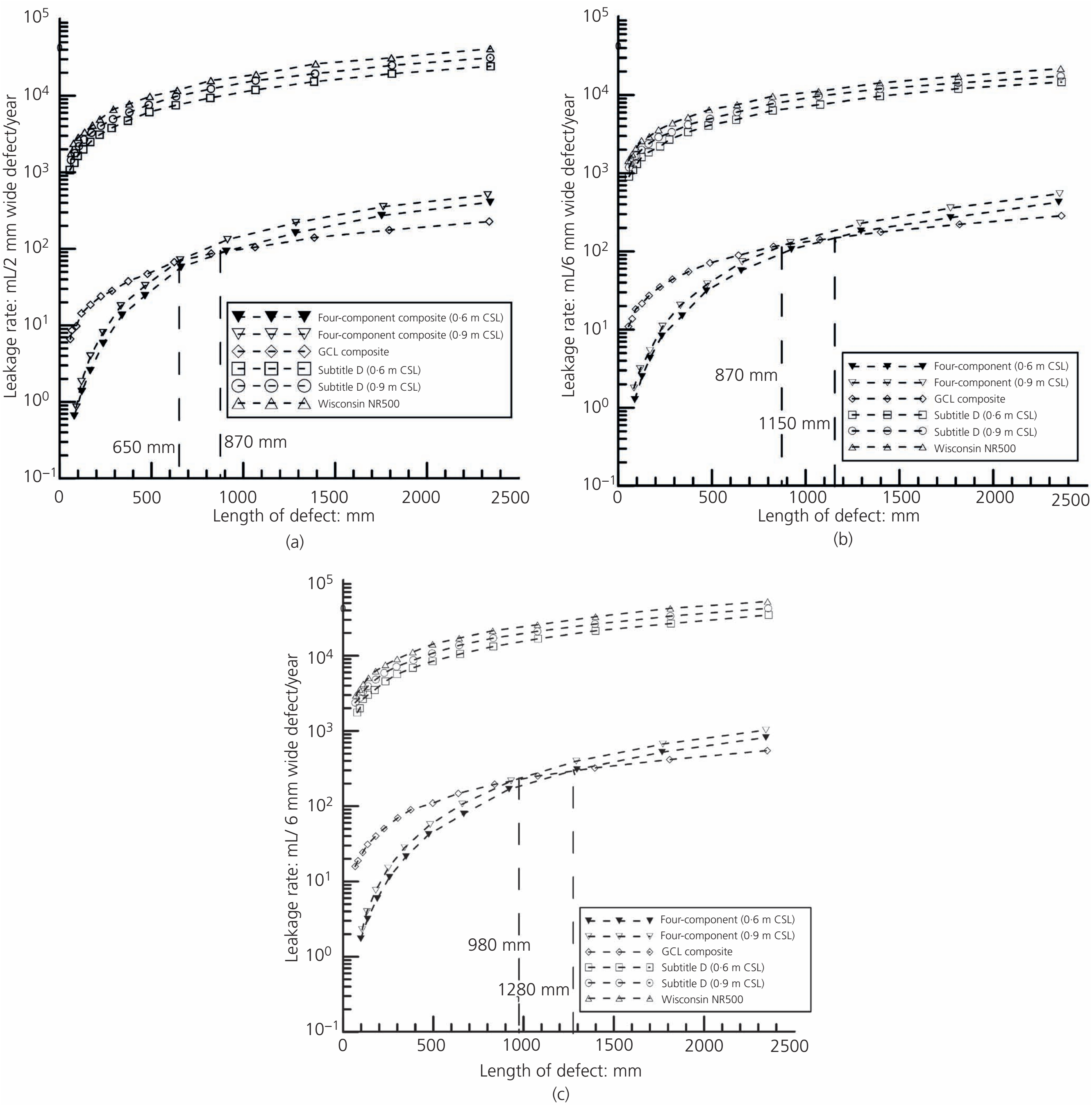


**Figure 6.** Effect of defect length on leakage rates with defect widths of (a) 2 mm, (b) 6 mm and (c) 10 mm

The transitional defect length for a defect width of 2 mm is estimated to be 650 and 870 mm for the proposed four-component composite liner with 0·9- and 0·6-m-thick CSL, respectively (see Figure 6(a) and (b)). Similarly, the transitional defect length for a defect width of 10 mm is estimated to be 980 and 1280 mm for the proposed four-component composite liner with 0·9- and 0·6-m-thick low hydraulic conductivity CSLs, respectively (see Figure 6). The transitional defect length varies with changes in liner system thickness and the size and shape of defects.

Comparing Figures 4 and 6 shows that the leakage rates through long defects are significantly greater than through circular defects which is also noted by Foose *et al*. (2001) and Giroud *et al*. (1992). Therefore, long defects can be a major source of leakage in landfill liner systems and can be prevented by active construction monitoring. The long defects are used herein for comparison purposes only but can be a major source of leakage through landfill liner systems. In summary, the proposed four-component composite liner system shows better performance, in terms of advective leakage rate, compared to the Subtitle D and NR500 liner systems and yields about the same performance as the GCL composite liner system for both circular and long defects. The next section investigates performance of these composite liner systems in terms of solute transport, that is, diffusion, instead of advection.

## Solute transport

### Review of existing solute transport analyses

Solute transport through composite liner systems is a combination of advective and diffusive processes of inorganic and organic solutes. The inorganic solutes can almost be completely contained by an intact GM (Haxo and Lahey, 1988; Rowe *et al*., 1995). Thus, inorganic solute transport through a composite liner is dominated by advection through GM defects and then advection, diffusion, or both through the underlying CSL ($<10^{-9}$ m/s). Conversely, organic solutes can diffuse through intact GMs (Mueller *et al*., 1998; Park and Nibras, 1993), so organic solutes can transport through composite liner systems in the following two ways: (1) identical to that for inorganic solutes which is through GM defects and (2) diffusion through the intact GM and underlying CSL. McWatters and Rowe (2007, 2009, 2010) present diffusive migration through various types of GMs including HDPE and PVC. Islam and Rowe (2008 and 2009) show the effect of ageing on diffusion of organic compounds through HDPE GMs while Rimal and Rowe (2009) present a diffusion-based model for OIT depletion in HDPE GMs. Cadmium and toluene are used herein as inorganic and organic solutes, respectively, to evaluate solute transport through the composite liner systems (Subtitle D, Wisconsin NR500, GCL and four-component) considered herein.

Solute transport through CSLs ($<10^{-9}$ m/s) has been analysed by Acar and Haider (1990), Crooks and Quigley (1984), El-Zein and Rowe (2008), Gillham *et al*. (1984), Rowe (1987) and Shackelford and Daniel (1991a, 1991b). Diffusion of VOCs through intact composite liners is described by Brown and Thomas (1998) and Mueller *et al*. (1998). Solute transport is also analysed by Foose *et al*. (2002) using numerical approaches for intact and defective composite liners. In this study, inorganic solute transport through GM defects in the four composite liner systems considered is simulated using MT3DMS (Zheng, 2006; Zheng and Wang, 1999).

For organic solute transport, the mass transport through GM defects is negligible compared to that through the intact portion of the composite liner (Foose *et al*., 2002). Organic solute transport through intact composite liners can be analysed using a one-dimensional model because the area of the liner is much greater than the thickness. Because there is no analytical solution for effectively analysing solute transport through composite liners, the composite liner systems being considered were analysed using a block-centred finite-difference model of diffusive transport developed during this study. This model uses an explicit method to calculate the mass flux of toluene transport. The various solute transport models are described in the following sections.

### Inorganic solute transport through four defective composite liner systems

#### Inorganic solute transport simulation and input parameters

Using the flow or leakage rates calculated using MODFLOW 2000, the inorganic solute transport through defects in the composite liner systems being considered was simulated using MT3DMS (Zheng, 2006; Zheng and Wang, 1999). The finite-difference mesh used for the flow solution in MODFLOW 2000 (see Figure 2(b)) was also used in MT3DMS. In the numerical simulation, the lateral sides and GMs are simulated as zero solute flux conditions. The defect in the upper GM and the bottom boundary are simulated as constant solute concentration cells. The upper GM defect cells represent a temporally invariant constant solute source, which is conservative. The GCL and CSL ($<10^{-9}$ m/s) are assumed to be fully saturated to represent the worst case for the performance of the composite liner systems. The constant solute concentration of cadmium is 100 μg/L and the other input parameters are shown in Table 1. The GCL is assumed to be hydrated/saturated in both the four-component composite liner system and the GM/GCL liner systems. This is in agreement with the GCL being able to hydrate from the underlying subgrade, but it is conceivable that the GCL in the four-component liner system would experience a lower degree of saturation owing to being encapsulated by two GMs. This could make the GCL more susceptible to changes in hydraulic conductivity due to hydration by the contaminant instead of groundwater. For analysis purposes, it is assumed there are sufficient defects in the primary and secondary GMs to create the same degree of saturation for both cases, so the GCL properties in Table 1 are used for both liner systems.

| | GM | Saturated GCL | Low hydraulic conductivity ($<10^{-9}$ m/s) CSL | References |
|---|---|---|---|---|
| Partitioning coefficient, $K_{d,gm}$, of toluene into GM (phase change) | 135 | — | — | Park and Nibras (1993) |
| Diffusion coefficient, $D_{gm}$, of toluene for GM | $3{\cdot}0 \times 10^{-13}$ m²/s | $1{\cdot}0 \times 10^{-14}$ m²/s | — | Koerner and Daniel (1993) and Park and Nibras (1993) |
| Distribution coefficient, $K_d$ | — | $2{\cdot}6 \times 10^{-3}$ m³/kg | $1{\cdot}0 \times 10^{-3}$ m³/kg | Benson and Lee (2000); Edil *et al*. (1995) |
| Total porosity, $n$ | — | 0·70 | 0·54 | Benson *et al*. (1999); Shackelford and Daniel (1991b) |
| Bulk density, $\rho_b$ | — | 790 kg/m³ | 1240 kg/m³ | Estornell and Daniel (1992); Shackelford and Daniel (1991b) |
| Apparent tortuosity, $\tau_a$ | — | 0·074 | 0·24 | Rowe *et al*. (1997); Shackelford (1989) |
| Free solution diffusion coefficient, $D_o$, for toluene | — | $8{\cdot}47 \times 10^{-10}$ m²/s | $8{\cdot}47 \times 10^{-10}$ m²/s | Yaws (1995) |

**Table 1.** Parameters used for diffusive transport modelling of toluene

## Inorganic solute transport results

To calculate the mass flux and cumulative mass of cadmium for 1 ha of liner system, the values obtained from MT3DMS for one defect are multiplied by 2·5 because Giroud and Bonaparte (1989b) conclude the frequency of GM defects is 2·5 defects/ha. To compare with Foose *et al*. (2002) results, the area of the circular GM defects in the four-component composite liner system is assumed to be 0·66 cm² and the defects are assumed to be located directly above each other. The total simulation period is 100 years for comparison with Foose *et al*. (2002).

Figure 7 presents a comparison of the mass flux and cumulative mass of cadmium transported through various composite liner systems estimated using MT3DMS and MT3D. The Wisconsin NR500, Subtitle D, and GCL composite liners were analysed using MT3DMS with the same input parameters used by Foose *et al*. (2002) to verify the simulation performed herein because Foose *et al*. (2002) used MT3D, that is, an earlier version of MT3DMS, and these same liner systems. The MT3DMS results are in good agreement with the MT3D results presented in Foose *et al*. (2002) (see Figure 7), which corroborated the MT3DMS model developed herein.

Figure 8 presents the results of the simulation of cadmium transport through GM defects in the Wisconsin NR500, Subtitle D, GCL composite, and proposed four-component composite liner systems using MT3DMS. The mass balance errors of the simulations in Figures 7 and 8 are less than 1%. The proposed four-component composite liner yields the lowest mass flux and cumulative mass from the base of the liner system during the 100-year simulation period of the composite liner systems considered. For the proposed four-component composite liner system with 0·6- and 0·9-m-thick CSLs ($<10^{-9}$ m/s), the mass flux and cumulative mass after 100 years are 3·75 μg/ha/year and 0·2 mg/ha, and 2·12 μg/ha/year and 0·09 mg/ha, respectively. The mass flux of cadmium through the GCL composite liner system reaches steady state after about 5 years, that is, mass flux rate stops increasing, while the mass flux of cadmium through the proposed four-component composite liner is negligible during the first 20–25 years. These results show good solute transport performance of the proposed four-component composite liner systems with small mass flux and cumulative mass of cadmium being transported through the liner system. Figure 8 also shows that the Subtitle D composite liner system exhibits the highest mass flux and cumulative mass of cadmium of the four liner systems considered. However, all four composite liner systems show a negligible amount of cadmium (inorganic solute) transport after 100 years.

## Organic solute transport through four intact composite liner systems

### Diffusive transport modelling for organic solute

The mass flux of toluene through the intact GM component of the composite liner systems is dominant compared to that through GM defects because of the small area of a defect compared to the large surface area of the intact GM. Therefore, only the mass flux of toluene through intact (non-defective) GMs is estimated. Figure 9 is a schematic of organic solute transport with leachate concentration $C_0$ through the intact (no GM defects) four-component composite liner system. In this analysis, the GCL and CSL are again assumed to be fully saturated to represent the worst case for the performance of the composite liner systems being

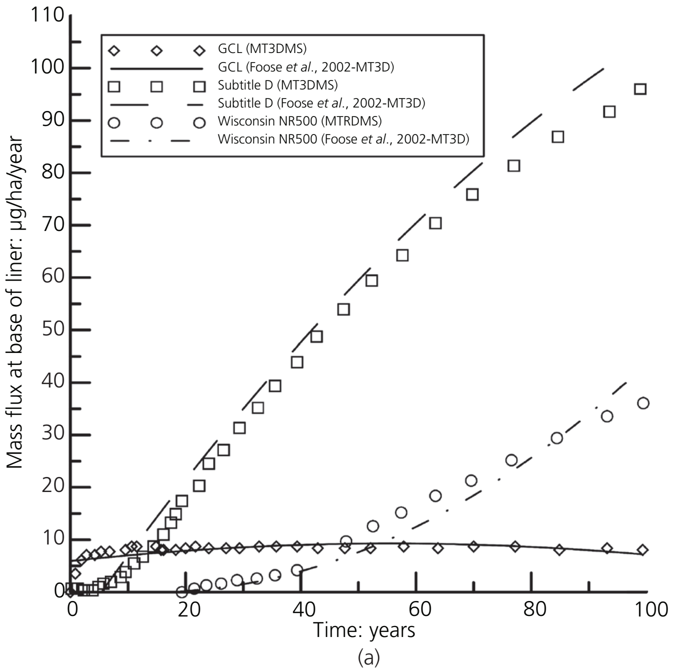


**Figure 7.** Comparison of MT3DMS and MT3D: (a) mass flux and (b) cumulative mass of cadmium transported through various composite liner systems

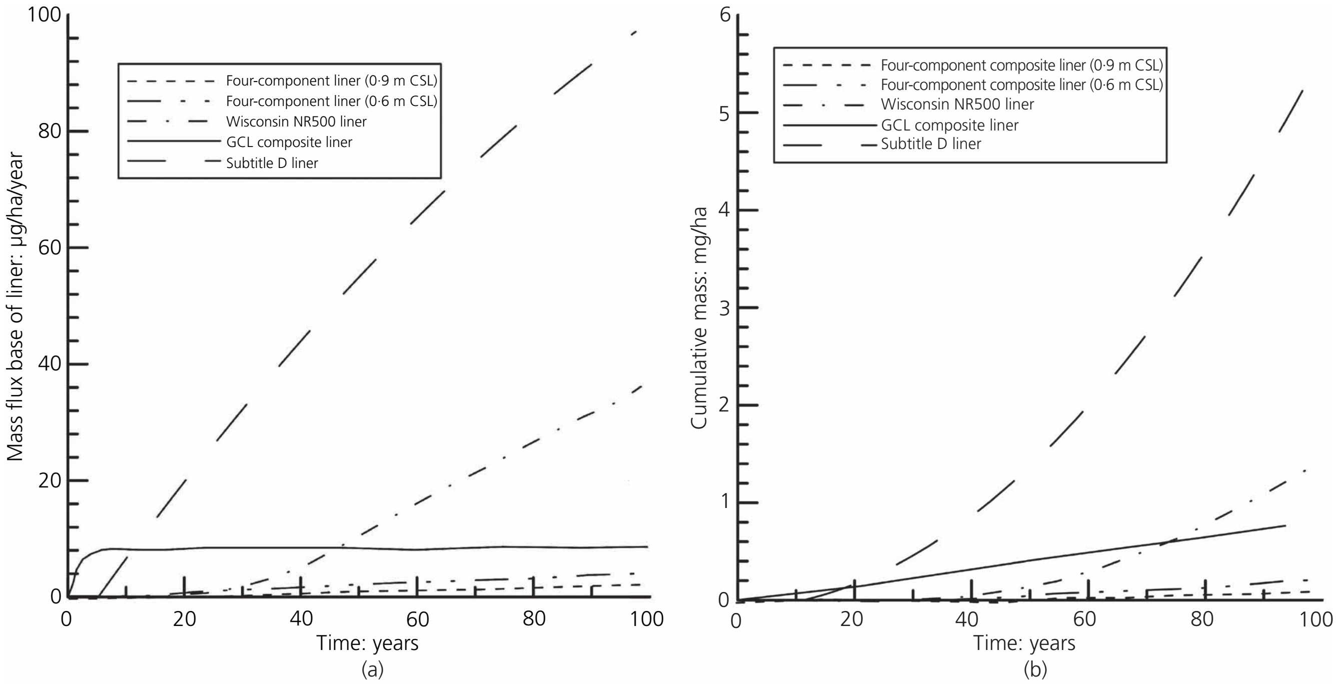


**Figure 8.** Comparison of (a) mass flux and (b) cumulative mass of cadmium transported through various composite liner systems

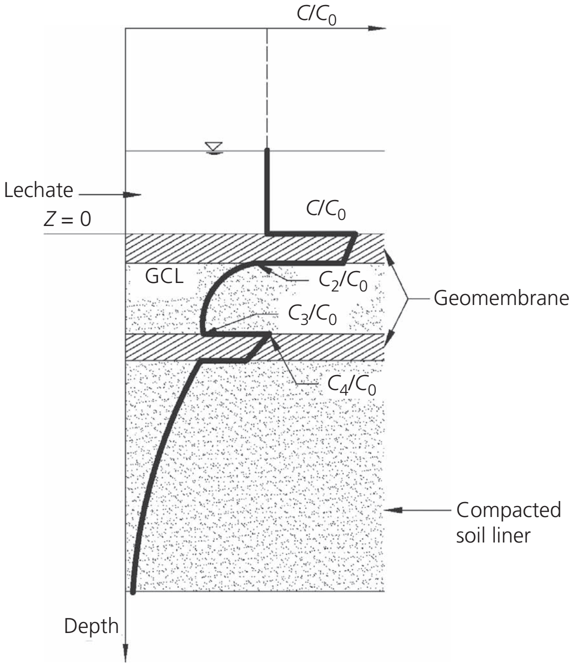


Figure 9. Concentration profile of toluene transport through four-component composite liner with no GM defects

considered. The toluene compound as an organic contaminant in the leachate initially partitions into the upper GM ($C_1 = K_{d,gm}{*}C_0$), then diffuses downward through the upper GM and partitions back into the pore water at the base of the upper GM ($C_2$). Subsequently, toluene diffuses through the GCL until partitioning occurs again into the lower GM ($C_4 = K_{d,gm}{*}C_3$). Subsequently, the transport process through the lower GM and the low hydraulic conductivity compacted soil is identical to that through the upper GM and GCL. The organic solute transport through the other intact composite liner systems considered in this study is similar to that through the lower GM and low hydraulic conductivity compacted soil of the intact four-component composite liner system shown in Figure 9.

The block-centred models of organic solute transport through the four intact composite liner systems with zero concentration at the base and semi-infinite bottom boundary condition are shown in Figures 10(a) and (b), respectively. These block-centred models were developed to solve the governing diffusive equations shown below

2. $$\frac{\partial c_m}{\partial t} = \frac{D_{gm}}{K_{d,gm}^2} * \frac{\partial^2 c_m}{\partial z_m^2} \quad \text{for GM layers}$$

3. $$R_d \frac{\partial c}{\partial t} = (D^*) * \frac{\partial^2 c}{\partial z^2} - \lambda * \left(c + \frac{\rho_b}{n} \bar{c}\right) \quad \text{for CSLs} \quad (<10^{-9}\ \text{m/s})$$

where

$c$ = concentration of toluene in the CSLs

$c_m$ = normalised concentration of toluene in the GM, $c_m = c_{GM}/K_{d,gm}$;

$K_{d,gm}$ = partition coefficient for the GM and toluene, $K_{d,gm} = 135$ (Park and Nibras, 1993)

$z$ = depth from the top of the four-component composite liner

$z_m$ = normalised coordinate in z-direction in GM, $\Delta z_m = \Delta z_{GM}/K_{d,gm}$;

$D_{gm}$ = diffusion coefficient of toluene through the GM, $D_{gm} = 3 \times 10^{-13}$ m$^2$/s (Park and Nibras, 1993)

$t$ = time

$D^*$ = effective diffusion coefficient of the CSLs, $D^* = D_o \tau_a$, $D_o$ = free solution diffusion coefficient, $D_o = 8{\cdot}47 \times 10^{-10}$ m$^2$/s for toluene (Yaws, 1995), $\tau_a$ = apparent tortuosity, $\tau_a = 0{\cdot}24$ for CSL and 0·074 for GCL (Rowe *et al*., 1997; Shackelford, 1989)

$\lambda$ = rate of constant of the first-order rate reactions (for a conservative calculation in this analysis, $\lambda$ was assumed to be zero)

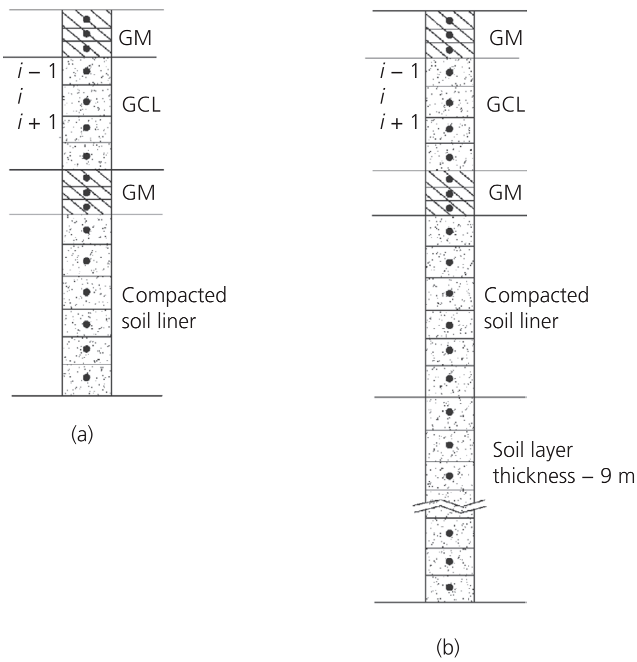


Figure 10. Block-centred model for transport of toluene through intact four-component composite liner: (a) zero concentration at the base and (b) semi-infinite bottom boundary condition

$\bar{c}$ = concentration of toluene sorbed on the CSLs

$R_d$ = retardation factor, which is defined as follows

$$R_d = 1 + \frac{\rho_b K_d}{n}, \quad (4)$$

where

$\rho_b$ = bulk density of the CSLs, $\rho_b$ = 1240 kg/m$^3$ and 790 kg/m$^3$ for compacted soil and GCL, respectively (Estornell and Daniel, 1992; Shackelford and Daniel, 1991b)

$K_d$ = partition coefficient for the CSL and toluene, $K_d = 1{\cdot}0 \times 10^{-3}$ m$^3$/kg and $2{\cdot}6 \times 10^{-3}$ m$^3$/kg for GCL and toluene, respectively (Benson and Lee, 2000; Edil *et al*., 1995)

$n$ = total porosity of the CSLs $n$ = 0·54 and 0·70 for compacted soil and GCL, respectively (Benson *et al*., 1999; Shackelford and Daniel, 1991b).

Three interfaces between the GM-GCL-GM-CSL in the four-component composite liner system cause a singular matrix if the implicit solution method is used for the differential equations above. Therefore, a block-centred formulation with an explicit solution scheme was developed herein for this analysis to provide a more applicable solution. The continuities of solute flux and concentration at the interfaces between the GM and CSLs are adopted as in Foose (1997) and Foose *et al*. (2002). The constant solute concentration of toluene ($C_0$) is 100 μg/L. The total simulation time used for this analysis is also 100 years to match Foose *et al*. (2002). In addition, a simulation time of 100 years is conservative for a typical landfill cell which may be open for less than 10 years but is used herein because it is a typical time period used for contaminant transport analyses. The two bottom boundary conditions for the block-centred models are as follows.

(*a*) The bottom boundary is located at the base of the liner system. The constant concentration at the bottom boundary is zero. This condition accounts for the situation where the organic solute can be conveyed away from the liner system by groundwater flow at the base of the liner system (see Figure 10(a)).
(*b*) The bottom boundary is located 9 m below the base of the liner system, at which the concentration is set to zero. To apply this condition, the liner system is underlain by a 9-m-thick layer of soil which has the same diffusion coefficient as the compacted soil layer and a retardation factor, Rd, of unity (1). The bottom boundary is at the base of the additional soil layer, which represents the semi-infinite bottom boundary (see Figure 10(b)).

## Diffusive transport results

Figures 11 and 12 present the diffusive transport results for the GCL, Subtitle D, and Wisconsin NR500 composite liner systems. The calculated mass fluxes of toluene shown in Figures 11 and 12 are based on an initial and constant solute concentration of 100 μg/L and a total simulation time of 100 years. The calculated mass fluxes of toluene for these liner systems are in excellent

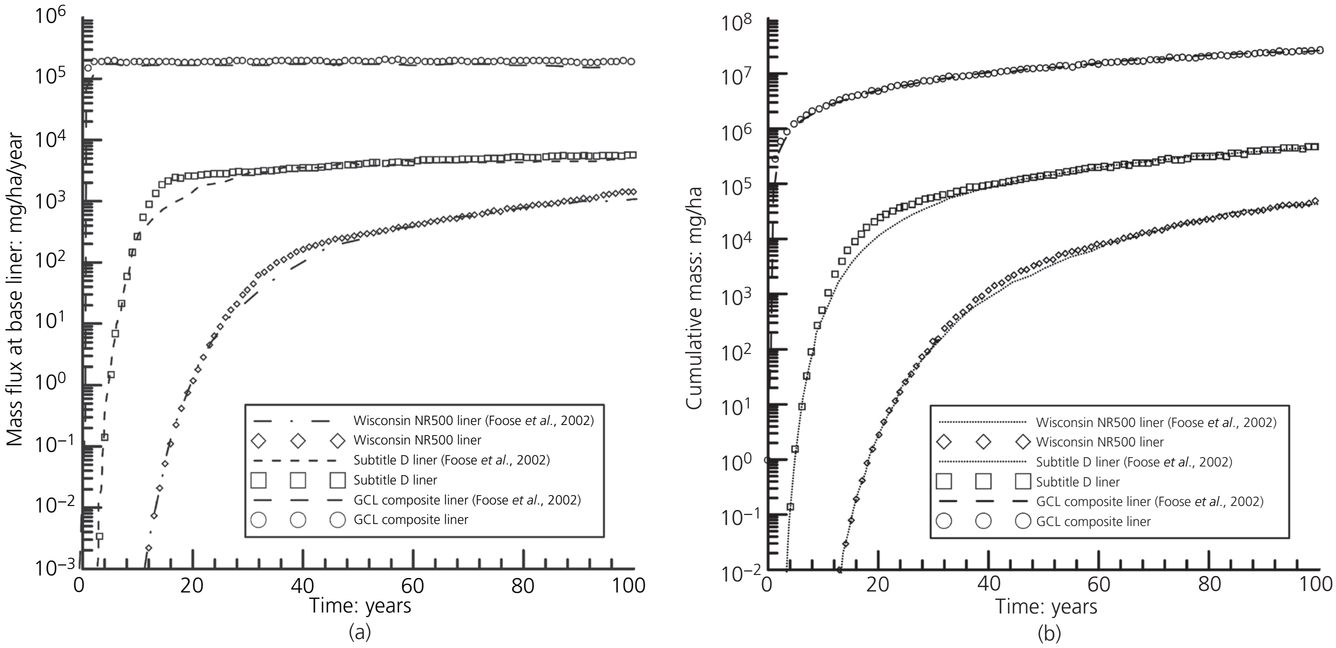


**Figure 11.** With zero concentration at liner base: (a) mass flux and (b) cumulative mass of toluene through various composite liner systems

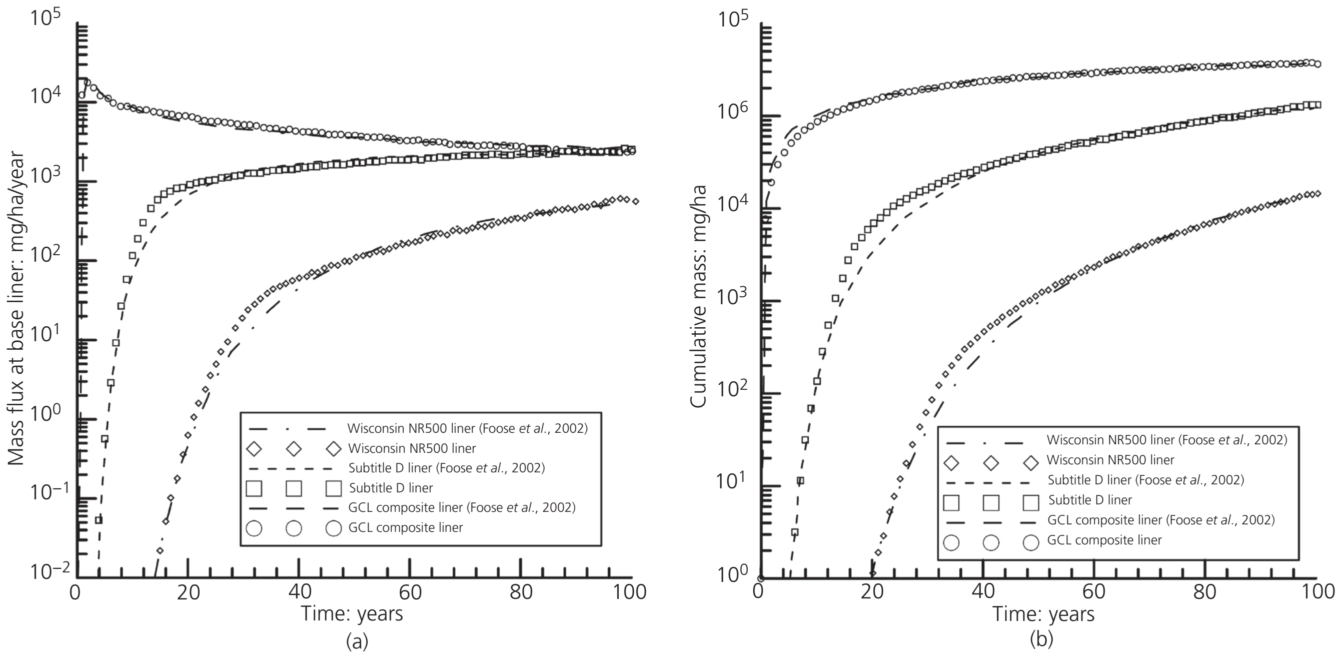


**Figure 12.** With semi-infinite bottom boundary condition: (a) mass flux and (b) cumulative mass of toluene through various composite liner systems

agreement with the values presented by Foose *et al*. (2002), which verifies the block-centred formulation with an explicit solution scheme developed herein and illustrated in Figure 10.

Figures 13 and 14 present the diffusive transport results for an intact four-component composite liner along with the other composite liner systems considered. For the case of a constant concentration of zero at the base of the various composite liner systems, Figure 13 shows that the proposed four-component composite liner is again the most effective in terms of mass flux of toluene after 100 years. The intact four-component composite liner system allows the smallest amount of toluene diffusion through of the composite liner systems considered. The mass fluxes of toluene through the intact four-component composite liner at the end of the simulation are 1432 and 489 mg/ha/year for low hydraulic conductivity ($<10^{-9}$ m/s) CSLs under the liner system having thicknesses of 0·6 and 0·9 m, respectively. The four-component composite liner system having a 0·6-m-thick CSL exhibits essentially the same mass flux as the Wisconsin NR500 liner, which has a GM overlying a 1·2-m-thick CSL. Similar trends were obtained for the estimation of cumulative mass flux through these four different composite liner systems (Figure 13(b)). The cumulative mass for the four-component composite liner with 0·6 m of low hydraulic conductivity compacted soil is 37 735 mg/ha at 100 years while the value for 0·9 m of CSL in the four-component composite liner is 10 366 mg/ha.

For the case of a semi-infinite bottom boundary condition, which is represented by the bottom boundary being at a depth of 9 m below the base of the composite liner system, Figure 14 shows that the proposed four-component composite liner is the most protective of the four composite liner systems considered with respect to toluene mass flux. The four-component composite liner with a 0·6-m-thick CSL ($<10^{-9}$ m/s) exhibits mass fluxes and a cumulative mass after 100 years that are lower than those of the Wisconsin NR500 liner system. In particular, the four-component composite liner mass fluxes at the end of the simulation are 445 and 153 mg/ha/year for CSL ($<10^{-9}$ m/s) thicknesses of 0·6 and 0·9 m, respectively. The cumulative masses are 11 678 and 3280 mg/ha at 100 years for 0·6 and 0·9 m of CSL thicknesses in the four-component composite liner system, respectively.

## Summary

The performance of a four-component composite liner system was analysed and compared to three other composite liner systems, that is, Subtitle D, Wisconsin NR500, and GM/GCL, in terms of leakage rate and solute flux. Numerical models and simulation results are presented herein that provide a means for evaluating the performance and protectiveness of these composite liner systems. The main findings of the study are as follows.

- Calculated advective leakage rates through circular and long defects in the four-component composite liner are lower than for the Subtitle D, Wisconsin NR500 and GM/GCL composite liner systems.
- For inorganic compound (cadmium) and organic compound (toluene) solute transport analyses, the four-component composite liner system also exhibited the lowest mass flux and cumulative mass of the composite liner systems considered

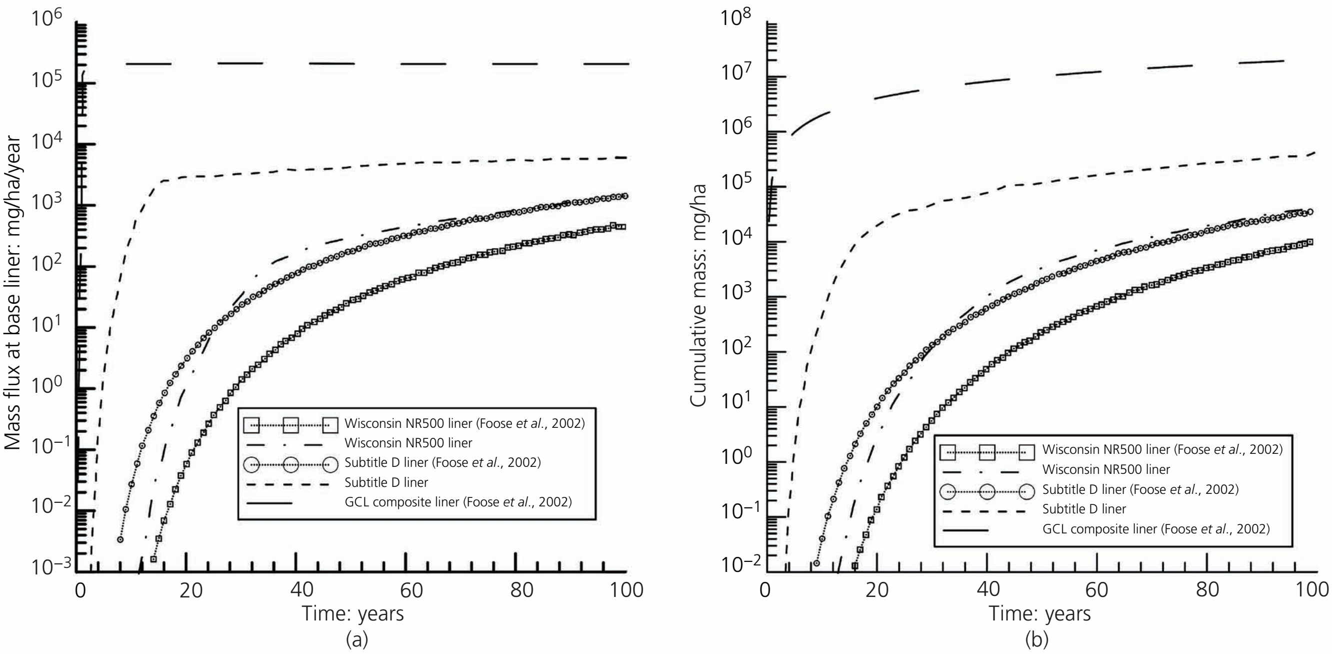


**Figure 13.** Transport of toluene with zero concentration at base: (a) mass flux and (b) cumulative mass through various composite liner systems

herein for a 100-year simulation period. Transport analyses for other chemical species through the four-component composite liner system are being performed to evaluate the effectiveness of this system for a range of constituents, simulation times, for example, 20 years to simulate landfill operations, and defect locations other than coaxial.

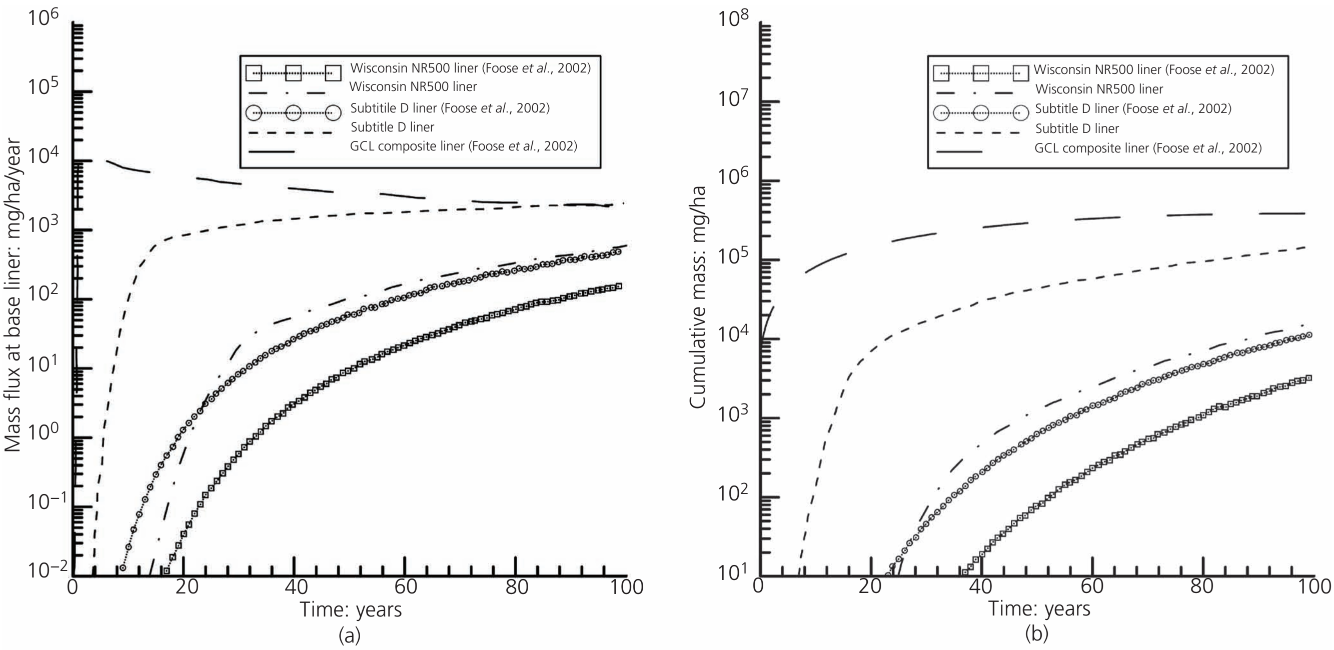


**Figure 14.** Transport of toluene with semi-infinite bottom boundary condition: (a) mass flux and (b) cumulative mass through various composite liner systems

- In terms of leakage rate, mass flux and cumulative mass, the proposed four-component composite liner exhibits better performance than the other three composite liner systems and may be a good alternative for a protective MSE landfill design assuming the engineering, ease of construction, materials availability, landfill airspace, site vulnerability and cost criteria also are favourable.
- Other benefits of the four-component composite liner system are an unhydrated GCL because of GM encapsulation, which means better slope stability, long-term durability and localised sealing of leaks in the upper and/or lower GMs by localised hydration of the GCL. Some of the limitations of the four-component composite liner system are additional material and construction costs, longer construction time, possible requirement of a slip sheet over the bottom GM to facilitate GCL placement if the GM is textured on both sides, and placement of the upper GM shortly after GCL placement to minimise GCL pre-hydration.

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