



## Analysis of diffusion-adsorption equivalency of landfill liner systems for organic contaminants

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### Abstract

The equivalence between multilayered barriers regarding diffusion and adsorption was studied. The bottom boundary of the liner system is defined by assuming concentration continuous and flux continuous conditions of the contaminant between the bottom liner layer and the underlying soil. Five different liner systems were compared in terms of solute breakthrough time. The results of the analysis showed that breakthrough time of the hydrophobic organic compounds for a 2-meter-thick compacted clay liner (CCL) could be 3–4 orders of magnitude is greater than the breakthrough time for a geosynthetic clay liner (GCL) composite liner. The GM/GCL and GM/CCL composite liner systems provide a better diffusion barrier for the hydrophilic organic compounds than that for the hydrophobic compounds due to their different Henry's coefficient. The calculated breakthrough times of the organic contaminants for the Chinese standard liner systems were found to be generally greater than those for the GCL alternatives, for the specific conditions examined. If the distribution coefficient increases to 2.8 for the hydrophobic compounds or 1.0 for the hydrophilic compounds, the thickness of the attenuation layer needed to achieve the same breakthrough time as the standard liner systems can be reduced by a factor of about 1.9–2.4. As far as diffusive and adsorption contaminant transport are concerned, GM or GCL is less effective than CCL.

**Key words:** liner system; equivalency; organic contaminant; landfill; diffusion; adsorption

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### Introduction

Organic chemicals are widely present in the waste disposed of in both municipal and hazardous waste landfills (Park and Nibras, 1993). A recent U.S. Environmental Protection Agency (USEPA) report characterizing landfill leachates from over 200 Municipal Solid Waste (MSW) landfills found organic compounds, such as benzene, toluene, ethylbenzene, and methylene chloride, in over 50% of the leachate samples tested (USEPA, 2000). Even though organic compounds generally occur at low concentrations in modern MSW leachate, they are still of concern because of the extremely low allowable concentrations in drinking water, and the fact that they have the potential to diffuse through both clay and plastic (geomembrane) liners (Haxo and Lahey, 1988; Brown and Thomas, 1998; Mueller *et al.*, 1998; Rowe, 1998; Foose *et al.*, 2001; Kalbe *et al.*, 2002). In order to protect underlying ground-water resources from these and other pollutants, waste disposal sites are commonly lined with clay and geomembrane (GM) composite liners. The standard liner recommended by The Ministry of Construction of China (MCPRC) (2004) consists of 75–100 cm of compacted clay liner (CCL) having a hydraulic conductivity  $< 1 \times 10^{-7}$  cm/s overlain with a GM or 2 m of clayey soil having a hydraulic

conductivity  $< 1 \times 10^{-7}$  cm/s. However, the recommended standard barrier types may not often be implemented in practice because of technical or financial reasons.

Over the past decade, geosynthetic clay liners (GCLs) have been proposed as a replacement for all or part of the clay component of composite liners (Bouazza, 2002). Designers and owners are inclined to propose using GCL composite liners because suitable clayey soil may not be available, the GCL composite liner uses less air-space in the landfill, and building a composite liner with a GCL may be more economically viable (Koerner, 1998; Bouazza, 2002).

US Subtitle D of the Resource Conservation Recovery Act includes a provision that permits an alternative liner, providing that the liner is equivalent to the Subtitle D standard liner (Foose *et al.*, 1999). The Chinese standard (CJJ 113-2007) also includes such a provision that permits the use of GCL composite liners, providing that an attenuation layer (AL) with certain thickness should be added beneath the GCL. The approval of such barrier replacement should be completed by means of contaminant transport equivalency calculations.

Research has shown that diffusive transport (contaminant migration driven by the difference in concentration between the upper and lower sides of the liner) is often the dominant mode of contaminant transport in well-built liner

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systems, and that liner equivalency analyses based solely on leakage rate can be misleading (Crooks and Quigley, 1984; Shackelford, 1990; Bouazza and Impe, 1998; Zheng and Zhao, 2000; Kim *et al.*, 2001; Foose *et al.*, 2002; Kalbe *et al.*, 2002; Xi *et al.*, 2006). Several numerical methods of varying complexity have been developed to simulate organic contaminant diffusion through composite liners. For example, Foose *et al.* (1999, 2002) used a multiple-layer finite-difference model to simulate diffusion of volatile organic compounds (VOCs) through composite liners. Kalbe *et al.* (2002) adopted the finite-layer methods to estimate acetone diffusion through composite liner. Finite-element method was developed by Yang and Lo (2004) to estimate gasoline diffusion through the composite liner. Such conventional numerical methods (e.g., finite elements, finite difference) have an important role to play in this type of modeling. However, the level of numerical sophistication often greatly exceeds the sophistication of the available data (especially at the site selection and preliminary design stages). Under these circumstances, the cost (in terms of man hours) of a detailed numerical analysis (with the necessary checks on discretization error) may not be justifiable, and simplified analytical methods provide an economical and efficient alternative to the numerical models in many ways (Rowe and Nadarajah, 1997). Although analytical solutions may involve simplified assumptions and idealization of the actual conditions, they can be easily used to assess the effect of uncertainties involved in the design of landfill liner systems.

In this article, the equivalence between multilayered liners was evaluated on the basis of an analytical method. The method presented here is an extension of the two-layered solution provided by Xie *et al.* (2006a). The bottom boundary condition of the liner systems is more appropriately treated by adopting concentration continuous and flux continuous conditions of the contaminant between two media, since it is difficult to explicitly define the bottom boundary condition of the liner systems. By means of the presented method, various liner systems were compared regarding diffusion and adsorption for two different types of organic contaminants. The thickness of the AL required for the GM/GCL composite liner to be equivalent to the Chinese standard liner systems was investigated based on the breakthrough time for the specific conditions. The article also outlines the level of barrier improvement achieved by the surface treatment of GM and the organo-clay treatment of GCL.

## 1 Experimental

### 1.1 Analytical solution

The mathematical model of one-dimensional diffusion of a single species of contaminant parallel to the  $z$  direction through a layered composite media is shown in Fig. 1. The upper  $n$  layers represent the liner layers and the lower  $(n+1)$ th layer represents the subgrade layer. The coordinate  $z$  has its origin at the top surface. The vertical distance from the top surface ( $z = z_0 = 0$ ) to the bottom of the  $i$ th layer is

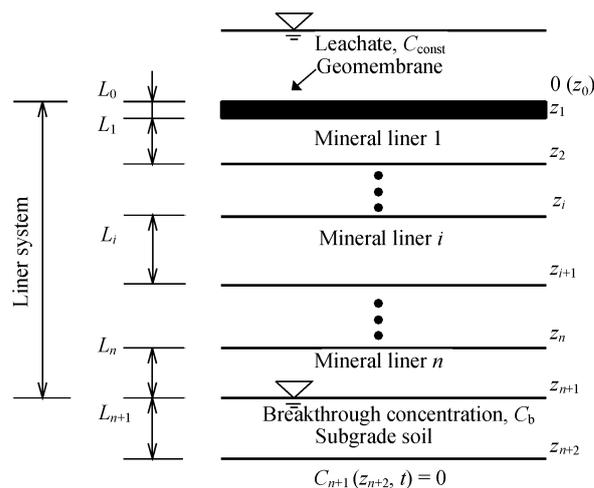


Fig. 1 Schematic of the concept model.

denoted by  $z_{i+1}$  and each layer ( $z_i \leq z \leq z_{i+1}$ ) is assumed to be homogeneous. An arbitrary layer is indexed by  $i$  with thickness  $L_i$ , effective diffusion coefficient  $D_i^*$ , void ratio  $n_i$ , dry density  $\rho_{di}$ , and distribution coefficient  $K_{di}$ .

Based on Fick's second law, the governing equation for diffusion through the  $i$ th layer at a particular depth  $z$  and time  $t$  (Bear, 1972; Freeze and Cherry, 1979; Shackelford and Daniel, 1991; Chen *et al.*, 2006a; Xie *et al.*, 2006b)

$$\frac{\partial C_i(z, t)}{\partial t} = \frac{D_i^*}{R_{di}} \frac{\partial^2 C_i(z, t)}{\partial z^2} \quad (i = 0, 1, 2, 3, \dots, n+1) \quad (1)$$

where,  $C_i(z, t)$  is the contaminant concentration in the  $i$ th layer at position  $z$  and time  $t$ ;  $C_0(z, t)$  is the contaminant concentration in the GM;  $R_{di}$  is the retardation factor and is determined by

$$R_{di} = 1 + \rho_{di} K_{di} / n_i \quad (i = 0, 1, 2, 3, \dots, n+1) \quad (2)$$

where  $R_{d0}$  for the GM is 1 since  $K_{d0}$  is assumed to be zero for the GM. The initial condition is assumed to be

$$C_i(z, 0) = 0 \quad (i = 0, 1, 2, 3, \dots, n+1) \quad (3)$$

For the top surface boundary, constant concentration is assumed to apply along the surface of the GM layer (Chen *et al.*, 2006b):

$$C_0(0, t) = C_{\text{const}} S \quad (4)$$

where,  $C_{\text{const}}$  is the concentration of the contaminants in the leachate. A constant source concentration was used because insufficient field data exist to support a more complicated boundary condition (Rowe, 1987; Shackelford, 1990).  $S$  is the Henry's coefficient, which is defined as the ratio of the concentration of the chemical in the GM at equilibrium to the concentration of the chemical in the solution in contact with the GM (Park and Nibras, 1993; Meller *et al.*, 1998). The bottom boundary condition of the subgrade layer is assumed to be

$$C_{n+1}(z_{n+2}, t) = 0 \quad (5)$$

Following Chen *et al.* (2006b) and Xie *et al.* (2006a), the interface boundary conditions between the GM and underlying soil liner are

$$\frac{C_0(z_0, t)}{S} = C_1(z_0, t) \tag{6}$$

$$D_0^* \frac{\partial C_0(z_0, t)}{\partial z} = n_1 D_1^* \frac{\partial C_1(z_0, t)}{\partial z} \tag{7}$$

The interface boundary conditions between the subsequent mineral layers are as follows:

$$\left. \begin{aligned} C_i(z_{i+1}, t) &= C_{i+1}(z_{i+1}, t) \\ n_i D_i^* \frac{\partial C_i(z_{i+1}, t)}{\partial z} &= n_{i+1} D_{i+1}^* \frac{\partial C_{i+1}(z_{i+1}, t)}{\partial z} \end{aligned} \right\} (i = 1, 2, 3, \dots, n) \tag{8}$$

Because of the linear nature of the problem described by Eq. (1) through Eq. (8), the above problem can be solved using the superposition method. The solution to Eq. (1) satisfying all relevant conditions can be expressed as follows:

$$\left. \begin{aligned} C_0(z, t) &= S(\phi_0(z) C_{\text{const}} + \theta_0(z, t)) \\ C_i(z, t) &= \phi_i(z) C_{\text{const}} + \theta_i(z, t), \quad i = 1, 2, \dots, n + 1 \end{aligned} \right\} \tag{9}$$

where the definitions and solutions of  $\phi_i(z)$  and  $\theta_i(z, t)$  are given in appendix A and appendix B, respectively. The model has been verified by comparing the results obtained by the present analytical solution with those obtained by laboratory tests for a two-layer system consisting of a GM and a CCL (Xie *et al.*, 2006a). And the analytical solution presented in this article is an extension of the two-layer solution presented in Xie *et al.* (2006a).

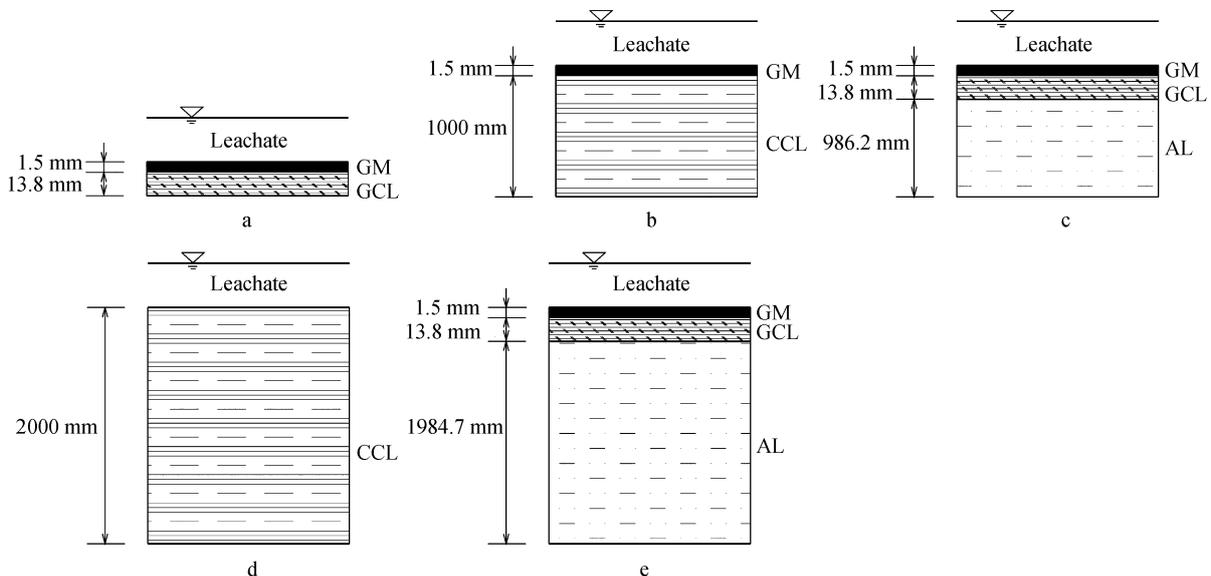
**1.2 Materials**

The provision for alternative liner designs in the standards of Chinese and the USA and the development of

GCLs for use in composite liner systems has resulted in a need for comparing alternative landfill liner systems. In this article, five different liner systems (Fig. 2) are compared in terms of equivalency: (1) a composite liner having a GCL; (2) the composite liner prescribed in the Chinese Standard (CJJ 17-2004); (3) the single clay liner with the depth of 2 m also prescribed in the Chinese Standard (CJJ 17-2004); (4) the composite liner consisting of a GM, a GCL, and an AL with the thickness equal to the Chinese Standard composite liner; and (5) the composite liner consisting of a GM, a GCL, and an AL with the thickness equal to 2 m CCL. The Chinese standard composite liners consist of a thick layer of compacted clay (100 cm) overlain by a 1.5-mm-thick high-density polyethylene (HDPE) GM. The GCL composite liner system adopted by the Tianziling landfill in Hangzhou, China, is similar, except that the compacted clay component is replaced with a 13.8-mm-thick GCL.

Dichloromethane (DCM) and benzene were selected to represent hydrophobic organic compounds of the leachate constituents, whereas acetone and phenol were selected to represent hydrophilic organic compounds. The reason for choosing these contaminants is that they are commonly found in landfill leachate, and the allowable concentrations of these contaminants in drinking water are relatively low. The source concentrations of the organic compounds summarized in Table 1 are based on the results provided by Bonaparte *et al.* (2002) and Kjeldsen *et al.* (2002). The breakthrough concentrations for the contaminants are based on the drinking water standards of Ontario Ministry of the Environment (OME) (2001), USEPA (2002), and MCPRC (2006). The breakthrough time is the time required for the concentration of a specific leachate constituent to reach the breakthrough concentration at the bottom of the liner system (Acar and Haider, 1990).

Based on the analytical method presented here, the contaminant concentration at the base of the composite liners for different types of organic contaminants was compared.



**Fig. 2** Five different liner systems examined.

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**Table 1** Representative concentration of the four organic contaminants in the leachate and the allowable concentrations in the drinking water standards

Organic contaminant	DCM	Benzene	Acetone	Phenol
Concentration in the leachate (mg/L)	4.15	1.63	4400	64
Maximum concentration recommended in the drinking water standards (mg/L)	0.005 <sup>a</sup>	0.005 <sup>a</sup>	1 <sup>b</sup>	0.002 <sup>c</sup>

DCM: dichloromethane; <sup>a</sup> USEPA, 2002; <sup>b</sup> OME, 2001; <sup>c</sup> MCPRC, 2006.

Representative material and contaminant properties used as inputs into the model are summarized in Table 2. The diffusion and Henry's coefficients for HDPE GM are from Kalbe *et al.* (2002) and Sangam and Rowe (2001). The diffusion and distribution coefficients for DCM and CCL were reported by Barone *et al.* (1991), as were the values assumed for the dry unit weight and porosity. Barone *et al.* (1992) reported the diffusion and distribution coefficients between the CCL and acetone. The effective diffusion coefficients and the distribution coefficients of benzene and phenol for CCL were reported by Hrapovic (2000). Lake and Rowe (2004) reported the material and chemical properties for the contaminants and GCL. Attenuation layer and the subgrade layer (SL) were assumed to be a silty clay layer and a sand layer, respectively. The material and chemical properties for the contaminants and these two layers (AL and SL) are from Badv and Rowe (1996). The subgrade layer was assumed to be 10 m when calculating the concentration at the bottom of the liner systems using

the analytical solution presented. This is because a pilot calculation indicates that the concentration at the bottom of the liner system will not be significantly affected by the subgrade layer when the thickness of this layer is increased to 10 m or greater.

## 2 Results and discussion

### 2.1 Comparisons of organic contaminant diffusion through five liner systems

The breakthrough curves of the contaminants for the different liner systems are compared in Fig. 3. The calculated breakthrough times for the contaminants and the liner systems are summarized in Table 3. In general, 2 m CCL provides the best diffusion-adsorption barrier for the contaminants (except for acetone) with the largest breakthrough times. For hydrophobic organic compounds, such as DCM and benzene, the breakthrough time for the 2 m CCL is 3–7 times greater than that of GM/CCL (Fig. 2b) and 2000–3000 times greater than that of GCL composite liner. This is because the effective diffusion coefficients and the Henry's coefficients (*S*) of the hydrophobic organic compounds for the GM are much greater than those of the heavy metals. For hydrophilic organic compounds, such as acetone, however, GM/CCL (Fig. 2b) provides the best barrier with the largest breakthrough time of 34.5 years compared with 0.57 years for GM/GCL (Fig. 2a) and 30.6 years for CCL (Fig. 2d). Similar to the hydrophobic organic compounds, the breakthrough time of phenol for

**Table 2** Physical and chemical properties for the media

Parameter	GM	CCL	GCL	AL	SL
Thickness (m)	0.0015	1.0	0.0138	Variable	10.0
Porosity	–	0.32	0.86	0.40	0.415
Dry density (g/cm <sup>3</sup> )	–	1.79	0.79	1.62	1.59
Diffusion coefficient (m <sup>2</sup> /s)					
DCM	$5.0 \times 10^{-13}$	$8.0 \times 10^{-10}$	$3.3 \times 10^{-10}$	$8.9 \times 10^{-10}$	$4.0 \times 10^{-7}$
Benzene	$3.5 \times 10^{-13}$	$5.0 \times 10^{-10}$	$3.3 \times 10^{-10}$	$8.9 \times 10^{-10}$	$4.0 \times 10^{-7}$
Acetone	$6.0 \times 10^{-13}$	$5.6 \times 10^{-10}$	$4.3 \times 10^{-10}$	$8.9 \times 10^{-10}$	$4.0 \times 10^{-7}$
Phenol	$1.1 \times 10^{-12}$	$2.5 \times 10^{-10}$	$4.3 \times 10^{-10}$	$8.9 \times 10^{-10}$	$4.0 \times 10^{-7}$
Henry's coefficient <i>S</i> (-)					
DCM	5.0	–	–	–	–
Benzene	30.0	–	–	–	–
Acetone	0.032	–	–	–	–
Phenol	0.021	–	–	–	–
<i>K<sub>d</sub></i> (mL/g)					
DCM	–	1.5	0	0.28	0
Benzene	–	0.7	20	0.28	0
Acetone	–	0.19	0	0	0
Phenol	–	0.11	0	0	0

GM: geomembrane; GCL: geosynthetic clay liner; AL: attenuation layer; SL: upgrade layer; –: parameter for a certain material does not exist. For example, the Henry's coefficient *S* is only the parameter of GM and is not a parameter of GCL, CCL, AL, and SL. *K<sub>d</sub>*: distribution coefficient.

**Table 3** Breakthrough time of the four organic contaminants for the five different liner systems

Sketch	Liner system	Breakthrough time (year)			
		DCM	Benzene	Acetone	Phenol
Fig. 2a	GM + 13.8 mm GCL	0.04	0.1	0.57	0.04
Fig. 2b	GM + 1 m GCL	35.0	38.6	34.5	20.3
Fig. 2c	GM + 13.8 mm GCL + 0.9862 m CCL	8.1	9.6	13.0	4.87
Fig. 2d	2 m CCL	120	236.9	30.6	36.5
Fig. 2e	GM + 13.8 mm GCL + 1.9847 m CCL	28.3	36.7	38.3	16.3

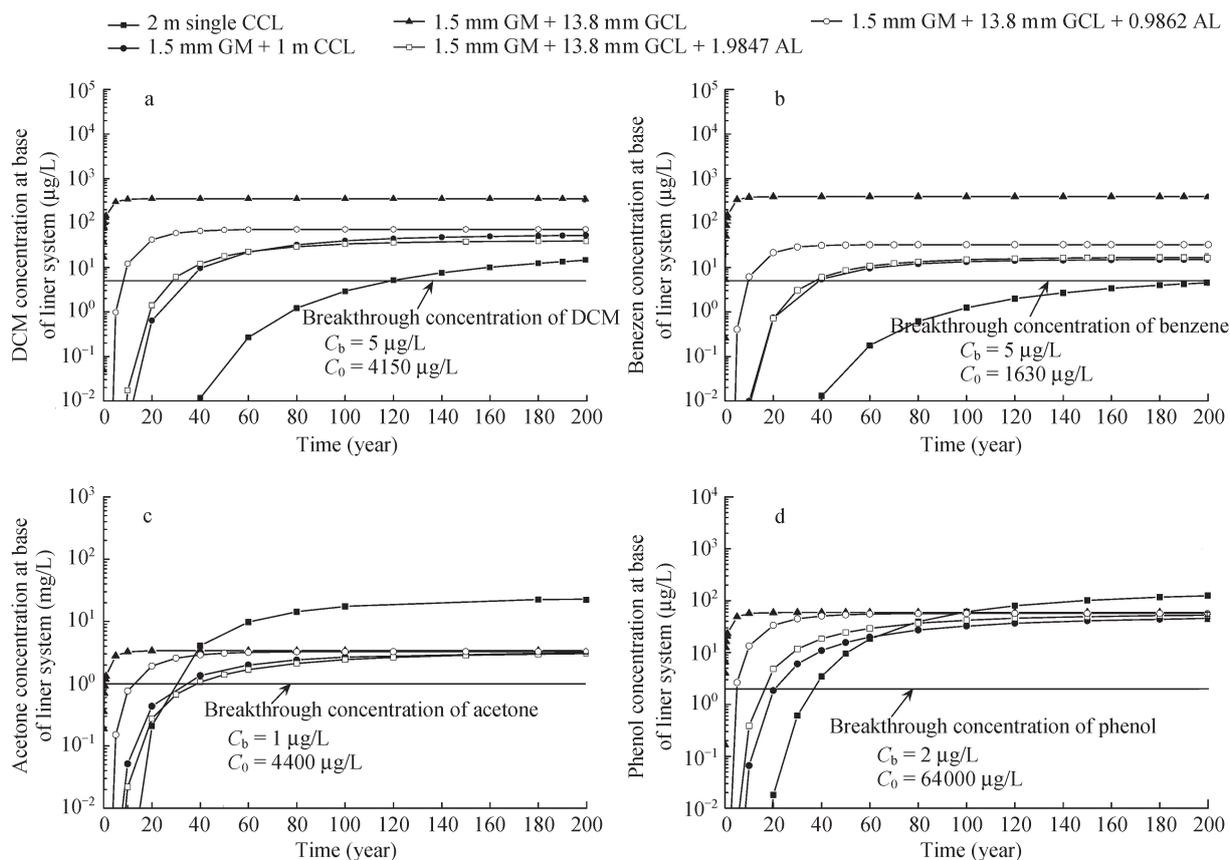


Fig. 3 Organic contaminant diffusion through different liner systems. (a) DCM; (b) benzene; (c) acetone; (d) phenol.

2 m CCL (Fig. 2d) is 1.8 times greater than GM/CCL and 915 times greater than GM/GCL. Furthermore, as shown in Fig. 3, unlike hydrophobic organic compounds, the concentrations of hydrophilic organic compounds at the bottom of 2 m CCL after 200 years are 2.8–7.4 times greater than those of GM/CCL and 2.1–6.7 times greater than GM/GCL. It is suggested that the HDPE GM can help reduce the contaminant impact of the hydrophilic organic compounds effectively due to the much lower values of Henry's coefficient for this type of organic contaminants and the GM.

The breakthrough times for GM/CCL composite barrier and the single CCL barrier are also compared with alternative composite barrier systems with GM, GCL, and AL, with the thickness of the AL such that the total thickness between the GM and the top of the SL is the same for a given regulatory design. The combined thickness of the GCL (thickness of 13.8 mm) and AL in Fig. 2c is the same as the thickness of the CCL in Fig. 2b. In all cases, the calculated breakthrough time for GM/CCL composite liners is larger than the breakthrough time for the corresponding GM/GCL/AL alternatives. For example, the breakthrough time for DCM and the GM + 1.0 m CCL liner in Fig. 2b is 4.3 times greater than that for the GM + GCL + 0.9862 m AL system in Fig. 2c. This may be caused by the larger adsorption capacity and lower diffusion coefficients of CCL compared with AL. Except for the case of acetone, the breakthrough time for 2 m CCL liner is also larger than that for the corresponding GM/GCL/AL alternative. The

breakthrough time for benzene and the 2.0 m CCL liner in Fig. 2d is 6.5 times greater than that for the GM + GCL + 1.9847 m AL system in Fig. 2e. The breakthrough time for acetone and the 2.0 m CCL liner in Fig. 2d, however, it is 30.6 years compared with 38.3 years for the GM + GCL + 1.9847 m AL system in Fig. 2e.

## 2.2 Effect of distribution coefficient and thickness of the AL

Due to the inability of GM/GCL/AL composite liner to impede diffusive transport of organic contaminant (mainly hydrophobic organic compounds) effectively, enhancement of the sorption capacity of earthen liner materials should be considered as means to improve liner performance (Shen *et al.*, 2004; Wang *et al.*, 2004; Chen *et al.*, 2005; Bartelt-hunt *et al.*, 2005). Lo (1996) showed that the distribution coefficients of the organo-clays can be 100 times greater than that of the untreated soil clays. In this article, the diffusion coefficients of the AL were assumed to remain unchanged when the distribution coefficient is increased, since Headley *et al.* (2001) showed that the diffusion coefficients of the organo-amended clay were even lower than those of the unamended clay.

Figure 4 presents the calculated variation in breakthrough times with the thickness of AL in GM/GCL/AL system with different values of  $K_d$  for the contaminants and the AL. The thickness of the additional AL required for the GCL composite liner to be equivalent to the Chinese standard liner is obtained based on breakthrough time.

**Table 4** Equivalent thickness of AL in GM/GCL/AL liner system with GM/CCL and CCL liner systems.

$K_d$ (mL/g)	$L_{AL(GM/CCL)}$ (m)					$L_{AL(CCL)}$ (m)				
	0.28	2.8	8.4	0	1.0	0.28	2.8	8.4	0	1.0
DCM	2.3	1.0	0.6	–	–	3.9	1.8	1.1	–	–
Benzene	2.1	1.0	0.6	–	–	4.2	2.2	1.4	–	–
Acetone	–	–	–	1.9	0.9	–	–	–	1.8	0.8
Phenol	–	–	–	2.5	1.1	–	–	–	3.3	1.4

$L_{AL(GM/CCL)}$ : equivalent thickness of AL with GM + 1 m CCL;  $L_{AL(CCL)}$ : equivalent thickness of AL with 2 m CCL.  
 –: values in the unit have not been calculated.

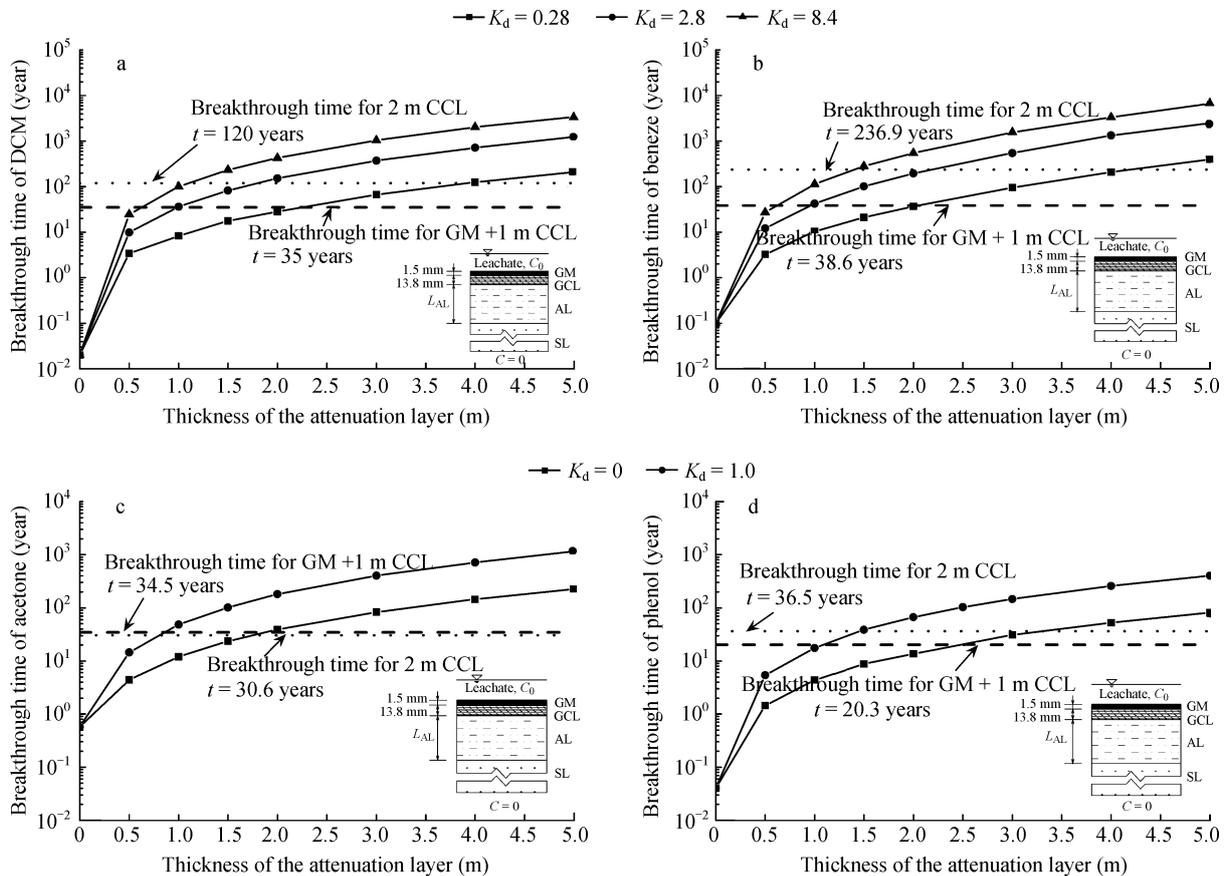
The calculated equivalent thicknesses of AL for different organic contaminants and liner systems are given in Table 4. Obviously, the equivalent thicknesses  $L_{AL(GM/CCL)}$  and  $L_{AL(CCL)}$  decrease when the distribution coefficients increase. For example, the equivalent thickness  $L_{AL(GM/CCL)}$  for DCM with the distribution coefficient  $K_d = 8.4$  mL/g is 3.8 times lower than that with  $K_d = 0.28$  mL/g. Similarly, the calculated equivalent thickness  $L_{AL(CCL)}$  for acetone is 0.8 m for an amended AL compared with 1.8 m for an untreated AL. The results reflect the fact that the breakthrough time increases with the increase of  $K_d$  values. It is indicated that if the distribution coefficient increases to 2.8 for the hydrophobic compounds or 1.0 for the hydrophilic compounds, the GM/GCL/AL composite liner systems (Figs. 2c and 2d) are approximately equivalent to the GM/CCL and 2 m CCL systems with the same thickness in terms of breakthrough time.

The effect of the total thickness of the soil beneath the GM on breakthrough time can also be observed from

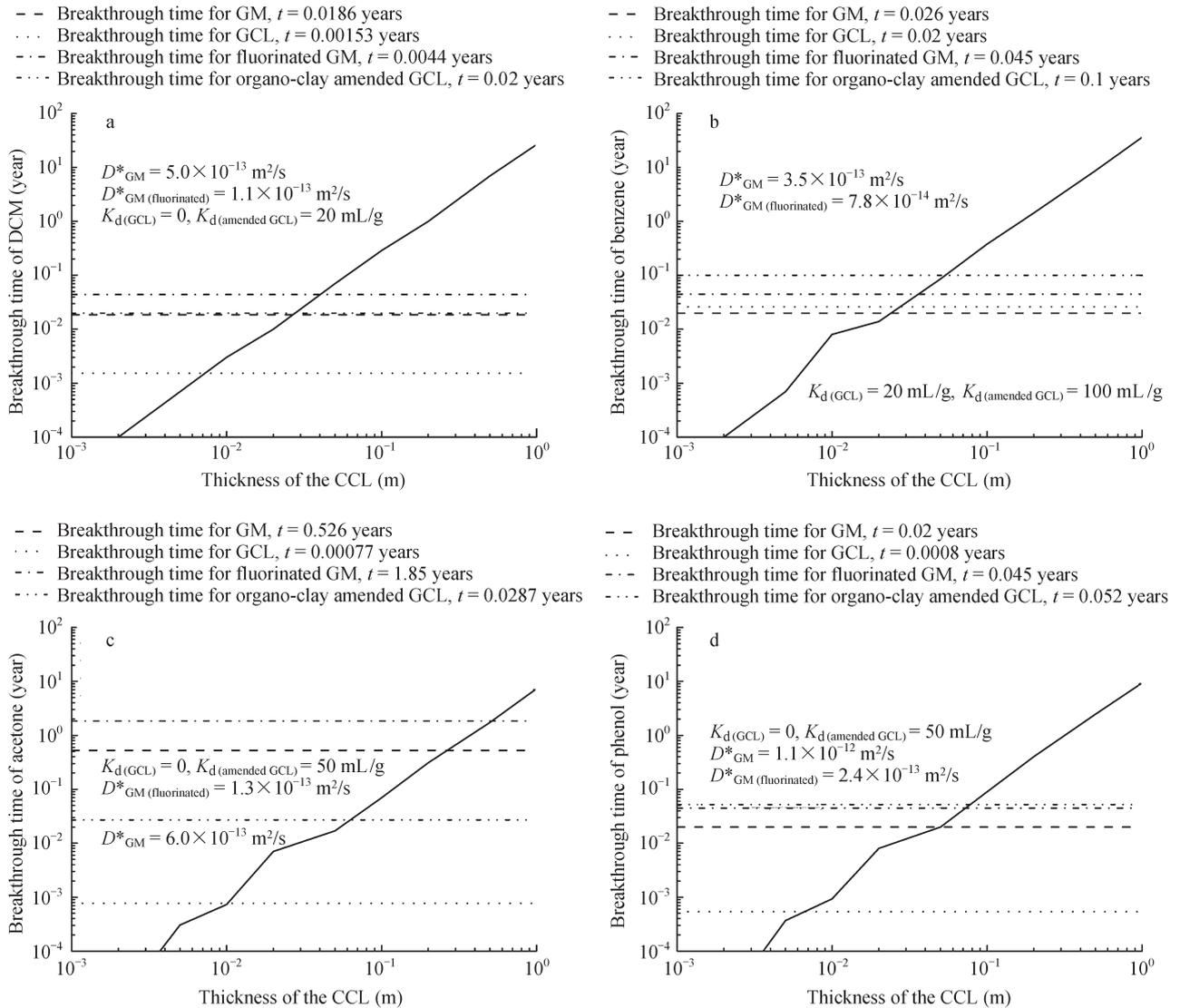
Fig. 4. As the total thickness of the soil barrier increases, the breakthrough time for the contaminants increases. The breakthrough time for benzene and the GM + GCL + 2 m AL system is 16 times greater than the GM + GCL + 0.5 AL system in case of  $K_d = 2.8$  (Fig. 4b). Similarly, the breakthrough time for phenol and the GM + GCL + 2 m AL system is 66.9 years compared with 5.4 years for GM + GCL + 0.5 AL system in case of  $K_d = 1.0$  (Fig. 4b). Larger breakthrough time occurs for a thicker AL because the greater thickness of soil beneath the GM increases the time it takes for the contaminants to diffuse through the barrier system and thereby giving a lower impact on the subgrade. These results imply that AL has an important effect on the diffusion of contaminants through the barrier system.

**2.3 Equivalency of single GM or GCL with CCL**

Figure 5 shows the variation in breakthrough time with the thickness of CCL and the single GM and GCL for



**Fig. 4** Variation in breakthrough time with thickness of AL for different contaminants. (a) DCM; (b) benzene; (c) acetone; (d) phenol.



**Fig. 5** Diffusion equivalency of GM and GCL with CCL for different contaminants. (a) DCM; (b) benzene; (c) acetone; (d) phenol.

various organic contaminants. Based on the criterion of the same breakthrough time, the equivalent thickness of GM and GCL with CCL was calculated with the results summarized in Table 5. Investigating the results of the calculations, it is obvious that the efficiency of the HDPE geomembrane and the GCL barriers against diffusive transport processes is much lower than that of the CCL. Depending on the product, the HDPE geomembrane of 1.5 mm thickness is equivalent to 27–50 mm CCL for all the organic contaminants except acetone regarding the mechanism of diffusive and adsorption. The equivalent thickness of GM with CCL for acetone, however, it is as large as 260 mm. It is indicated that the equivalent thickness of GM with CCL for the hydrophilic organic compounds such as acetone and phenol is larger than that for the hydrophobic organic compounds such as DCM and benzene. This result is understandable because the hydrophilic organic compounds have much lower Henry's coefficients than the hydrophobic organic compounds. It is also shown in Fig. 5 and Table 5 that the 13.8 mm GCL is equivalent to 7–27 mm CCL for all the organic

**Table 5** Equivalent thickness of GM and GCL with CCL

	Equivalent thickness (m) with CCL			
	GM	Fluorinated GM	GCL	Organo-clay amended GCL
DCM	0.027	0.04	0.007	0.03
Benzene	0.02	0.036	0.027	0.05
Acetone	0.26	0.52	0.01	0.06
Phenol	0.05	0.07	0.01	0.08

contaminants regarding the mechanism of diffusive and adsorption. It is suggested that single GCL is not a good substitute for CCL as a diffusion-adsorption barrier for landfill.

The above results have shown that the organic contaminants (especially the hydrophobic organic compounds) can readily migrate through the GM and the GCL, and hence could potentially pollute groundwater if there is no adequate CCL and/or an AL below them. The study of Sangam and Rowe (2005) indicated that the surface fluorination of GM can result in a reduction in diffusion coefficients by factors as high as 4.5. It is shown in this study

that if the diffusion coefficients for the contaminants and fluorinated GM is decreased to two-ninth of the untreated GM and the Henry's coefficients remain unchanged, the equivalent thickness of the fluorinated GM with CCL is 1–2 times greater than that of the untreated GM (Table 5). Moreover, the equivalent thickness of the organo-clay amended GCL with CCL is 2–8 times greater than that of the unamended GCL using the distribution coefficients between the organic contaminants and the organo-clay amended GCL reported by Lake and Rowe (2005). It is also indicated that the maximal equivalent thickness of the amended GCL with CCL is less than 10 cm.

### 3 Conclusions

The equivalence of composite liners with a geomembrane and geosynthetic clay liner to traditional liner systems was assessed in terms of contaminant breakthrough time. An analytical method for one dimensional contaminant diffusion through composite liners was used to calculate the concentration of the organic contaminants at the bottom of the liner systems. For the organic contaminants and the range of parameters considered, the following may be concluded. (1) GM+CCL and 2 m CCL provide better diffusion barriers than GM+GCL. It is also indicated that the HDPE GM provides a better diffusion barrier for the hydrophilic organic compounds than for the hydrophobic ones due to the fact that the Henry's coefficients of the hydrophobic organic compounds for the GM are much greater than those of hydrophilic compounds. (2) The breakthrough times of DCM and benzene for the Chinese standard liner systems were found to be greater than those for the GM/GCL/AL alternatives. The additional thickness of AL below the GM+GCL system should be about 4.0 m for equivalency with the standard liners. In effect, the additional soil layer makes the thickness of GCL composite liner generally larger than the standard liners. (3) The thickness of the AL needed to achieve the same breakthrough time as the standard liner systems can be reduced by a factor of about 1.9–2.4 when the adsorption capacity of the AL is increased by a factor of about 10.

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