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Performance-based Evaluation for Efficiency of Landfill Liner Systems

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SYNOPSIS : Efficiency of landfill liners system is usually evaluated based on leakage rate and mass flux. In this study, composite liner systems including the GCL(geosynthetic clay liner) composite liner, the Subtitle D liner, the Wisconsin NR500 liner, and the recently utilized double composite liner, which is a combination of the GCL composite liner and Subtitle D-type liner, have been examined. The leakage rate through circular and long defects in the geomembrane (GM) of the liner system was analyzed with the aids of analytical and numerical methods. For the mass flux criterion, contaminant transport through defects in the GM of landfill liners can be evaluated based on the calculated leakage rates. The diffusion rate of volatile organic compounds through intact landfill liners was evaluated by performing a one-dimensional numerical model. Cadmium and toluene were adoptted in the analyses as typical inorganic and organic substances, respectively, which will be chemical species encountered during landfill operation. The performance-based evaluation indicates that the double composite liner systems are superior to the other types of liner.

Keywords : composite landfill liner, leakage rate, mass flux, geomembrane, geosynthetic clay liner.

1. Introduction

Three types of composite liner systems widely used in solid waste landfills in the US are the GCL composite liner, the Subtitle D liner, and the Wisconsin NR500 liner. The GCL composite liner is a staking combination of a geomembarne (GM) and a geosynthetic clay liner (GCL). The Subtitle D liner and the Wisconsin liners are composed of a cover GM and a thick layer of compacted clay liner (CCL) with a thickness of 61 cm (2 ft) and 122 cm (4 ft), respectively. Foose et al. (2002) analyzed the three composite liners based on the performance estimation of leakage rate and mass flux. Cadmium and toluene were adopted in their analysis as two typical inorganic and organic leachate constituents, respectively. The results from Foose et al. (2002) shows that the GCL composite liner has the lowest leakage rate, but the mass flux for toluene of the GCL composite liner is two to three orders of magnitude greater than that of the Subtitle D linerand Wisconsin NR500 liner. Therefore, the need for a more effective composite liner, which has not only low leakage rate but also low mass flux, has emerged recently. A double composite liner which is stacked in order of GM-GCL-GM-CCL from the top has been used in several landfill constructions. The bottom CCL is usually 61 cm (2 ft) to 91.5 cm (3 ft) think. This type of liner is believed to satisfy all performance requirements for a landfill liner. However, there is no study on the performance of this type of liner published to date.

In this paper, the double composite liner was compared with the other composite liner systems based on two performance criteria: (1) leakage rate, and (2) mass flux. Estimation of leakage rate was implemented in the cases of defects in GM. Solute transport analysis for evaluating mass flux was performed in the case of intact liners.

2. Criteria of Leakage Rate

2.1 Analysis method

Observations of the defects in GMs were reported by Giroud and Bonaparte (1989a, b). The defects can be cicular or longitudinal with the size ranging from a very small hole to a long defective seam. The quality of the interface is defined as perfect or excellent contact (Giroud and Bonaparte 1989a, b); good or poor contact (Giroud 1997). In this analysis, the contacts between the GMs and soil liners were assumed to be perfect. These assumptions are reasonable because the liners are generally below many meters of material (Foose 1997).

For the case of perfect contact, Walton and Sagar (1990) used famous Forchheimer' s equation for calculating the leakage through a small circular defect in a composite liner with perfect contact between the GM and soil liner. The Forchheimer' s equation is as follows:

$$Q_c = 4K_s h_t r \tag{1}$$

where Q_c = leakage rate through the circular defect; K_s = saturated hydraulic conductivity of the soil liner; h_t = total head drop across the composite liner; and r = radius of the defect. The Forchheimer' s equation was verified by laboratory tests by Walton et al. (1997) and numerical analyses by Walton and Sagar (1990), Walton et al. (1997), and Foose (1997).

Walton and Seitz (1992) proposed an equation for estimating fluid flow through fractures in concrete vaults in intimate contact with soil. This solution can be applied to the case of long defect with perfect contact. Foose et al. (2001) recommended empirical equations similar to (1) for predicting leakage rates through defects with perfect contact based on the results of numerical model. His first equation for the case of cicular defects is as follows:

$$Q_c = F_c K_s h_t r \tag{2}$$

where F_c = nondimensional flow factor for circular defects. F_c is a linear function of r/L_s:

$$F_c = 4 + 3.35\frac{r}{L_s} \tag{3}$$

where L_s = thickness of the soil liner. The second equation for the case of long defects is as follows:

$$Q_l = F_l K_s h_t \tag{4}$$

where F_l = nondimensional flow factor for long defects. F_l is a function of w/L_s:

$$F_l = \frac{1}{0.52 - 0.76\log\left(\frac{w}{L_s}\right)} \tag{5}$$

where w = width of defect. The equations (2) and (4) are the most useful and easy-to-use equations which has been published. The equations were verified by comparing their results with that of other equations (Walton and Sagar 1990, Walton and Seitz 1992, Walton et al. 1997). More information can be found in Foose et al. (2001).

2.2 Numerical model for leakage rate

Foose (1997) employed the MODFLOW program (McDonald and Harbaugh 1988) to calculate the leakage rates through the composite liners having defects. MODFLOW solves the governing equation for 3D flow of water through porous media as follows:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h_t}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h_t}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h_t}{\partial z}\right)+W=S_s\frac{\partial h_t}{\partial t} \tag{6}$$

where K_{xx}, K_{yy}, and K_{zz} = hydraulic conductivity along the x-, y-, and z-axes parallel to the major axes of the hydraulic conductivity; h_t = potentiometric head; W = flow rate of sinks and sources; S_s = specific storage; and t = time.

The modeling of the composite liners and the boundary conditions were instructed by Foose (1997); Foose et al. (2001, 2002). The results reported by Foose et al. (2001) were in good agreement with those that were computed using the equations by Walton and Seitz (1992), and Giroud (1997). More information can be found in Foose et al. (2001). In this study, a new version MODFLOW 2000 was used to solve the gorverning equation of 3D flow through double composite liners for the steady-state condition. The conceptual model for flow through two vertically coaxial defects in double composite liners is presented in the Fig. 1.

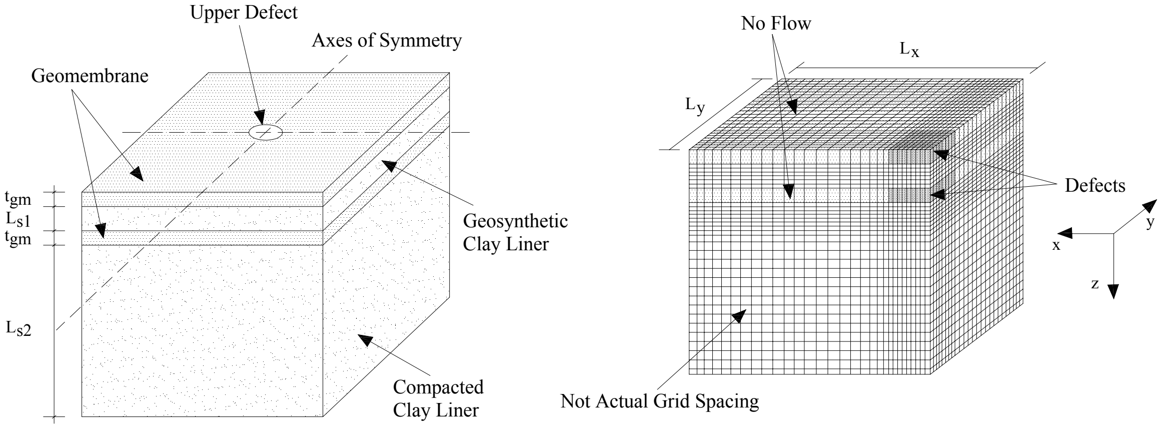

FIG. 1. Conceptual model for flow through two defects in double composite liners

Only one quadrant of the leakage through a circular defect was modeled due to the symmetry of the steady-state flow. Two layers of no-flow cells were used to simulate the two GMs. To consider the most critical case, the two defects were assumed to be vertically coaxial. The upper defect was simulated as constant head rectangular cells. The constant head assigned to these cells is $h_t = 2t_{gm} + L_{s1} + L_{s2} + h_p$, where h_p = depth of leachate equal to 30 cm. It was assumed that the depth of leachate was constant due to the lack of data about the variation of leachate depth with time (Foose et al. 2002). The side boundaries were also modeled as no-flux boundaries. The bottom boundary was modeled as a fully draining boundary with a constant head of zero. The geosynthetic and compacted clay liners were assumed to be saturated, homogeneous, and isotropic. The width of the model was 100 cm, which was large enough for a simulation of flow through defects to converge to an analytical solution (Foose et al. 1998). As discussed previously, the contacts between the GMs and soil liners were assumed to be perfect.

The cell size was chosen following the succesful model suggested by Foose (1997). This modeling was based on the requirement of small mass balance errors and convergence to an analytical solution for leakage for in composite liners (Foose et al. 2001). The hydraulic conductivities of the geosynthetic clay and compacted clay liners were selected as 1×10^{-9} and 1×10^{-7} cm/s, respectively. These representative values were selected from the common regulation and in most studies for the clay liners (Giroud and Bonaparte 1989a,b; Giroud 1997).

2.3 Leakage rate evaluation

The leakage rates through defects of two types of liner systems popularly used in practice and the double composite liners were estimated in this section. Two first cases belong to the well-known type of compacted clay liner Subtitle D of the Resource Conservation and Recovery Act. Those are two systems of 61 cm (2 feet) or 92 cm (3 feet) thick compacted clay liner underlain a GM. Two other cases are double composite liners with 2 or 3 feet of compacted clay liner. The two systems have the identical structure consisting of, in the vertical direction from the top to the bottom, a first GM, a 6.5 mm thick GM, a second GM, and 61 cm (2 feet) or 92 cm (3 feet) thick compacted clay liner. Lastly, the leakage rates through the GCL composite liner were also calculated for comparison.

(1) Circular defects

Fig. 2 shows the leakage rates for the GCL, Subtitle D, and double composite liners obtained from the simulations by the program MODFLOW 2000. Two circular defects in the two GMs in the double composite liner have the equal sizes. The double composite liners almost block all the leakages from the pond of leachate above the liner. The leakage rate for this type of liner is extremely small from 10^{-3} to 10^{-1} mL/defect/year for the range of radius of defect from 1 to 6 mm. The GCL composite liner allows the leakage rate which is around two orders of magnitude higher than that for the double composite liner. Similarly to the cases of Subtitle D liners, the thicker double composite liner has slightly higher leakage rate.

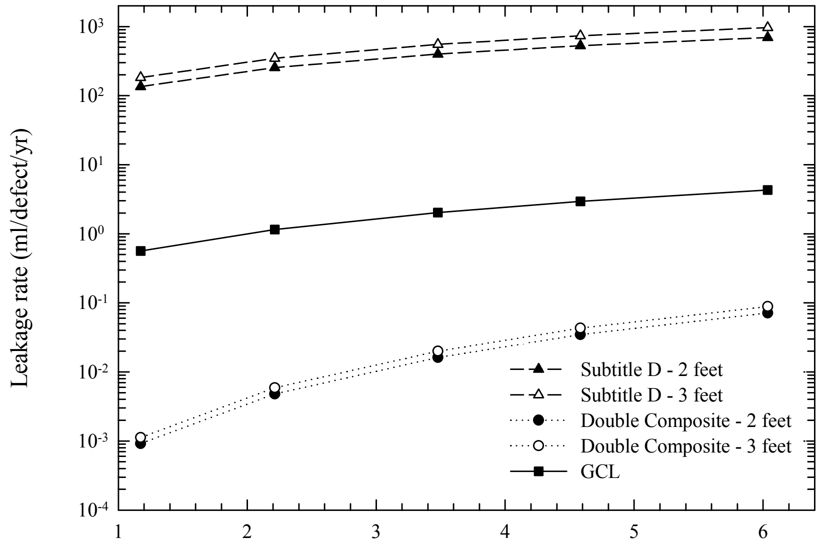

FIG. 2 Leakage rates through circular defects in composite liners with perfect contact

The unexpectedly higher leakage rates for the case of thicker liners seem to be illogical. However, Foose (1997) reasoned that due to the total head of zero everywhere in the soil liner, the total potential drop in the thicker liner is greater and the leakage rate for the thicker liner is greater. Foose et al. (2002) obtained the similar results with the higher leakage rate for the thicker

Wisconsin NR500 liner (122 cm (4 feet) thick compacted clay liner underlain a GM) than that for the 2 feet thick Subtitle D liner.

(2) Long defects

Fig. 3 shows the results of leakage rates per unit length of defect for two Subtitle D liners. The leakage rates calculated by the Foose et al.' s (2001) equation were in very good agreement with those that were obtained using MODFLOW 2000. The leakage rates for the 3 feet thick Subtitle D liner are about 30 to 40 mL/cm of defect/year higher than those that for the 2 feet thick Subtitle D liner.

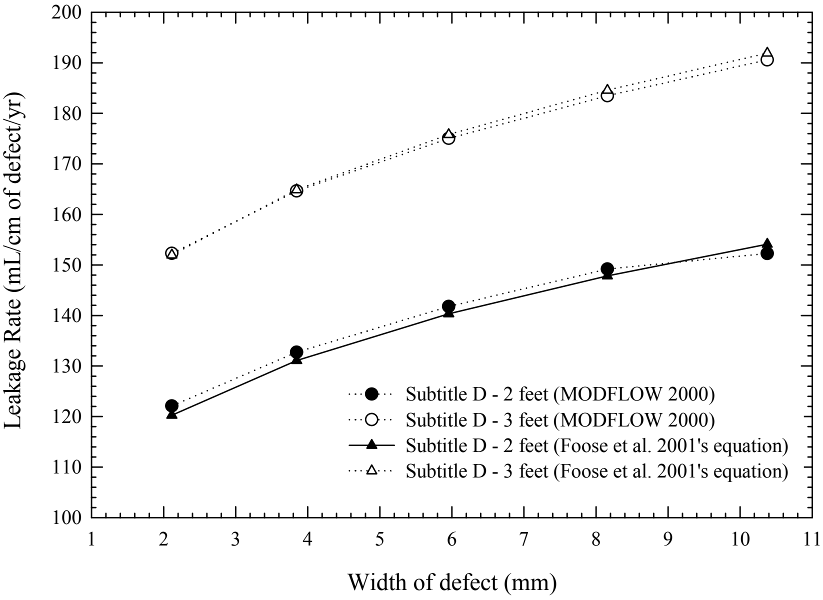

FIG. 3 Leakage rates through long defects in Subtitle D liners with perfect contact

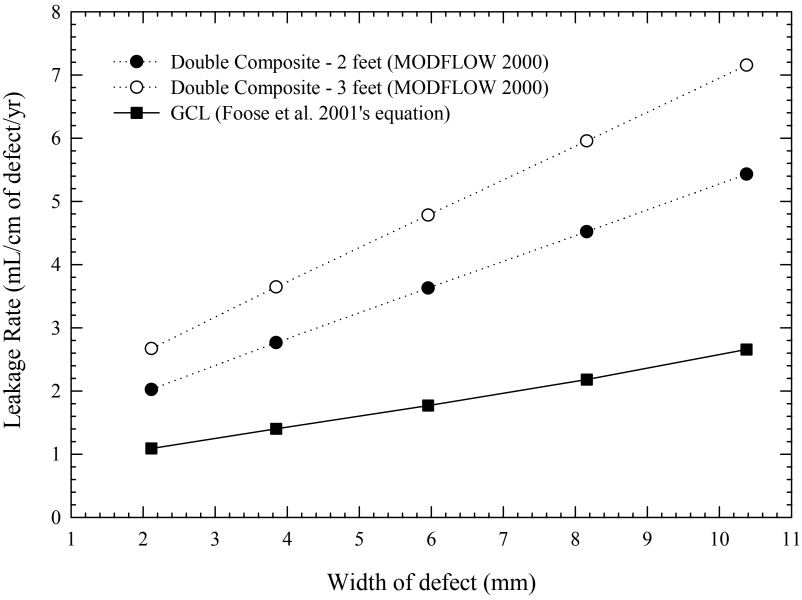

FIG. 4 Leakage rates through long defects in double composite liners with perfect contact

The leakage rates through long defects in double composite liners with perfect contact are much smaller than that in Subtitle D liners. The leakage rates through long defects for the double composite liners are about 30 to 40 times lower than those that for the Subtitle D liners. However, contrary to the cases of circular defects, the double composite liners in this case are slightly less effective than the GCL composite liners in obstructing the leakages of leachate (see Fig. 4). The leakage rates for the double composite liners are higher than that for the GCL composite liners. The authors discovered that with the width of defect equal to 2 mm, the leakage rates for the double composite liners start to be higher than that for the GCL composite liners when the length of defect exceeds 65 cm and 87 cm for the cases of 3 feet and 2 feet thick double composite liners, respectively (see Fig. 5). Similar to the cases of circular defects, the 3 feet thick double composite liner also has the higher leakage rates than does the 2 feet thick double composite liner.

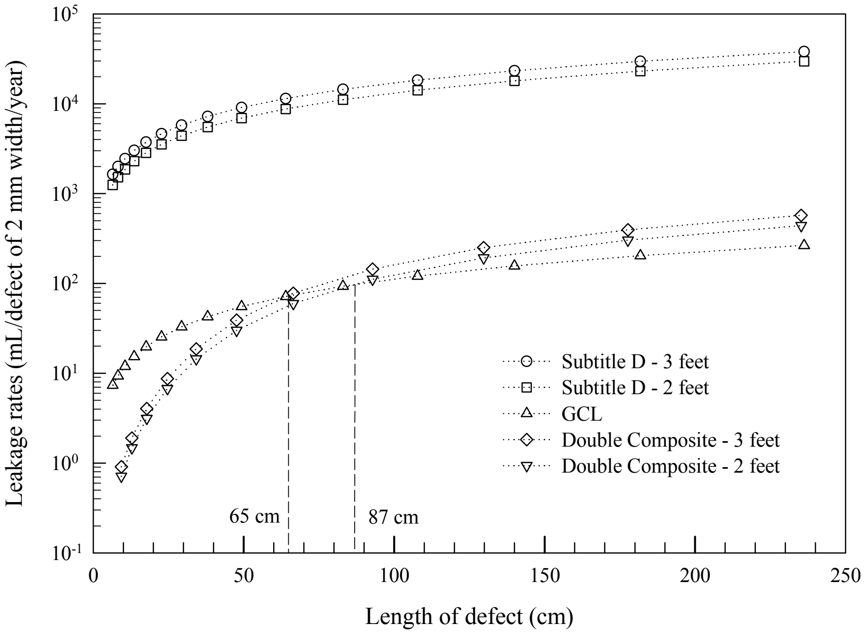

FIG. 5 Leakage rates through the defects of 2 mm width and varying length with perfect contact

The leakage rates through long defects are much higher than that through circular defects for the Subtitle D liners (Foose et al. 2001). For the double composite liners, the similar trend was confirmed. Therefore, the long defects are the major source of leakage in the constructions of liner. The thicker liners tend to have higher leakage rates in most cases of defects. It can be concluded that the leakage rate is not the crucial criterion in the assessments of liner systems. A similar conclusion was drawn by Foose et al. (2002). The double composite liners show very good performance based on the criterion of leakage rate compared to the Subtitle D liners. Other criteria should be considered for the type of double composite liner to assess its efficiency.

3. Criteria of Mass Flux

3.1 Analysis method

Several analyses of solute transport through the soil liners were done by Rowe (1987), Shackelford and Daniel (1991 a,b). The diffusion of volatile organic compounds through intact composite liners was studied by Mueller et al. (1998). The solute transport was fully analyzed by Foose et al. (2002) using numerical approach for both cases of intact and defective composite liners.

From the results in the section of leakage rates, it can be seen that the governing transport process through defects in the GMs of the double composite liners is diffusion. Therefore, the mass flow rates through defects in the GMs of the double composite liners can be calculated similarly to that for the GCL composite liners (Foose et al. 2002). In addition, it can be concluded that the mass flow rates through defects for double composite liners are smallest since the double composite liners have lowest leakage rates among the investigated composite liners.

For the organic solute transport, the mass transport through defects can be negligible if compared with that through the intact portion of composite liners (Foose et al. 2002). The organic solute transport through the intact composite liners can be analyzed by a one-dimensional model due to the large extent of the landfill construction and the small number of defects. One-dimensional models of organic solute transport in porous media having an infinite thickness were proposed by Ogata and Banks (1961). An analytical method for calculating the time to steady-state flux for the diffusion of organic solute in a composite liner was suggested by Mueller et al. (1998). Foose et al (2002) provided a numerical approach for analyzing the organic solute transport through intact composite liners. The governing equation for diffusive transport of toluene through composite liners was solved using a Crank-Nicholson node-centered finite-difference algorithm. More information on the finite-difference formulation can be found in Foose (1997). Since there is no analytical method for effectively analyzing the solute transport in composite liners, the double composite liners will also be analyzed using numerical method. A block-centered finite-difference model of diffusive transport through intact double composite liners was developed using explicit method to calculate the mass flow rate of toluene transport. More details on this model will be provided in the next section.

3.2 Numerical model for diffusive transport

Fig. 6 shows the transport process of toluene having concentration C_o through the intact double composite liner. The toluene compound in the leachate initially partitions into the upper GM ($C_1 = K_{d,gm}C_o$), 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 compound diffuses through the GCL layer until partitioning again into the lower GM ($C_4 = K_{d,gm}C_3$). Next, the transport process identical to that through the upper GM and the GCL layer occurs through the lower GM and the compacted clay liner layer.

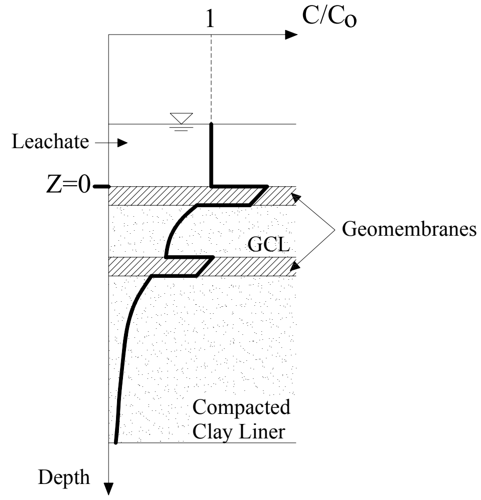

FIG. 6. Concentration profile of transport of toluene in intact double composite liners

The block-centered model of toluene transport through intact double composite liners was developed to solve the governing diffusive equation as follows:

$$\frac{\partial c_m}{\partial t} = \frac{D_{gm}}{K_{d,gm}^2} \frac{\partial^2 c_m}{\partial z_m^2} \text{ for GM layers} \tag{8}$$

$$R_d \frac{\partial c}{\partial t} = D^* \frac{\partial^2 c}{\partial z^2} - \lambda \left(c + \frac{\rho_b}{n} \overline{c} \right) \text{ for soil liner layers} \tag{9}$$

where c = concentration of toluene in the soil liners; c_m = normalized concentration of toluene in the GM, c_m = $c_{GM}/K_{d,gm}$; $K_{d,gm}$ = partition coefficient for the GM and toluene; z = depth from the top of double composite liner; z_m = normalized coordinate in z-direction in GM, Δz_m = $\Delta z_{GM}/K_{d,gm}$; D_{gm} = diffusion coefficient of toluene through the GM; t = time; D^* = effective diffusion coefficient of the soil liners, D^* = $D_o \tau_a$, D_o = free solution diffusion coefficient, τ_a = apparent tortuosity; λ = rate of constant of the first-order rate reactions (for a conservative calculation in this analysis, λ was assumed to be zero); $\overline{c}$ = concentration of toluene sorbed on the soil liners; R_d = retardation factor, which is defined as follows:

$$R_d = 1 + \frac{\rho_b K_d}{n} \tag{10}$$

where ρ_b = bulk density of the soil liner layers; K_d = partition coefficient for the soil liner and toluene; n = total porosity of the soil liner layers.

The block-centered model with explicit method was employed in this analysis. This approach has an advantage that the interfaces can be handled without difficulty since there is no node on the interface. The bottom boundary conditions for the block-centered models were chosen as previously defined by Foose (1997) and Foose et al. (2002). The constant concentration at the bottom boundary was zero and the locations of it were at the base of the liner or 9 m from the base of liner. In addition, the time of simulations was also selected to be 100 years as in Foose (1997) and Foose et al. (2002).

3.3 Mass flux evaluation

As previously discussed, the mass flow rate for cadmium solutes can be calculated based on the leakage rates through defects in the GM of the composite liners. Since the leakage rates for the defective double composite liners are lowest, the mass flow rate of cadmium solutes through defects in the GM of double composite liners is also smallest.

For the toluene compound, the mass flux through intact liner is dominant compared to that through defects. Therefore, in this section, only the mass flux of toluene compound through intact double composite liners was estimated. The following figures present the results for intact double composite liners along with that for other composite liners. The mass fluxes of toluene through other intact composite liners were provided by Foose et al. (2002).

Fig. 7 shows that the double composite liners are the most effective liners in terms of the mass flow rate of toluene at 100 years for the case of a constant concentration of zero at the base of the liners. The intact double composite liners permit minimum diffusion of toluene among the composite liners. The mass fluxes of toluene through intact double composite liners at the end of the simulation are 1432 and 489 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively. It is interesting that the double composite liner having a 2 feet thick compacted clay liner layer has the almost equivalent mass flux compared with that of the Wisconsin NR500 liner, which has the double thickness of the said double composite liner (GM overlain 4 feet thick compacted clay liner).

For the case of the semi-infinite bottom boundary condition, which was represented by the bottom boundary at the depth of 9 m from the base of the liner, the results also show that the double composite liners are very efficient for the landfill constructions. With the double composite liner of 2 feet of compacted clay liner, the mass flux after 100 years is almost equal to that for the Wisconsin NR500 liner. In this case, the mass fluxes at the end of the simulation are 445 and 153 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively. Along with its excellent performance in terms of leakage rate, the double composite liner provides a very good solution for the landfill constructions in controlling contaminant transport.

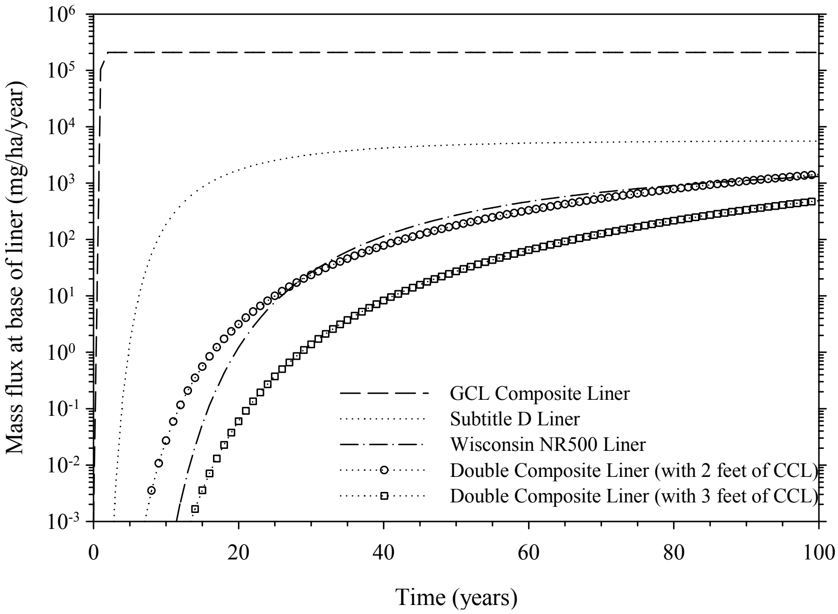

FIG. 7. Mass flux for transport of toluene with concentration at base equal to 0 μg/L

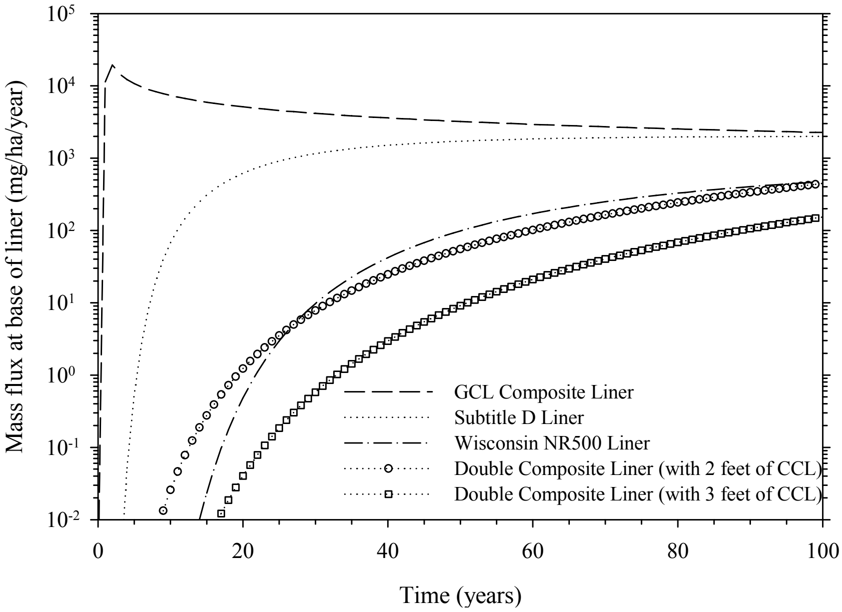

FIG. 8. Mass flux for transport of toluene with semi-infinite bottom boundary condition

4. Conclusions

The double composite liners were analyzed and compared to other composite liners based on leakage rate and mass flux using numerical models. Though the results have not been verified yet due to the lack of laboratory and field data, numerical models are one of useful and available approaches to evaluate the performance of composite liners. The leakage rates through defects in double composite liners are very low compared to other composite liners. Even in the case of long defects, this advantage is still maintained by the leakage rates for the double composite liners comparable with the leakage rates for the GCL composite liners. On the criterion of mass flux, the double composite liners are the best choices for landfill constructions. The mass flux after 100 years of toluene through intact double composite liners is smallest compared to those that through other composite liners. Therefore, the authors strongly suggest the consideration of double composite liner in design progression for landfill liner constructions.

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