Organic Compound Containment Using Ground Tires in Soil-Bentonite Slurry Cutoff Walls

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ABSTRACT: Soil-bentonite (SB) slurry cutoff walls have been used to contain contaminants; however, such systems are susceptible to organic compound breakthrough. Using the capability of ground tires to sorb organic compounds, it may be possible to retard the movement of organic compounds through a SB slurry cutoff wall. Mathematical modeling is used to evaluate the transport of organic compounds through SB slurry cutoff walls with and without ground tire amendment under various seepage velocities. When 10% by weight of ground tires are added into a 1 m thick SB slurry cutoff wall, the times for methylene chloride, trichloroethylene, and *m*-xylene to break through are delayed by 1.8, 16, and 70 times, respectively, for a seepage velocity of 2.2×10^{-6} cm/sec.

INTRODUCTION

Since the soil-bentonite (SB) slurry cutoff wall was first used in the United States in the early 1940's, the technology has been used as one of the lowest-cost alternatives to reduce the spread of groundwater contamination (D'Appolonia 1980; Ryan 1985). Several studies have provided considerable evidence that organic compounds have high mobility through engineered containment systems (Johnson et al. 1989; Edil et al. 1994; Park et al. 1995a). Park et al. (1995a; 1995b) showed that automobile tires could sorb a significant amount of volatile organic compounds (VOCs) and proposed its use as a supplement to the engineered waste containment systems, e.g., solid waste landfill liner systems and slurry cutoff walls, in order to retard organic compound migration. Column tests showed that the hydraulic conductivity of the SB slurry cutoff wall backfill material is not affected by the addition of ground tires (Park et al. 1995a). According to the study, *m*-xylene did not break through a ground tire amended SB slurry cutoff wall backfill material in 450 days; however, in the case of a conventional SB slurry cutoff wall backfill material, *m*-xylene broke through the specimen in 180 days to 10% of the incoming concentration.

This study is based on the concept of placing a SB slurry trench around a leaking hazardous waste site to control off-site migration of contaminated groundwater during remediation activities. Although the conventional SB cutoff wall is effective in reducing groundwater flow, the movement of organic compounds would not successfully be retarded due to the lower sorption capacity of the SB slurry cutoff wall material and the diffusivity of organic compounds. Thus, to retard the off-site migration of the organic contaminants in the groundwater, it is proposed to mix ground tires in the SB slurry cutoff wall backfill material to provide a higher sorption capacity for organic compounds, thus converting the SB slurry cutoff wall into a more effective reactive barrier.

The performance of the SB slurry cutoff wall material amended with ground tires is compared with the conventional SB slurry cutoff wall under various conditions and the effect of the ground tire content on the organic compound retardation of the SB slurry cutoff wall is evaluated by mathematical modeling.

MASS TRANSPORT MODEL

Under the isotropic and homogeneous conditions of a porous medium, the one-direction (z direction) mass transport of a non-decaying and non-reactive compound by advection and dispersion through the medium can be written as follows:

$$\frac{\partial C}{\partial t} = \frac{D_h}{R_f} \cdot \frac{\partial^2 C}{\partial z^2} - \frac{v_z}{R_f} \cdot \frac{\partial C}{\partial z} \tag{1}$$

where C = concentration of a target compound [M/L^3], t = elapsed time [T], D_h = hydrodynamic dispersion coefficient [L^2/T], z = distance [L], v_z = seepage velocity [L/T], and R_f = dimensionless retardation factor used to describe the attenuation of a target compound during the transport process through the porous medium.

When the partition of the target compound between the solid and the solution is assumed to be linear, the retardation factor can be expressed using the partition coefficient, particle density, and total porosity of the medium (Hashimoto et al. 1964):

$$R_f = 1 + \left(\frac{1 - n_t}{n_t}\right) \cdot \rho_p \cdot K_p \tag{2}$$

where n_t = total porosity of the medium, ρ_p = particle dry density [M/L^3], and K_p = partition coefficient [L^3/M].

Eq. 1 has been used to express the movement of contaminants in groundwater. The solution of Eq. 1 depends on the initial and boundary conditions. Using the following initial and boundary conditions:

$$C(0,t) = C_0; \quad t \geq 0$$
$$C(z,0) = 0; \quad z > 0$$
$$C(\infty,t) = 0; \quad t \geq 0$$

an analytical solution was obtained (Ogata and Banks 1961):

$$\frac{C(z,t)}{C_0} = \frac{1}{2} \cdot \mathrm{erfc}\left(\frac{R_f \cdot z - v_z \cdot t}{2\sqrt{R_f \cdot D_h \cdot t}}\right) + \frac{1}{2} \cdot \exp\left(\frac{v_z \cdot z}{D_h}\right) \cdot \mathrm{erfc}\left(\frac{R_f \cdot z + v_z \cdot t}{2\sqrt{R_f \cdot D_h \cdot t}}\right) \tag{3}$$

In this study, Eq. 3 was used to estimate the concentration of a target contaminant at the outer end of the SB slurry cutoff wall. The concentration of a target contaminant at the outer end of the SB slurry cutoff wall can be expressed as follows:

$$C_{out,t} = \frac{C_0}{2} \cdot \mathrm{erfc}\left(\frac{R_f \cdot L - v_z \cdot t}{2\sqrt{R_f \cdot D_h \cdot t}}\right) + \frac{C_0}{2} \cdot \exp\left(\frac{v_z \cdot L}{D_h}\right) \cdot \mathrm{erfc}\left(\frac{R_f \cdot L + v_z \cdot t}{2\sqrt{R_f \cdot D_h \cdot t}}\right) \tag{4}$$

where $C_{out,t}$ = concentration of a target contaminant at the outer end of the SB slurry cutoff wall at a certain time [M/L^3], and L = width of the SB slurry cutoff wall [L].

The seepage velocity, v_z, can be estimated from the hydraulic conductivity, the hydraulic gradient, and the effective porosity of the SB slurry cutoff wall:

$$v_z = \frac{K_h \cdot i}{n_e} \tag{5}$$

where K_h = hydraulic conductivity [L/T], i = hydraulic gradient, and n_e = effective porosity of the medium.

When the SB material is mixed with ground tires, the overall partition coefficient and particle density can be calculated as follows using the partition coefficient and particle density of each material:

$$K_p = \sum_{i=1}^{n} K_{p,i} \cdot \theta_i \tag{6}$$

$$\rho_p = \sum_{i=1}^{n} \rho_{p,i} \cdot \theta_i \tag{7}$$

where n = number of components, and θ = weight fraction.

PARAMETERS USED FOR MODELING

Before conducting mathematical modeling of the contaminant transport through a SB slurry cutoff wall, the parameters required were selected. Most of the parameters were determined as closely as possible to the field condition.

The typical width of the SB slurry cutoff wall is between 0.5 to 1.5 m (D'Appolonia 1980; Evans 1994). The width of 1 m was selected for the purpose of modeling. Even though the filter cake plays an important role in the control of the hydraulic conductivity of the overall SB slurry cutoff wall, the thickness and the sorption capacity of the filter cake were ignored in the modeling. The thickness of the filter cake is generally less than 3 mm (D'Appolonia 1980).

For the estimation of the seepage velocity of groundwater flow, the hydraulic gradient and effective porosity are required. The hydraulic conductivity of the overall SB slurry cutoff wall is a function of both the filter cake and the backfill materials. For a wide variety of practical applications, the hydraulic conductivity of the filter cake is in the magnitude of 10^{-9} cm/sec. The hydraulic conductivity of the backfill material is more site dependent. It is affected significantly by the characteristics of the native soil and the bentonite mixing content. The typical value of the hydraulic conductivity of the backfill widely ranges between 10^{-5} and 10^{-7} cm/sec. In most SB slurry cutoff walls, the hydraulic conductivity of 1×10^{-6} cm/sec can be achieved (D'Appolonia 1980). The typical hydraulic conductivity of a SB slurry cutoff wall is ranged between 1×10^{-7} and 1×10^{-8} cm/sec (Evans 1994).

The hydraulic gradient is another site dependent factor. The hydraulic gradient may vary during the service life of a SB slurry cutoff wall. Based on column tests (Park et al. 1995a), the effective porosity of a SB slurry cutoff wall backfill material was estimated to be ranged from 70 to 100% of the total porosity by a tracer test. The total porosity of the specimen was approximately 0.45. In this study, seepage velocity was simplified to be constant and different levels of seepage velocity values were tested. The total porosity of 0.45 was applied for modeling.

Shimizu et al. (1992) derived an empirical relationship between the soil organic carbon partition coefficient and the octanol-water partition coefficient of organic compounds based on 150 data reported by various investigators. Accordingly, the soil-water partition coefficient of organic compounds can be estimated using Eqs. 8 and 9.

$$\log K_{oc} = 0.98 \cdot \log K_{ow} - 0.26 \tag{8}$$

$$K_p = f_{oc} \cdot K_{oc} \tag{9}$$

where K_{oc} = organic carbon partition coefficient, K_{ow} = octanol-water partition coefficient, and f_{oc} = soil organic carbon content.

The organic carbon content in SB material was assumed to be 1% by weight. In the case of ground tire, another empirical equation, Eq. 10, was used to estimate the partition coefficients of organic compounds (Kim et al. 1995):

$$\log K_p = 0.978 \cdot \log K_{ow} - 0.124 \tag{10}$$

The hydrodynamic dispersion includes the molecular diffusion and the mechanical dispersion (Domenico and Schwartz 1990). Due to the relatively slow groundwater flow through the SB slurry cutoff wall system (in most cases), the mechanical dispersion can be considered negligible. The hydrodynamic dispersion coefficient of contaminant was estimated by multiplying the free solution diffusion coefficient by 0.707 (Carman 1939; Perkins and Johnston 1963).

Three different levels of ground tire content were tested: 0, 5, and 10% by weight. The values of the specific gravity of soil and ground tires used were 2.70 and 1.15, respectively (Edil and Bosscher 1994).

Using Eqs. 8,9, and 10, the retardation factors of organic compounds by the ground tire amended SB slurry cutoff wall were computed. Figure 1 shows the effect of the ground tire content on the retardation factor for a wide range of octanol-water partition coefficients.

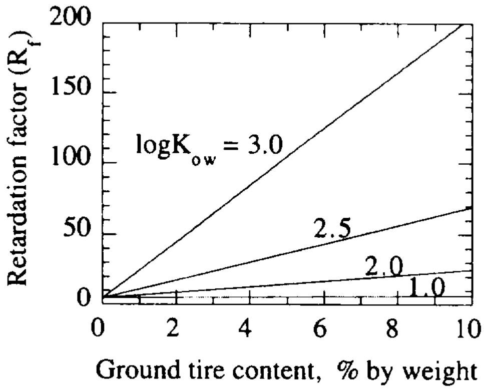

Figure 1. Effect of the ground tire content on the retardation factor of the ground tire amended SB slurry cutoff wall.

As the ground tire content increases, the retardation factor also increases. Furthermore, the greater octanol-water partition coefficient of an organic compound has, the more significantly affected is the retardation factor by the ground tire content.

MODELING RESULTS

Methylene chloride is one of the most widely and frequently detected organic compounds in the hazardous solid waste landfill sites (Plumb and Pitchford 1985). Figure 2 is the breakthrough curves of methylene chloride with various seepage velocity conditions in the conventional SB slurry cutoff wall which contains no ground tires. The seepage velocity of 0, 10^{-7}, 10^{-6}, and 10^{-5} cm/sec were applied. The values of the octanol-water partition coefficient and the free solution diffusion coefficient were adopted from U.S. EPA. (1990) and Yaws (1995).

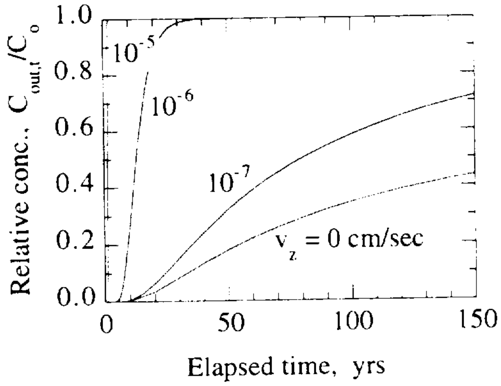

Figure 2. Methylene chloride breakthrough curves of the conventional SB slurry cutoff wall with different seepage velocities.

As the seepage velocity increases, methylene chloride breaks through the SB slurry cutoff wall faster. If the seepage velocity of the SB slurry wall is kept low enough, the mass transport of contaminants can be effectively retarded. The seepage velocity can be controlled by hydraulic gradient or hydraulic conductivity. However, the hydraulic conductivity of the SB slurry cutoff wall can be increased by the loss of fine particles (Marcotte et al. 1994). The filter cake can be lost due to the low hydraulic conductivity and small thickness or damaged by the back[illegible] process (D'Appolonia 1980). The loss of filter cake can significantly increase the overa[illegible]draulic conductivity of the cutoff wall. The exposure to contaminants can also affect th[illegible]draulic conductivity. According to the column tests, the hydraulic conductivity of a SB slur[illegible]ecimen increased up to 40 times in a period of a year (Gipson 1985).

The addition of ground tires to a SB slurry cutoff wall can compensate for the inc[illegible] mass transport of contaminant caused by the deterioration of the cutoff wall. Figure 3 [illegible]s the breakthrough curves of methylene chloride in the ground tire amended SB slurry cutoff [illegible]at the seepage velocity of 1 × 10^{-5} cm/sec. When a SB slurry cutoff wall is amended w[illegible]% of ground tires, the initial and complete breakthrough times of methylene chloride are [illegible]ed by approximately 1.7 times.

In the case of more hydrophobic organic compounds, the breakthrough is more significantly affected by the addition of ground tires. Figure 4 shows the trichloroethylene (TCE) breakthrough curves. TCE can break through the conventional SB slurry cutoff wall in two years. However, the complete breakthrough of TCE is delayed by approximately 16 times with addition of 10% ground tire.

The mass transport of three organic compounds, i.e., methylene chloride, TCE, an[illegible]ylene are simulated under the following conditions: (1) the hydraulic conductivity of the [illegible]all SB slurry cutoff wall is 1 × 10^{-7} cm/sec; (2) the hydraulic gradient is 10; and (3) the effect[illegible]rosity is 0.45, identical to the total porosity. The resulting seepage velocity was 2.2×10^{-6} cm[illegible]

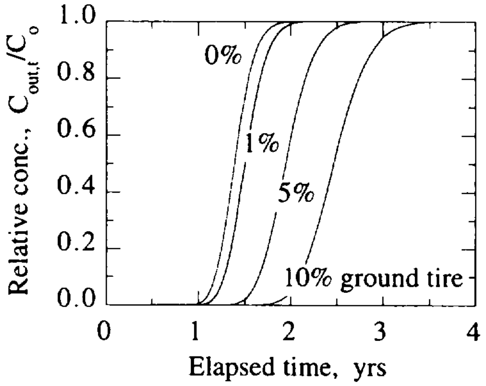

Figure 3. Methylene chloride breakthrough curves of different SB slurry cutoff walls.

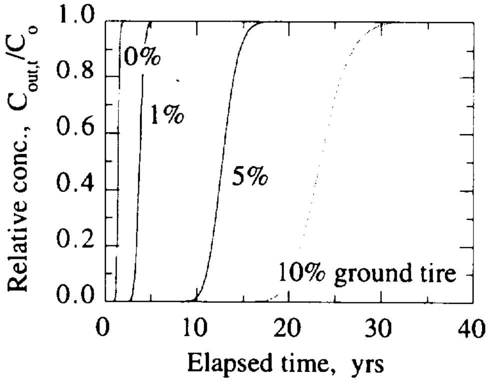

Figure 4. TCE breakthrough curves of different SB slurry cutoff walls.

The times for 10% and 50% breakthrough of the target compounds were computed by the model using the above parameter values and the results are summarized in Table 1. It appears that a conventional SB slurry cutoff wall cannot effectively retard the target compounds under the testing conditions. All the target compounds reach 10% and 50% of the incoming concentrations in five and seven years, respectively, without ground tires. With 10% ground tire additions, however, breakthrough times were delayed by 16 times for TCE and 70 times for *m*-xylene, respectively.

Table 1. Required times (years) for 10 and 50% breakthrough at different ground tire contents.

	10% Breakthrough			50% Breakthrough		
	Ground tire content			Ground tire content		
Organics	0%	5%	10%	0%	5%	10%
Methylene chloride	4.3	6.1	7.7	6.0	8.5	10.7
TCE	4.7	42.5	77.9	6.4	57.2	105.1
m-Xylene	4.9	182.0	348.5	6.5	237.7	455.2

The times for 10% breakthrough of the incoming concentration are compared for three different ground tire contents and a range of hydraulic gradients (Figures 5, 6 and 7). Under the pure diffusion condition, i.e., zero hydraulic gradient, the time for 10% breakthrough of methylene chloride is delayed by 25 years with the addition of 10% ground tire by weight (Figure 5). As the seepage velocity increases, the difference between the conventional and the ground tire amended SB slurry cutoff walls becomes less significant, e.g., 3.4 years delay with 10% ground tire addition. It is caused by the high diffusivity and hydrophilicity of methylene chloride. More hydrophobic compounds such as TCE and *m*-xylene have longer breakthrough times than methylene chloride, even under a higher seepage velocity condition (Figures 6 and 7). When the hydraulic gradient was 10, the times for 10% breakthrough of TCE and *m*-xylene with 10% ground tire addition were 16 and 70 times longer than those in a conventional SB slurry cutoff wall. The 10% breakthrough time of *m*-xylene was delayed from 4.9 to 348.5 years when 10% of ground tires were added.

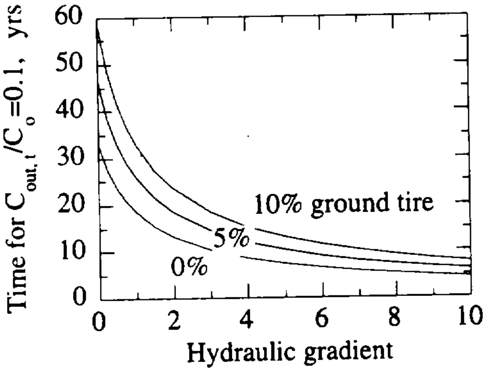

Figure 5. Effect of ground tire content on the methylene chloride 10% breakthrough time.

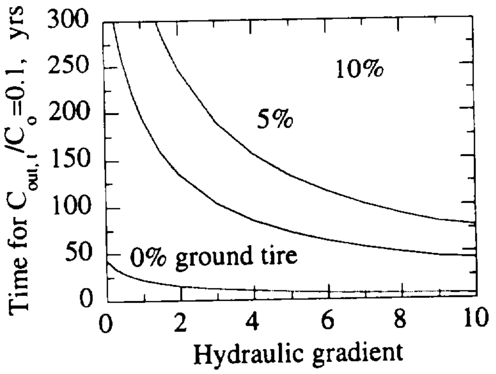

Figure 6. Effect of ground tire content on the TCE 10% breakthrough time.

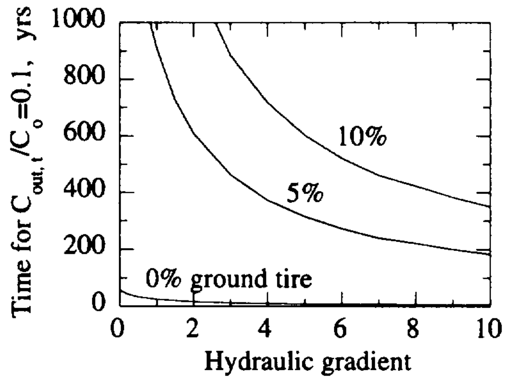

Figure 7. Effect of ground tire content on the *m*-xylene 10% breakthrough time.

CONCLUSIONS

Addition of ground tires into a conventional SB slurry cutoff wall leads to a significant increase in the retardation factor. This in turn results in a significant delay in organic compound breakthrough times. Addition of 10% ground tires to a 1 m thick SB slurry cutoff wall delays the breakthrough times of methylene chloride, TCE and *m*-xylene by 1.8, 16, and 70 times, respectively at the seepage velocity of 2.2 × 10^{-6} cm/sec. Addition of ground tires can significantly improve the organic compound retardation of the SB slurry cutoff wall with minimal additional construction costs.

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