United States
Environmental Protection
Agency

Hazardous Waste Engineering
Research Laboratory
Cincinnati OH 45268

Research and Development

EPA/600/S2-88/045 Sept. 1988

Project Summary

Determination of Effective Porosity of Soil Materials

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Hazardous waste disposal landfills require liners constructed of compacted soil material to help prevent the migration of hazardous wastes. The performance of a compacted soil liner is partly a function of the porosity. Porosity is important because the transport of materials through the liner will occur via the pore space. The main purpose of this project is to study the pore spaces of compacted materials and to estimate the effective porosity, which is the portion of the pore space where the most rapid transport of leachate occurs.

The pore space of three soil materials with a range in clay content, till, loess, and paleosol, is studied by using mercury intrusion porosimetry, water desorption, and image analysis. These analyses provide cumulative porosity curves from which the pore size distribution of a soil sample may be estimated.

Theory is developed to estimate the effective porosity of a compacted soil material based upon a model of its pore size distribution and pore continuity. The effective porosities of the compacted till, loess, and paleosol materials are estimated to be 0.04, 0.08, and 0.09, respectively. These values are 10 to 20% of the total porosities.

Comparisons between measured and predicted Cl^- travel times through compacted soil samples are made to verify the estimated effective porosities. The estimated effective porosities are reasonable because predicted first breakthrough times of Cl^- are similar to the measured first breakthrough times in compacted till, loess, and paleosol materials. For the three soil materials used in this study, predicted first breakthrough times are 5 to 10 times earlier when effective porosity is used in calculations based on the Darcy equation compared with calculations that utilize total porosity. This suggests that effective porosity should be consideed when estimating the lifetimes of landfill liners.

This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Compacted clay is frequently used to line hazardous waste disposal landfills. The purpose of the compacted clay liner is to restrict the movement of hazardous liquid materials out of the landfill. Currently, saturated hydraulic conductivity (usually referred to as soil permeability in the Environmental Protection Agency's design standards) is the most common measurement used to estimate the ability of liner material to contain wastes. Soil saturated hydraulic conductivity, K ($L^3/L^2/T$), is defined for Darcy's equation:

$$K = J/I \qquad [1]$$

where J is the fluid flux density ($L^3/L^2/T$) and I is the hydraulic gradient (L/L). Soil saturated hydraulic conductivity has dimensions of volume per unit area of liner per unit time, and thus, it is a bulk parameter related to the areal average fluid flow in the liner. Saturated hydraulic conductivity is often used to make prelimnary estimates of solute transit times, but knowledge of average fluid flow alone is not adequate for accurate prediction of pollutant breakthrough of travel time. Nonuniform flow velocities through a cross-sectional area should be accounted for because faster-than-average fluid flow may be responsible for the first appearance of the pollutant below the liner.

Effective porosity, E, has been described as that portion of the total liner porosity that contributes significantly to fluid flow. Effective porosities are less than total porosities because some of the pore space is discontinuous (dead end) and some of the pore space is so narrow that fluids in these spaces are essentially immobile. This project develops a new technique based upon Darcy's equation for estimating effective porosity and solute travel time. Because the fluid flux density through a clay liner can be determined by using Darcy's equation, the mean effective fluid velocity, $\bar{V}_E$, can be described by:

$$\bar{V}_E = KI/E \qquad [2]$$

With a constant hydraulic gradient and the liner K and E both known, the average pollutant travel distance per unit time can be estimated. Thus, the time of first breakthrough, T, of a noninteracting pollutant can be predicted by the equation:

$$T = EL/KI \qquad [3]$$

where L is the liner thickness (m).

The Environmental Protection Agency, requires that a disposal unit liner *prevent* migration during the active life of a unit. The active life of a unit containing noninteracting pollutants can be estimated by using Equation (3). Knowledge of the liner permeability alone is not sufficient information to accurately estimate the length of time of liner effectiveness. When a disposal unit is constructed with known liner thickness, L, and designed for a known hydraulic gradient, I, measurement of both *permeability* and *effective porosity* are required to estimate the active life of the unit with Equation (3). Although methods to estimate permeability of compacted clay materials have received much attention in the literature, determination of effective porosity has received little attention.

This project develops a method for estimating the effective porosity of compacted clay materials. This method is based upon the soil pore size distribution. The estimates of effective porosity are used in Equation (3) to predict the travel time of a noninteracting solute through samples of compacted materials.

Materials and Methods

We collected subsurface samples from three soils developed in major Iowa soil parent mateials: till (21% clay), loess (35% clay), and paleosol (44% clay). The clay fraction of each material was dominated by smectite, with small amounts of clay mica and kaolinite.

The pore size distribution of samples of each compacted subsoil material was determined by mercury porosimetry. Samples were freeze-dried before mercury was intruded in four steps. Standard soil-water characteristic data were obtained by determining soil water contents of samples at 0.05, 0.1, 0.2, and 1.5 MPa matric tensions. These pressures correspond to equivalent pore radii of 3, 1.5, 0.75, and 1 μm, respectively, and were chosen to measure pores in size ranges roughly comparable to those measured by the mercury porosimeter. In addition, soil porosity was studied by image analysis methods.

Permeability of compacted soil materials was measured using fixed-wall permeameters. Three replicates of each subsoil material were ocmpacted at moisture contents ~1 to 2% above optimum, determined from the moisture-density relations. De-aired, saturated $CaSO_4$ solution (adjusted to 0.06% formaldehyde to control microbial growth) was introduced at 6.9 kPa pressure at the bottom of the permeameter to slowly saturate the compacted sample. The source of the pressure was compressed air. The air was separated from the saturated $CaSO_4$ solution by a rubber membrane within the solution container to help prevent the desaturation of the soil material. After saturating the material, the $CaSO_4$ solution was introduced at the top of the permeameter at hydraulic gradients of ~170 to 270, and the rate of solution movement through the sample was measured over time.

Solute breakthrough measurements were made for compacted soil samples. The breakthrough measurements were made on the same soil samples used to determine permeability. A de-aired, 0.05 *N* $CaCl_2$ solution with 0.016% Acid Fuchsin (red dye), and 0.06% formaldehyde was used as the tracer solutio The tracer solution was exchanged f the saturated $CaSO_4$ solution an allowed to leach through the compacte soil sample under the same hydraul gradient used in the permeability tes The leachate was collected in equa volume increments with a fractio collector and was analyzed for chlorid concentration with an automatic titrator.

Theoretical

Theory based upon water flow throug interconnected cylindrical pores wa used to describe pore water velocit distributions within samples undergoin solute breakthrough measurements. Th theory estimates sample effectiv porosity from total porosity, θ_S, and pore size distribution parameter, r Effective porosity is defined here as th portion of the soil pore space that allow liquid to travel at velocities greater tha the overall mean liquid velocity.

Figure 1 shows a relationship betwee the effective porosity, E, and the soil por size distribution parameter, n, for sever values of total porosity, θ_S. This figur summarizes the theoretical relationshi developed by this project.

Once E is determined for a soil material, the time of first chemical breakthrough can be estimated using Equatio (3).

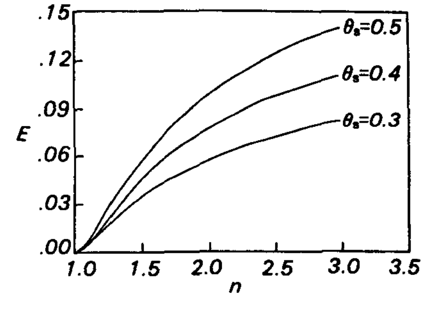

Figure 1. *Influence of n on effective porosity (E) at various values of θ_s.*

Results and Conclusions

Mercury intrusion porosimetry was th method that best measured the fulles range of pore sizes of the compacte samples. Results from mercur porosimetry measurements are presented in Table 1. Values of tota porosity, θ_S, ranged from 0.28 to 0.40 while the pore size distriubtio parameter, n, ranged from 1.5 to 2.1. Th smaller the value of n, the wider th distribution of pores within a sample. Thus, the loess samples were most uniform in pore size.

Table 1. Total porosity, θ_s, and pore size distribution parameters for the three soil materials

Soil Material	θ_S	*n*
till	*0.28*	*1.52*
loess	*0.40*	*2.11*
paleosol	*0.40*	*1.98*

Table 2 presents measured values of permeability and times of first chloride breakthrough (relative effluent concentration equal to 0.01), estimated effective porosities, and predicted times of first breakthrough of noninteracting pollutants for compacted till, loess, and paleosol samples. Each compacted soil material had permeability less than the EPA-maximum value of 1 x 10^{-9} $m^3/m^2/s$ for hazardous waste disposal liners. The estimated effective porosities were between 10 and 20% of the total porosities of the compacted samples. The predicted breakthrough time was calculated based on the mean permeability. The measured chloride breakthrough time was adjusted to correspond to the breakthrough time of a permeameter with the mean permeability.

The predicted noninteracting pollutant breakthrough times agreed well with the measured chloride breakthrough times. Predicted breakthrough values were about equal to measured values for loess. Predicted breakthrough was earlier than measured for till and later than measured for paleosol. For one replicate of till and one replicate of paleosol, the measured and predicted breakthrough times were nearly equal. Because the clay fractions of the compacted samples had a net negative charge and chloride is an anion, it is reasonable to assume that chloride could move through the samples somewhat faster than a true noninteracting pollutant (i.e., tritiated water). Till soil material had less clay than the other materials, and thus anion exclusion would be expected to be less.

The theory presented provides the basis for estimating effective porosity of compacted clay liners. To predict the travel time of noninteracting substances through a clay liner, the hydraulic gradient, liner permeability, liner thickness, and effective porosity are required. As an example of how the theory can be used, we will now make such a prediction for a hypothetical liner constructed of till soil material. The information that we assume is: liner thickness = 1 meter, hydraulic gradient = 1.33, liner permeability = 10^{-9} $m^3/m^2/s$.

If we follow only the Darcy equation, Equation (1), fluid flux density is 1.33 x 10^{-9} $m^3/m^2/s$. However, the fluid flux density does not represent the fluid velocity within the liner. We know that a portion of the total porosity is responsible for conducting fluid at velocities higher than the average velocity and the remaining portion of the porosity conducts fluids at velocities lower than the average velocity. What is important in

Table 2. Permeabilities, measured time of first chloride breakthrough, estimated effective porosities, and p[redicted noninteracting pollutant breakthrough times for the compacted soil materials (peameters were 11.64 cm long)

Soil Material	*Permeability ($m^3/m^2/s$)*	*Measured Cl^- Breakthrough Time (d)*	*Estimated Effective Porosity*	*Predicted Breakthrough Time (d)*
Till				
Rep 1	*5.47 x 10^{-11}*	*3.0*	*0.04*	*2.6*
Rep 2	*6.58 x 10^{-11}*	*4.2*		
Rep 3	*1.22 x 10^{-10}*	*4.6*		
Mean	*8.08 x 10^{-11}*	*3.9*		
Loess				
Rep 1	*2.84 x 10^{-10}*	*1.7*	*0.08*	*1.6*
Rep 2	*2.67 x 10^{-10}*	*1.2*		
Rep 3	*2.61 x 10^{-10}*	*1.5*		
Mean	*2.71 x 10^{-10}*	*1.5*		
Paleosol				
Rep 1	*3.38 x 10^{-11}*	*4.8*	*0.09*	*5.1*
Rep 2	*2.17 x 10^{-10}*	*4.4*		
Rep 3	*1.11 x 10^{-10}*	*3.9*		
Mean	*1.21 x 10^{-10}*	*4.4*		

pollutant transport is the portion of porosity that conducts fluid at higher-than-average velocities. To determine the average effective fluid velocity, we must first estimate the effective porosity.

Effective porosity is determined based on theory previously presented. From mercury porosimetry data for the till materials the n-parameter is 1.5 and θ_s is 0.28 (Table 1). By using Figure 1, effective porosity is estimated to be 0.04. Based upon Equation (3) the travel time for noninteracting solutes through a till clay liner in this example is predicted to be 0.95 years. Therefore, under these conditions, we predict that after about one year, noninteracting pollutants will reach the bottom of the clay liner. Although the concentration of the noninteracting pollutant may be low because of dilution and lateral mixing by diffusion, the initial fraction is predicted to appear after one year. In this example, if the product of liner permeability and hydraulic gradient (i.e., fluid flux density, J) is mistakenly used as the fluid velocity, the pollutant travel time is calculated to be 23.8 years. If the fluid velocity is mistakenly assumed to be equal in all soil pores, the noninteracting pollutant travel time is calculated as 6.7 years. Thus, travel time for noninteracting pollutants is significantly overestimated if effective porosity is not taken into account. The active lifetime of hazardous waste disposal units may be overestimated if liner effective porosity is not properly estimated and used in the prediction of pore-fluid velocity.

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The complete report, entitled "Determination of Effective Porosity of Soi Materials," (Order No. PB 88-242 391/AS; Cost: $19.95, subject to change, will be available only from:
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