

occur, resulting in a possible increase in overall hydraulic conductivity.

Conclusions:

Clay liners for use in landfills or impoundments are typically used to provide a barrier between the stored materials and the natural ground surface. To provide a sufficient barrier, this clay material needs to possess a low hydraulic conductivity which in many cases is required to be less than 1×10^{-7} cm/sec. Construction of liners with low hydraulic conductivities must be accomplished by determining the construction method in test fills which evaluate material preparation, placement and compaction methods. During construction, the placement of the material should be monitored for construction procedures, moistures and densities. Field hydraulic conductivity tests should be conducted to further evaluate if the compacted liner is achieving the desired hydraulic conductivities. Laboratory permeabilities on relatively undisturbed samples of the in-place liner may be conducted to further evaluate the suitability of the liner materials.

The data included herein, indicates that when liners are constructed with careful construction, monitoring of preparation, placement and compaction methods, the field and laboratory hydraulic conductivities can be within one order of magnitude.

Appendix - References

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CLAY LINER/LEACHATE COMPATIBILITY MODELING

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Abstract

Over the past several years, the results of many laboratory studies assessing the effect of various combinations of organic and inorganic chemical mixtures on the hydraulic conductivity of clays have been published. Although these studies have increased our knowledge and awareness of the potential effects of waste/soil interactions, there has been little emphasis on the development of predictive models to describe the transient change in the hydraulic conductivity. This paper treats the clay/leachate hydraulic test experiment as a dynamic physical-chemical interaction process and attempts to lay the framework within which the modeling of variations in soil flow characteristics may be undertaken.

Introduction

The effect that a specific liquid waste will have on the hydraulic conductivity of a given clay liner is an important variable that should be addressed for any proposed waste containment scheme. Several studies have shown dramatic increases in conductivity attributed to the alteration of the original soil pore structure due to soil/chemical interaction. This has most notably been observed in experiments using high strength organic liquids (Brown and Anderson, 1983; Brown et. al., 1983,1984; Foreman and Daniel, 1984). Indeed, these results, in addition to the inability of the present state of the art to predict a priori the effect of a specific liquid waste on the conductivity of a given clay liner, has been responsible for the current lack of confidence that the EPA has in the use of clay liners for hazardous waste containment systems.

This current situation strongly points to the need to begin to develop general modeling strategies for predicting the rate and extent to which the hydraulic conductivity of a soil liner system may be altered. This paper will attempt to demonstrate the importance of incorporating the potential transient effects of soil/liquid chemical interactions in predictions of flow field changes within the soil matrix.

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Alteration of Hydraulic Conductivity

In order to discuss changes in the ease with which fluids pass through soil, it is necessary to refer to the definition of the hydraulic conductivity term in Darcy's Law (Nutting, 1930):

$$K = \frac{k\rho g}{\mu} \quad (1)$$

where K = hydraulic conductivity (LT^{-1}); k = intrinsic permeability (L^2); ρ = fluid density (ML^{-3}); μ = viscosity of the fluid ($ML^{-1}T^{-1}$); and g = acceleration due to gravity (LT^{-2}). Since the hydraulic conductivity depends on both the soil matrix and fluid properties, any changes in the hydraulic conductivity brought about by the displacement of one pore liquid with another of different chemical composition are either the result of differences in the fluid properties ρ and μ , or induced changes in the intrinsic permeability, k .

The intrinsic permeability depends only on the soil matrix properties (pore size distribution, pore shape, pore arrangement, tortuosity, etc.). Mechanisms which alter these properties will directly affect the conductivity. Table 1 contains a listing of potential mechanisms and their effect on hydraulic conductivity. Mechanisms (1) through (4) alter conductivity by modifying the available flow pore space through physical changes in the structure and distribution of the clay portion of the solid matrix. These are most likely a result of differences in liquid ionic strength or specific species concentrations that change the size of the double layer surrounding each clay particle. Changes in the double layer cause variation in the interparticle forces which control particle spacing and thus, flow porosity.

Chemical precipitation, solid dissolution, cation exchange/surface complexation, and gas generation or dissolution are dependent on the concentrations of the chemical species resulting from transient soil/liquid interactions as the system tends toward a steady-state condition. Solid introduction and microbiological activity are functions of the liquid characteristics (total suspended solids, organic type and concentration, and initial biomass concentration), and act to reduce porosity and conductivity by adding mass to the solid phase.

For complex liquid wastes (eg. landfill leachates) containing multiple organic and inorganic chemical species, several of these mechanisms may act simultaneously to change the conductivity. In order to begin to model these changes, the relative contribution of each of the mechanisms to altering the soil matrix must be understood. In specific soil/waste interaction problems, only one or two may be primarily responsible for the observed flow field fluctuations.

Table 1. - Mechanisms Causing Changes in Hydraulic Conductivity of a Porous Medium (after Mundell and Jennings, 1986)

No.	Mechanism	Effect on		Effect on Bulk Hydraulic Conductivity
		Flow Porosity	Solid Phase	
1	Dispersion 1 ^a	decrease	increase	decrease
2	Dispersion 2 ^b	increase	decrease	increase
3	Shrinking	increase	none	increase
4	Swelling	decrease	none	decrease
5	Chemical Precipitation	decrease	increase	decrease
6	Solid Dissolution	increase	decrease	increase
7	Solid Introduction	decrease	increase	decrease
8	Microbiological Activity	decrease	increase	decrease
9	Ion Exchange/ Surface Complex.	c	c	incr/decrease
10	Gas Generation	decrease	none	decrease
11	Gas Dissolution/ Displacement	increase	none	increase

^aincludes translocation and lodgment within domain

^bincludes translocation out of domain

^cdependent on specific type of reaction

Modeling Approach

The standard approach for determining the effects of a given waste liquid on a specific compacted clay is to use the waste liquid as the permeant in a laboratory hydraulic conductivity test. The test may be a falling or constant head test in a flexible or fixed-wall permeameter under a prescribed hydraulic gradient. The amount of flow observed passing from the soil sample with time is recorded until some set number of pore volumes pass through the sample or "steady-state" conditions are reached. This "black box" approach observes how much enters and leaves the sample, but does not consider what mechanisms cause the flow variations within the sample. Values of hydraulic conductivity as a function of time are calculated, and the difference between the initial conductivity and the "final" conductivity is used to draw conclusions about the effect the specific liquid has on the particular soil sample. Considerable judgment and qualitative observations are used to evaluate the mechanisms causing conductivity changes. Quality and nature of the permeant as it passes from the sample (cloudy or clear, color, etc.) and defective areas (shrinkage cracks, soil fabric irregularities, channelization) noted in post-test examination of the sample provide "clues", but generally cannot be used in a quantitative fashion for predictive purposes.

The modeling method proposed (Fig 1) incorporates the physical and

chemical characteristics of the liquid and soil into a description of the multicomponent transport of solutes through the soil domain. As the solutes in the liquid are transported, various chemical interactions between the solutes and soil (eg. precipitation, dissolution, sorption) may cause changes in the pore flow structure which in turn alters the conductivity within specific portions of the soil sample. Quantitative relationships involving mass transport and chemical interactions provide a means of predicting possible outcomes.

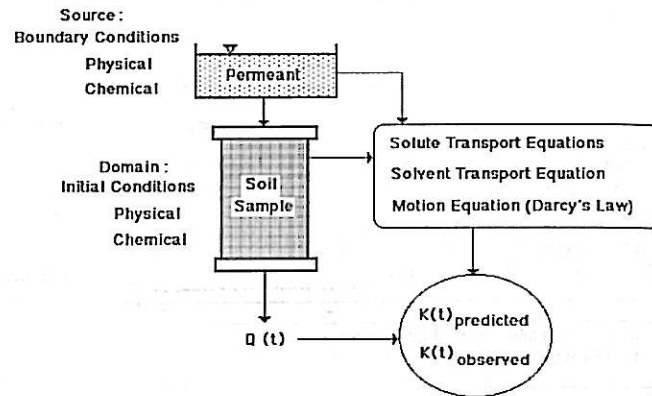
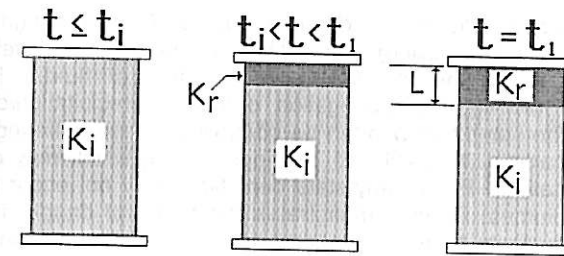


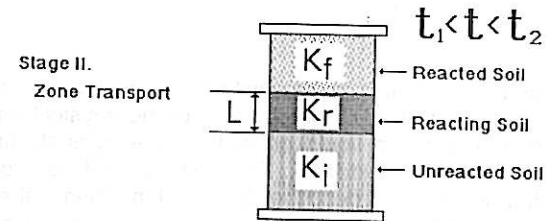
Fig. 1. Modeling of Transient Hydraulic Conductivity

The transient changes in hydraulic conductivity of the bulk soil sample are dependent on the dynamic propagation of a reacting fluid front through the test sample (Fig. 2). The experiment may be idealized as occurring in three stages. The initial stage describes the growth of the reacting zone, in which the conductivity is being transformed from an initial "unreacted" value, to some "reacting" value. The second stage begins when the transformation reaches steady state near the top of the column, and the reacting zone, of some thickness, begins to propagate through the sample. The final stage involves the time during which the reacting zone begins to decrease in thickness once it has reached the end of the column. At the end of the experiment, steady-state conditions have been achieved throughout the column length, and the bulk soil sample exhibits a final "reacted" hydraulic conductivity.

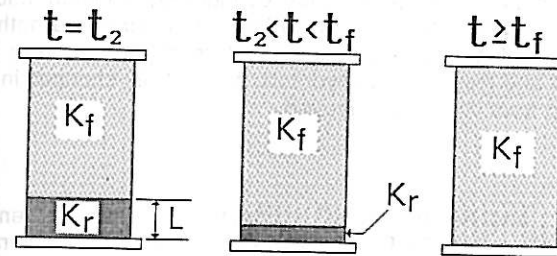
Although the conductivity throughout the entire soil column is constant at the beginning and at the end of the test, it should be recognized that bulk values calculated during the experiment actually represent averaged values which result from the transient variation of the intrinsic permeability across the sample. The bulk conductivity is then given by the expression:



Stage I. Growth of the Reacting Zone



Stage II. Zone Transport



Stage III. Completion of the Reaction

Fig. 2. Idealized Flow Experiment

$$K(t) = L / \int_0^L \frac{dx}{k(x,t) \rho g / \mu} \quad (2)$$

where L = the length of the soil sample.

The transient nature of the intrinsic permeability couples the transport equations with the motion equation (Darcy's Law), requiring an iterative solution procedure to model the changing soil domain flow environment. The rate of transformation of the bulk sample conductivity is dependent upon the rate at which the reacting fronts propagate through the soil sample. For conductivity transformations which are dependent on ionic strength or the

concentration of a specific adsorbed solute (such as Na^+ exchange for Ca^{+2} causing montmorillonite swelling), conductivity change occur relatively rapidly, usually within about one to three pore volumes of fluid. However, transformations involving the propagation of multiple precipitation/dissolution fronts through the sample may often be controlled by the buffering capacity within the soil sample (Mundell and Jennings, 1986), which may drastically retard transformation. Full steady-state conditions may not occur until after tens of pore volumes. This demonstrates the potential danger in running laboratory conductivity tests to apparent "steady-state" conditions without taking into account the retarded chemical effect that may produce drastic conductivity changes after additional pore volumes.

Conclusions

The modeling of hydraulic conductivity alterations within soils due to soil/liquid interactions requires an understanding of the physical and chemical characteristics of the soil and liquid as well as the possible mechanisms which transform the conductivity. The use of multicomponent solute transport modeling schemes to describe the transient chemical environment within the soil sample and its effect on the pore domain in the soil matrix allows a quantitative description of the conductivity transformations. The concepts discussed illustrate the need to begin to incorporate both physical and chemical principles in the flow experiment description in order to predict the potential rate and magnitude of hydraulic conductivity changes in clay liner systems resulting from leachate infiltration.

References

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