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Project Summary

Rate of Flow of Leachate through Clay Soil Liners

David E. Daniel, Charles D. Shackelford, Wing P. Liao, and Howard M. Liljestrand

The objective of this research was to measure the time of travel (TOT) of inorganic solutes passing through laboratory columns of compacted clay and to compare measured and predicted TOT's. Two clay soils were used: kaolinite and Lufkin clay. Anionic tracers were chloride and bromide; potassium and zinc were the cationic tracers.

Column tests were used to measure the TOT of tracers and to determine the effective porosity ratio, which is defined as effective porosity divided by total porosity, of the soils. The effective porosity is equal to the volume of the void space that conducts most of the fluid flow divided by the total (bulk) volume of the soil. The effective porosity ratio increased with increasing hydraulic gradient in kaolinite from a low of about 0.25 at a gradient of 1 to a high of 1 at a gradient of 20. With Lufkin clay, the effective porosity ratio was between 0.02 and 0.16. Breakthrough times were controlled much more by the low effective porosities than by molecular diffusion.

The computer program SOILINER, which was developed by EPA for predicting TOT's through soil liners, predicted TOT's that were larger than actual TOT's by a factor of up to 52. The failure to account for effective porosity ratios less than 1 was the cause for the poor predictions from SOILINER.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the data evaluations that are fully documented in a separate report of the same title (see Project Report ordering information at back).

Objectives

The objectives of this research were to perform experiments to determine the TOT of inorganic chemicals through clay soils, to measure the physical and geochemical parameters that control the TOT through specimens of compacted clay soil, and to compare the measured TOT's with those predicted from analysis with the computer program SOILINER. The research was intended to provide information to help in answering the following questions:

1. What magnitude of effective porosity should be used in calculating TOT of constituents through a soil liner?
2. Can retardation factors calculated from batch adsorption isotherms be used with confidence to predict TOT of reactive solutes?
3. How important is molecular diffusion in determining the TOT of solutes through soil liners?
4. What methods of calculation should be used in calculating TOT of constituents through a soil liner?

Methods

Two soils were used: kaolinite, which is a low-plasticity, commercially-produced clay, and Lufkin clay, which is a highly plastic, naturally-occurring clay soil. the soils were compacted with standard Proctor procedures at a water content just wet of optimum. The tracers used included two anions (chloride and bromide) and two cations (potassium and zinc). Most tests were performed with the tracers mixed in water (0.01 N $CaSO_4$) at a concentration of 0.01 N, but some tests were performed using a concentration of tracer of 0.001 N. After compaction, most soil columns were presoaked with water for about 1 month, and then the tracer solution was introduced. However, some tests were performed without presoaking the soil, i.e., by introducing the tracer solution immediately after the soils were compacted.

Batch adsorption tests were performed by adding soil to tracer solutions at different concentrations, mixing the soil/liquid solution, and analyzing the remaining solution to determine the sorbed mass of a reactive (cationic) tracer. Diffusion coefficients were measured in fixed-wall diffusional cells in which, after a long soaking period to destroy any capillary suction in the soil, the tracer solutions were exposed to one end of a soil column. Diffusion coefficients were calculated from the rate of change of concentration of a tracer in the sealed reservoir containing the tracer solution and from profiles of concentration determined by sectioning the soil after the diffusion test was complete. Column tests were performed in fixed-wall cells using hydraulic gradients of 1, 5, 10, and 20 for kaolinite and gradients of 20 and 50 for Lufkin clay. The effluent from column tests was analyzed for the tracers, and the data were plotted in the form of relative effluent concentration versus pore volumes of flow (termed a "breakthrough curve"). A solution to the advection-dispersion equation was fitted by trial to the experimental data from anionic tracers; the effective porosity ratio (defined as effective porosity divided by total porosity and equal to the ratio of the volume of pore space conducting most of the flow to the total volume of void space in the soil) and hydrodynamic dispersion coefficient were adjusted until a best fit (by eye) was obtained. For cationic tracers, the effective porosity ratio and hydrodynamic dispersion coefficient determined for an anionic tracer were assumed to apply to the cationic tracer as well, and the retardation factor was determined by trial-and-error curve fitting.

Results

Batch adsorption tests produced nonlinear isotherms that could be modelled well with the Freundlich and Langmuir equations. For kaolinite, zinc and potassium were adsorbed about equally, but for Lufkin clay, zinc was sorbed much more strongly than potassium.

Diffusion tests showed that the effective diffusion coefficient for anions was approximately 6 - 7 x 10^{-6} cm^2/s for kaolinite and 1 - 15 x 10^{-6} cm^2/s for Lufkin clay. The effective diffusion coefficient was somewhat less for cations, but experimental problems with precipitation of cations in the tracer solution and difficulty in achieving complete extraction of cationic tracers from soil slices made the data difficult to interpret. The computed values of tortuosity factor varied from 0.29 to 0.35 for kaolinite and between 0.05 and 0.71 for Lufkin clay. The tortuosity factors determined in this study are within the range of values reported in the literature for soils.

Column tests for presoaked soils showed that the effective porosity ratio for kaolinite varied from a low of 0.25 - 0.3 at a hydraulic gradient of 1 to a high of 1 at a hydraulic gradient of 10 and 20. It was postulated that at low hydraulic gradient, viscous water adsorbed to the surfaces of kaolinite particles blocked flow paths and produced a relatively low effective porosity. At higher hydraulic gradient, the viscous water was mobilized and contributed to, rather than blocked, flow paths. With Lufkin clay, effective porosity ratios were very low — only 0.02 to 0.16. Adsorbed water layers or preferential flow paths (or both) evidently produced the low effective porosities. With lufkin clay, the effective porosity ratio was approximately the same on soil columns permeated at hydraulic gradients of 20 and 50. There was no evidence of a threshold hydraulic gradient (below which no flow occurs) in the column tests.

Hydrodynamic dispersion coefficients in the kaolinite columns varied with hydraulic gradient. At low gradient (1 and 5), the hydrodynamic dispersion coefficient was on the same order as the effective diffusion coefficient, indicating that mechanical mixing was unimportant compared to molecular diffusion. At the highest hydraulic gradient used for testing kaolinite (20), the hydrodynamic dispersion coefficient was 3 to 4 times larger than the effective diffusion coefficient, indicating (as expected) that mechanical mixing was much more important at high hydraulic gradient. With Lufkin clay columns, the hydrodynamic dispersion coefficient was on the same order as the effective diffusion coefficient.

Retardation factors for potassium and zinc calculated from batch adsorption tests compared favorably with values determined from column tests, although there were discrepancies involving up to 100% difference in retardation factors. Several geochemical differences existed between the column and batch tests and probably combined to cause the differences.

An analysis of the relative importance of molecular diffusion in determining the TOT of nonreactive (anionic) tracers through the soil columns revealed that diffusion was of little significance in these particular experiments; the relatively fast breakthrough times (less than 1 month) in the column tests were controlled more by low effective porosity than by molecular diffusion.

Soil columns that were not presoaked were analyzed with the computer program SOILINER to determine breakthrough times. SOILINER is a computer program that predicts TOT of nonreactive solutes through a compacted soil liner. SOILINER consistently predicted longer TOT's through the soil columns than were measured. With kaolinite, the actual TOT was 2 to 5 times less than predicted, and with Lufkin clay, nonreactive tracers broke through the column more than 50 times faster than predicted (the predicted breakthrough time was > 2 years, but the actual breakthrough time was about 2 weeks). The cause for the poor results with SOILINER was the assumption in SOILINER that the effective porosity equals the total porosity; the soil columns used in this study had effective porosities that were generally much less than the total porosity.

Conclusions

The main conclusions from this study are:

1. The effective porosity of compacted kaolinite was a function of hydraulic gradient; lower values of effective porosity were measured at low hydraulic gradient than at high gradient in kaolinite.
2. The magnitude of effective porosity ratio (defined as effective porosity divided by total porosity) was 0.25 to 0.3 for kaolinite tested at a hydraulic gradient of 1, and was 0.02 to 0.16 for Lufkin clay tested at a hydraulic gradient of 20 and 50. These effective porosity ratios, it is noted, are significantly less than unity.
3. Breakthrough of nonreactive tracers occurred much faster than predicted by the computer program SOILINER. The problem with results from SOILINER appeared to be that the effective and total porosity are assumed to be equal in SOILINER.
4. Molecular diffusion played a relatively unimportant role in determining the TOT of constituents through the soil columns used in these experiments; low effective porosity had a much more significant effect.

Recommendations

The main recommendations that are made as a result of this research are:

1. Effective porosity should not be assumed to equal total porosity unless actual experimental data confirm that the two are equal.
2. Column tests similar to those utilized for this research are recommended for the determination of effective porosity; the tests should be performed at a hydraulic gradient that is as close to the anticipated field value as possible and not at a grossly elevated gradient.
3. SOILINER should not be used to predict TOT of constituents through a soil liner, unless the total porosity is approximately equal to the effective porosity. A simple, direct calculation of TOT, using the velocity of seepage equal to the hydraulic conductivity times hydraulic gradient divided by effective porosity, is recommended instead.
4. The computer program SOILINER should be refined to account for effective porosity less than total porosity.

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David E. Daniel, Charles D. Shackelford, Wing P. Liao, and Howard M. Liljestrand are with The University of Texas, Department of Civil Engineering, Austin, TX 78712.
Walter E. Grube, Jr. is the EPA Project Officer (see below).

The complete report, entitled "Rate of Flow of Leachate through Clay Soil Liners," (Order No. PB91-196 691/AS; Cost: $23.00 subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency
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