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Vapor Phase VOC Transport in Physically-Mixed Clay Soils

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ABSTRACT

Experiments were conducted to provide insight into the controlling removal mechanisms for a mixed region vapor stripping process in clay soils. Results of soil column experiments were compared to a mathematical model to determine intra-aggregate diffusion coefficients and sorption coefficients at different temperatures. Under the assumption that intra-aggregate diffusion was the rate limiting removal mechanism, the mathematical model predicted the removal of trichloroethylene at 20 °C, 40 °C, and 60 °C. Agreement between the experimental observations and the model were very good. Faster removal of TCE was observed with increasing temperature.

INTRODUCTION

Mixed region vapor stripping (MRVS) has been demonstrated to be an effective remediation technique for removing volatile organic chemicals (VOCs) from clay soils (Siegrist et al. 1993a, b). Mixing is accomplished with large cutting blades mounted on the end of a rotating kelly bar, which is forced down through a contaminated clay soil while a gas mixture of air and/or steam is pumped down through the bar and out the rotating blades (Figure 1). The mixing action caused by the rotating blades increases the permeability of the clay and provides more contact area between the sweep gas and the contaminated soil. The injected gases permeate up through the mixed region, removing VOCs. The gas is collected at the surface by a vacuum shroud and subsequently treated. Steam injection is an enhancement that is used to increase soil temperature and hence the volatility of the VOCs (Gierke et al. 1992).

Several different *in situ* treatment technologies were coupled to the physical mixing process and demonstrated in May 1992 at the X-231B site at the U. S. Department of Energy (DOE) Portsmouth Gaseous Diffusion Plant in Ohio. The primary VOCs targeted for removal were trichloroethylene and 1,1,1-trichloroethane, both were present at levels below 20 ppm on a dry soil mass basis. The soil at the site was a tight clay (Minford member) and not amenable to treatment using conventional vapor extraction techniques. Ambient-temperature and thermally-

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enhanced MRVE removed about 90% of the VOCs during a four-hour demonstration (Siegrist et al. 1993). The experiments reported herein were performed to quantify the controlling removal mechanisms so that a mathematical model could be tested against the field results (Gierke et al. 1993).

In this research, a soil column was used to simulate a cylinder of mixed aggregated clay soil developed when the kelly bar is advanced through a tight clay formation. Experiments were performed with a methane tracer gas and trichloroethylene (TCE), which was the predominant contaminant at the X-231B site. A previously developed computer model (Gierke el at. 1992) was used to simulate the transport of methane and TCE in the soil columns.

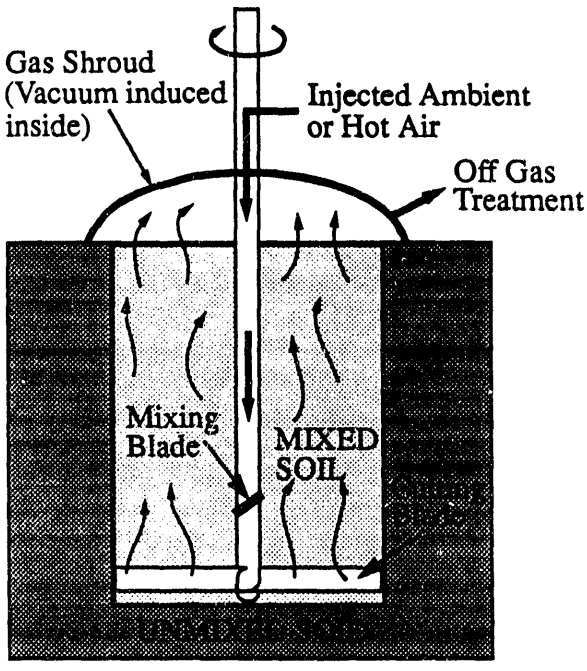

Figure 1: Schematic of Mixed Region Vapor Stripping Process

Figure 2 shows a conceptual picture of the mechanisms controlling movement of a volatile organic compound in a aggregated clay soil; the mathematical model was derived based on this schematic. The complete details of the model development are reported elsewhere (Gierke et al. 1992, Gierke et al. 1990). What follows is a summary of the model assumptions and limitations. Air flow, soil temperature, porosity, and moisture content are assumed to be uniform and constant. The aggregates are represented by a homogeneous packing of uniform-size porous spheres. Moisture is assumed to be contained in the aggregates and is immobile. The air phase is continuous. The model accounts for a single dissolved VOC. Nonlinear sorption can be accounted for, but for most conditions a linear sorption coefficient can be used. Degradation is not considered.

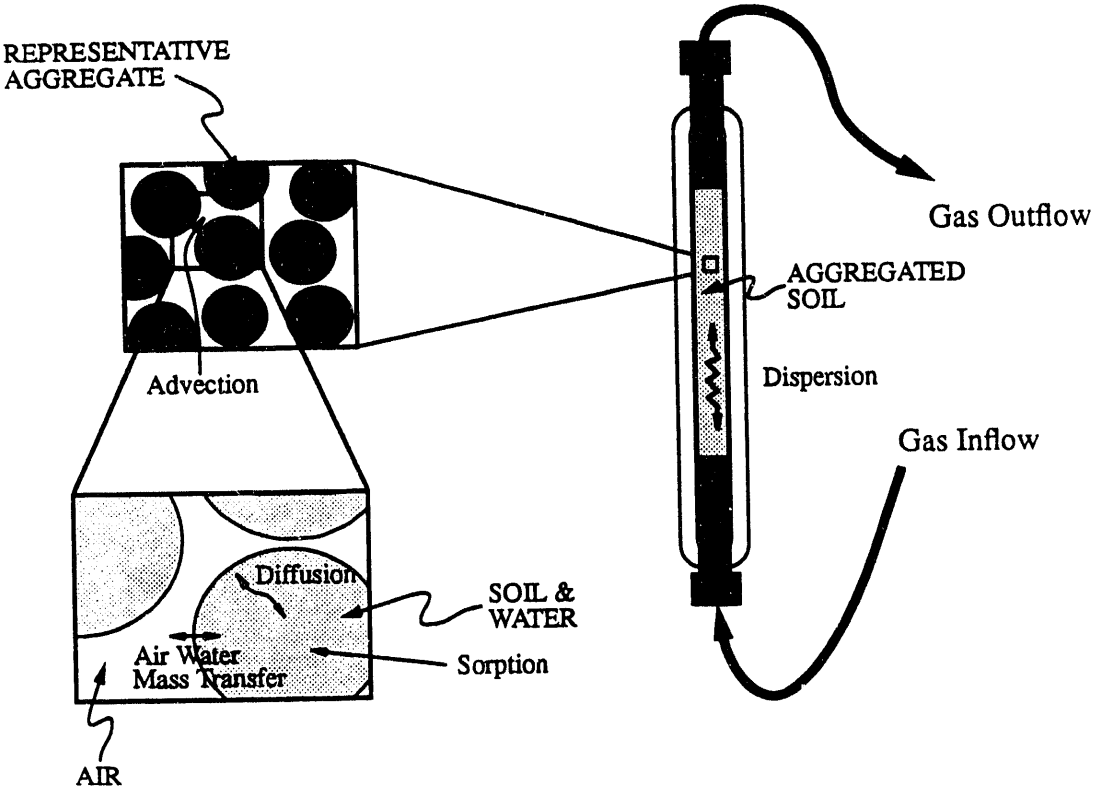

Figure 2: Conceptual Picture of an Aggregated Clay Soil in a Soil Column

The model accounts for nonequilibrium conditions between the moving (sweep) gas phase and the aggregates, and within the aggregates. Inside the aggregates, mass transfer occurs by diffusion (in gas, if the aggregates are dry, and/or in water, if they are wet). A first-order mass transfer approach is used to simulate the transfer of VOC between the moving gas phase and the aggregate surface. In addition to transport in the moving gas phase by advection, the model also accounts for vapor diffusion and dispersion in the interaggregate region.

MATERIALS AND METHODS

A schematic of the experimental apparatus used for this study is shown in Figure 3. A jacketed glass column (ACE Glass, Inc., Vineland, NJ) was packed with clay aggregates as uniformly as possible. The column was 2.54 cm I.D. and the length was varied between 13 and 17 cm depending on the amount of soil. The moveable platens holding the soil in place were made of Teflon and were modified to distribute flow uniformly across the column cross section. Influent gases were introduced from pressure-regulated tanks through Teflon tubing. Injection-gas flow rate was controlled using a micrometer valve. The flow rate was measured using a soap film bubble meter. At specified times, an internal vacuum pump in the gas chromatograph (GC) (Microsensor Technology, Inc., Freemont, CA) withdrew a representative sample from the effluent stream. After flushing the sample tube in the GC, a sample was injected into the chromatograph column and then a thermal conductivity detector measured the vapor

concentration. The GC was connected to a personal computer loaded with EZCHROM integration software (Microsensor Technology, Inc., Freemont, CA), which would integrate the area beneath the peaks on the resulting chromatographs.

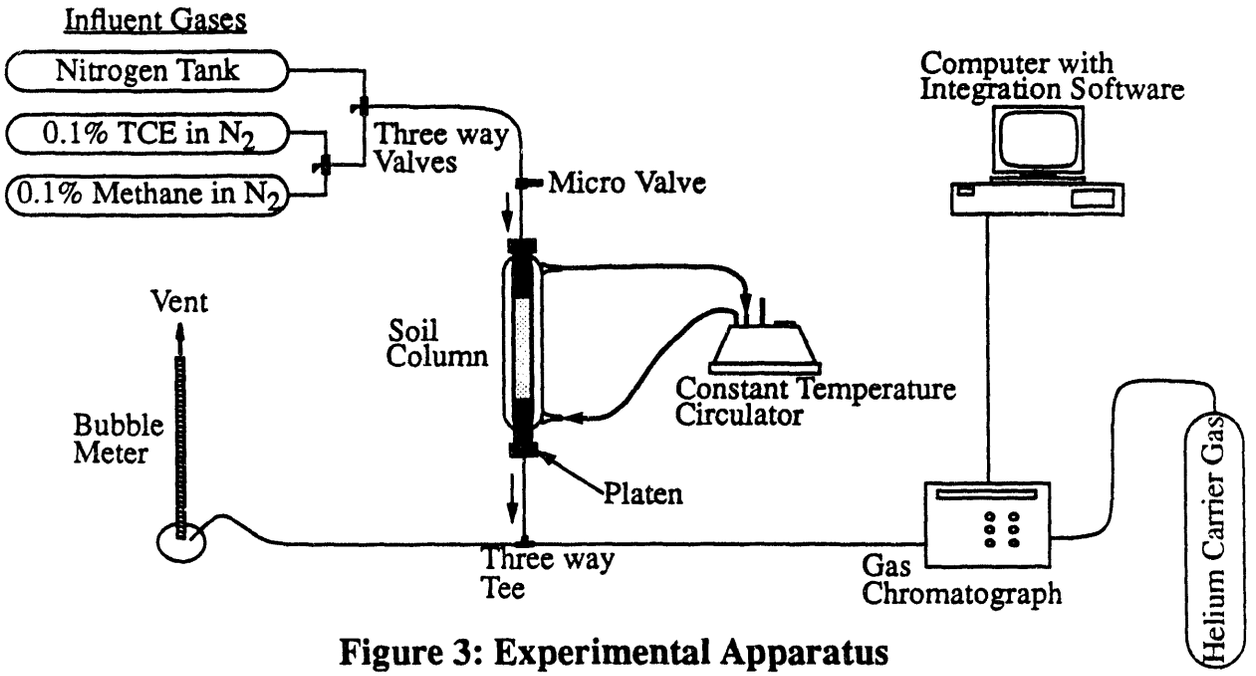

Figure 3: Experimental Apparatus

An experimental run involved both contaminating and remediating the clay soil. In the contamination step (breakthrough), the system was first flushed with high purity (99.99%) nitrogen gas, then a three-way valve was switched to allow flow from either a 0.1% (1000 ppmv) methane in nitrogen gas mixture or a 0.1% (1000 ppmv) TCE in nitrogen gas mixture, both were calibration standards (Matheson Gas Products, Chicago, IL). The duration of the breakthrough ranged from 3.5 to 14 hours, which was long enough for the soil to equilibrate with the influent gas. Flow was then switched back to the organic-free nitrogen to perform the remediation (elution). The elution continued until the effluent concentration was below the detection limit of the GC (10 ppmv). Breakthrough experiments were conducted to ensure uniform contamination and to perform a mass balance. Methane was used as a tracer to determine the apparatus dead volume, apparatus induced dispersion, and the aggregate micropore tortuosity. Trichloroethylene (TCE), a common ground water contaminant, was used as the organic contaminant.

The experimental conditions and soil properties for each experiment are summarized in Table 1 and the parameters used in the model calculations are given in Table 2. Four TCE experiments were conducted in wet aggregated clay. Two were conducted at 20(±2) °C and one each at 40(±2) °C and at 60(±5) °C. A water circulator (Haake, Berlin, Germany) was used to maintain a constant temperature in the column jacket. Prior to the elevated temperature experiments, the column jacket would be flushed with water at the desired temperature for over two hours. One methane experiment was conducted at 20 °C with air-dry aggregated clay. CH4-1 is the methane tracer experiment. TCE-1 and TCE-2 are experiments run on the Minford clay at 20 °C and 60 °C, respectively. TCE-3 and TCE-4 are experiments run on the X-231B clay at 20 °C and 40 °C, respectively.

The two clay soils used in these experiments were from the same soil member but at different locations. One was contaminated Minford clay from the X-231B site and the other was Minford clay from nearby the X-231B. Because of health and safety issues, clay samples from the X-231B site could not be obtained for this work until about four weeks prior to the deadline for this manuscript. Therefore, Minford clay samples were taken from nearby the X-231B site and used in place of the clay from the X-231B site for some of the experiments. The organic carbon fraction of the Minford clay (f_{oc}) was determined to be 0.0010 (Gierke and Wang (1993)). The clay, silt, and sand fractions are 22, 65, and 12%, respectively (West et al. 1993).

To simulate the mixing process, the soils were chopped up and sieved. The fraction retained between the U.S. Standard Sieve No. #9 and #5 (2.0 mm - 4.0 mm) were packed in the columns.

The methods for determining the model parameters are discussed more completely in Gierke et al. (1990, 1992). Below is a summary of the estimation methods.

Column size, temperature (T), soil mass, degree of saturation (S), soil porosity (ε), bulk density (ρ_b), and gas flow rates (Q) were measured directly. Gas flow rates were difficult to prescribe so a constant flow rate was established for both breakthrough and elution prior to each experiment. We tried to establish the same flow rate for both breakthrough and elution, but we were usually not successful. Flow rates varied less than 5% during an experiment.

Gas and liquid diffusion coefficients for TCE at 20, 40, and 60 °C were calculated using the Wilke-Lee modification of the Hirschfelder, Bird-Spotz method (Wilke and Lee 1966) and the Hayduk and Laudie correlation (*loc. cit.* Sherwood et al. (1975)), respectively. Henry's dimensionless partitioning coefficient for TCE (H) was estimated according to a correlation reported by Ashworth et al. (1988):

$$H = [101\ 325/(8.314\ T)] \exp(7.485 - 3702/T) \qquad [1]$$

The effective diffusion coefficients were taken as the gas or liquid diffusion coefficient divided by a pore tortuosity. The interaggregate (macropore) tortuosity (τ_p) was estimated using the Millington correlation (Millington (1959)); the intra-aggregate (micropore) tortuosity (τ_a) was determined by model calibration to the CH4-1 data. Linear sorption was assumed. Sorption coefficients (K_p) were calculated from the observed retardation coefficients (R_d), which were obtained from integration of the breakthrough and elution curves:

$$R_d = 1 + S/[(1-S)H] + \rho_b K_p/[\varepsilon(1-S)H] \qquad [2]$$

A value of K_p was estimated to be 0.1 ml/g using a correlation related to compound solubility reported by Hassett et al. (1983). The air-water mass transfer coefficient was chosen so that the model would simulate equilibrium between the gas and aqueous phases (Gierke et al. 1992). This meant that intra-aggregate diffusion was the rate-controlling mechanism for equilibrium between the mobile gas and the aggregates (Gierke et al. (1990)). The aggregate diameter ($2R_a$) was assumed to equal to the mean sieve size (3.0 mm). Particle density (ρ_s) for the clay was assumed to be 2.6 g/ml.

Table 1: Experimental Conditions and Soil Properties

Experiment	Soil	Temp. (°C)	Column Length (cm)	Column Volume (ml)	Dry Bulk Density (g/ml)	Total Porosity (dimls)	Water Saturation (dimls)	Air Filled Pore Volume (ml)	Gas Flow Rate (ml/min)	Sorption Coef. * (ml/g)
CH4-1	Minford	20	17.2	87.15	1.03	0.61	0.049	50.17	9.38	0.0
TCE-1	Minford	20	14.8	74.74	0.87	0.67	0.286	35.5	10.50	0.7
TCE-2	Minford	60	14.8	74.74	0.87	0.67	0.286	35.5	8.88	1.3
TCE-3	X-231B	20	13.3	67.39	0.81	0.69	0.244	36.5	5.18	0.9
TCE-4	X-231B	40	13.3	67.39	0.81	0.69	0.244	36.5	7.80	1.6

* - Calculated from integration of column results

Table 2: Equilibrium and Mass Transfer Parameter Values for Model Calculations

Model Input Parameter	CH4-1	TCE-1	TCE-2	TCE-3	TCE-4
Henry's Partitioning Coef. (dimls)	N/A	0.35	1.4	0.35	0.73
Air-Water Mass Transfer Coef. (1/sec)	0.1	0.1	0.1	0.1	0.1
Effective Intraparticle Diff. Coef. (cm^2/sec)	0.25 and 2.5×10^{-5} *	1.7×10^{-6}	4.2×10^{-6}	1.7×10^{-6}	2.9×10^{-6}
Effective Gas Diff. Coef. (cm^2/sec)	0.18	0.059	0.16	0.059	0.067
Sorption Coef. (ml/g)	0.0	0.7	0.7	0.7	0.7
Retardation Coef. (R_d)	1.0	5.5	3.0	5.8	4.7
Liquid Diffusion Coef. (cm^2/sec)	N/A	8.7×10^{-6}	2.1×10^{-5}	8.7×10^{-6}	1.5×10^{-5}
Gas Diffusion Coef (cm^2/sec)	0.25	0.083	0.23	0.083	0.094

* - Using $\tau_a = 1$ and 10,000, this accounts for gas diffusion in dry aggregates.

RESULTS AND DISCUSSION

The combination of experiments used in this work were intended to provide independent estimates of the important mass transfer and equilibrium parameters. The methane tracer was designed to verify the use of the Millington correlation for the interaggregate porosity, which it did, and to provide data for calibration of the intra-aggregate tortuosity, which as will be shown below was not successful. Literature estimates of the model parameters were used initially to predict the TCE experiments. To improve the agreement between the model simulations and the data, model calibration of the sorption coefficient and intra-aggregate tortuosity were performed with the TCE-1 data, and the calibrated parameters were used in subsequent simulations of the other experiments (TCE-2, TCE-3, and TCE-4). The relatvie concentrations reported on the following graphs are effluent concentrations relative to the influent concentration in the gas cylinders that were used for the breakthrough. Influent concentrations were measured prior to each experiment and the precision was on the order of a few percent.

Figure 4 compares the breakthrough curves of TCE through wet aggregated clay at 20, 40, and 60 °C. The time scale on Figure 4 is the number of gas pore volumes displaced. Temperature may have a slight effect on the movement of TCE through this clay soil. The effects are difficult to discern because of the scatter of the concentration measurements. Differences should be most noticeable after C/C_o has increased beyond 0.8. Beyond this point is where nonequilibrium (in this case, nonequilibrium is due to intra-aggregate diffusion) should have the greatest affect the rate of TCE transport (commonly called "tailing"). At higher temperatures, the TCE liquid diffusion coefficient is higher and therefore the intra-aggregate diffusion rate should be is faster. The center of mass of each breakthrough curve should appear where the air-filled pore volumes displaced is equal to the retardation coefficient (Eq. [2]). Differences in the retardation coefficients are rather slight for this soil/VOC combination.

Table 2 shows the retardation values for the three different temperatures. The lower the value of R_d is, the more quickly the TCE travels in the soil column. TCE-1 and TCE-3 have similar retardation coefficients, indicating that TCE behaves similarly in the two soil samples. The retardation coefficients for TCE-4 and TCE-2 are both lower than TCE-1 and TCE-3, indicating that TCE transport is faster at higher temperatures.

The sorption coefficients calculated from the data (Eq. [2]) show a significant increase of K_p with temperature. Highly hydrophobic compounds frequently display higher values of K_p with increasing temperature (Weber et al. 1982). The increase in sorption with temperature may be an artifact of the estimation method. If the Henry's constant correlation (Eq. [1]) over predicted H at the higher temperatures (the correlation was tested between 10 and 30 °C), then a lower K_p would have been calculated.

The retardation coefficients of the breakthrough curves were consistently higher than those for the elution curves. The GC could not measure effluent concentrations below about 10 ppmv, and because this resulted in less "tailing" of the elution curve, the observed retardation coefficients for the elution parts of the experiments were less than those for breakthrough. To minimize the use of model-calibrated parameters, it was decided to use the value of the micropore tortuosity and sorption coefficient fit to the TCE-1 experiment for the model calculations of the other TCE experiments.

Figure 5 depicts the results of the methane tracer experiment in the dry aggregated clay soil. The model was used to determine the sensitivity of the micropore tortuosity on the shape of the breakthrough curve. The original intent for using methane, a non-sorbing, insoluble gas, under dry conditions was to estimate the micropore tortuosity independent of the TCE experiments. However, as can be seen from the sensitivity analysis, the methane breakthrough was insensitive

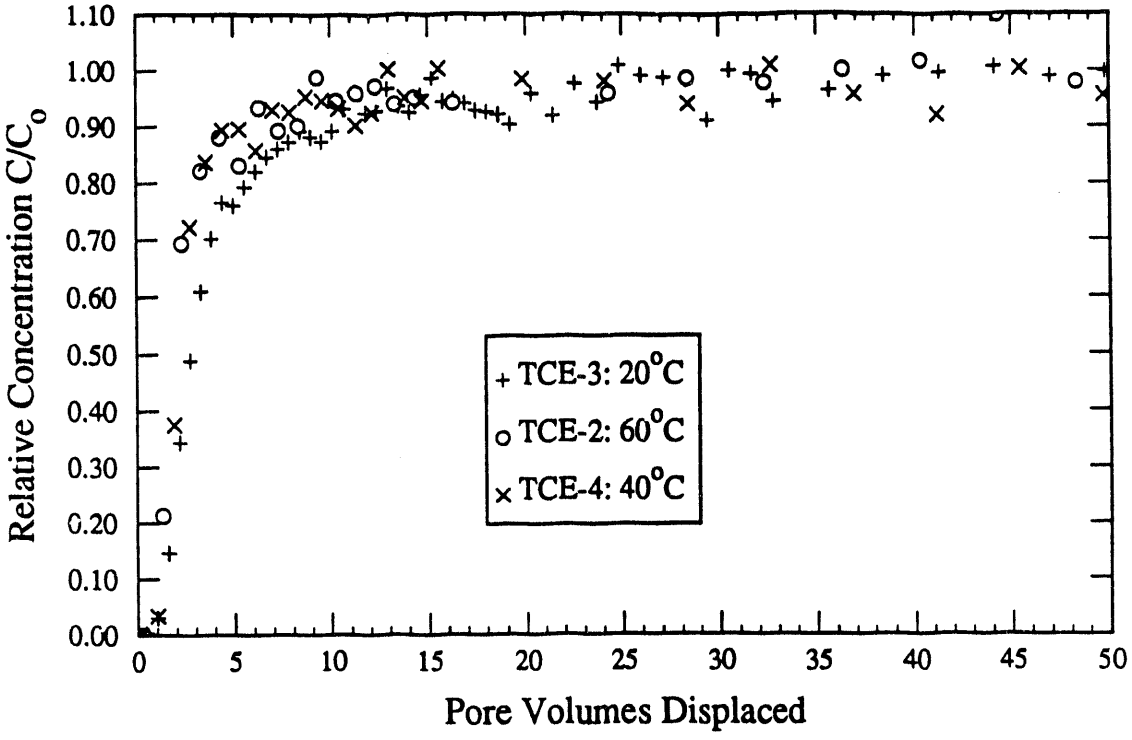

Figure 4: Temperature Effects Comparison of TCE-2, TCE-3, and TCE-4 Breakthrough Curves

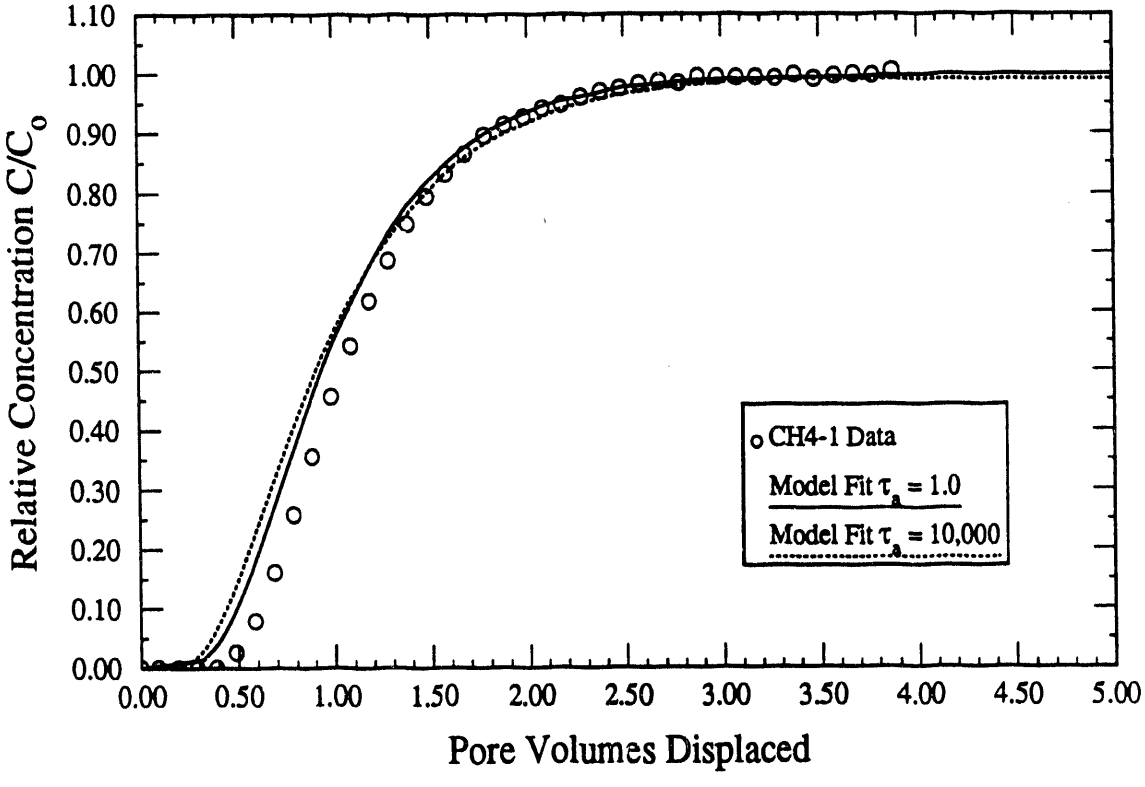

Figure 5: Model Sensitivity of Micropore Tortuosity in Air Dry Minford Clay

to the micropore tortuosity, possibly due to the small aggregate size. The methane diffused into the aggregates very quickly, appearing to approach local equilibrium conditions. The two model simulations show that it would be very difficult to see an effect of intra-aggregate diffusion under these conditions. A much smaller effective intra-aggregate diffusion coefficient is needed to observe the importance of the micropore tortuosity.

The diffusion coefficient of TCE in water is much smaller than gas diffusion coefficient of methane so a greater effect was observed in its transport in the wet aggregated clay soil. Figures 6-9 show model simulations of the TCE data using the parameter values in Tables 1 and 2.

The first TCE experiment (TCE-1) was performed with the Minford clay at 20 °C (Figure 6). The solid line shows a model simulation using a calibrated value of the micropore tortuosity and the literature estimate of K_p (Hassett et al. 1983). It was found that a micropore tortuosity between 1 and 10 resulted in the best fit. A value of five was arbitrarily chosen. The dashed line corresponds to a model calibration of K_p, based on the retardation of the breakthrough data.

Figure 7 depicts the results of the TCE experiment with the Minford clay at 60 °C (TCE-3). The model prediction based on the literature K_p is shown as a solid line, and the value of K_p fit to the TCE-1 data was used for the prediction shown by the dashed line (*i.e.*, no change in sorption with temperature). The agreement between the model predition based on the TCE-1-calibrated parameters and the TCE-3 data is good.

Figures 8 and 9 show the results of TCE-2 and TCE-3, respectively, which were performed with the clay soil from the X-231B site. As above, the solid curves on both figures correspond to the literature K_p, and the dashed curves are based on the K_p fit to TCE-1. Despite the differences in the observed retardation coefficients, the agreement between the model and the data is very good. Therefore, eventhough there is up to a factor of 2 difference in the observed R_d, its impact is not great in terms of simulating the data obtained herein.

One additional comment can be made on the agreement between the model simulations and the data depicted in Figures 6-9. There is a general trend in the agreement between the model and the data; that is, the agreement is better as the gas flow rate decreases.

CONCLUSIONS

A previously-developed mathematical model was able to adequately simulate TCE vapor transport experiments in columns of clay soil modified to represent soil resulting from a mixed region vapor stripping process. The observed mass transfer rates and sorption for TCE in this clay soil were within an order of magnitude of literature estimates of the model parameters for all temperatures between 20 and 60 °C.

The intra-aggregate mass transfer rate could not be determined from the methane tracer in the dry soil column experiment because the intra-aggregate diffusion rate was too fast, essentially approaching local equilibrium conditions. The results of experiments at higher temperature indicated slightly faster movement of TCE with increasing temperature. Although not conclusive, it does appear that both soil sorption and aqueous diffusion rates of TCE in this clay soil increase slightly with temperature. Because the sorption coefficient was deduced from the observed retardation, the apparent increase in sorption may be due to an overestimate of Henry's constant at higher temperatures.

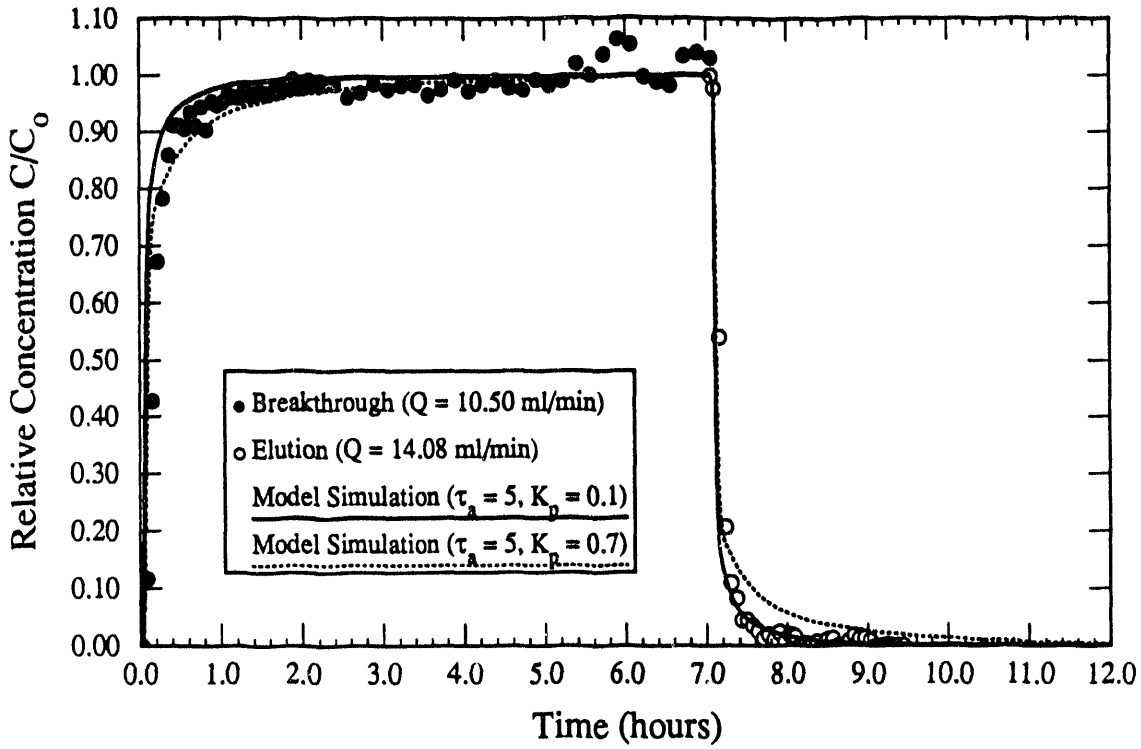

Figure 6: Model Simulation of TCE in 20°C Wet Minford Clay

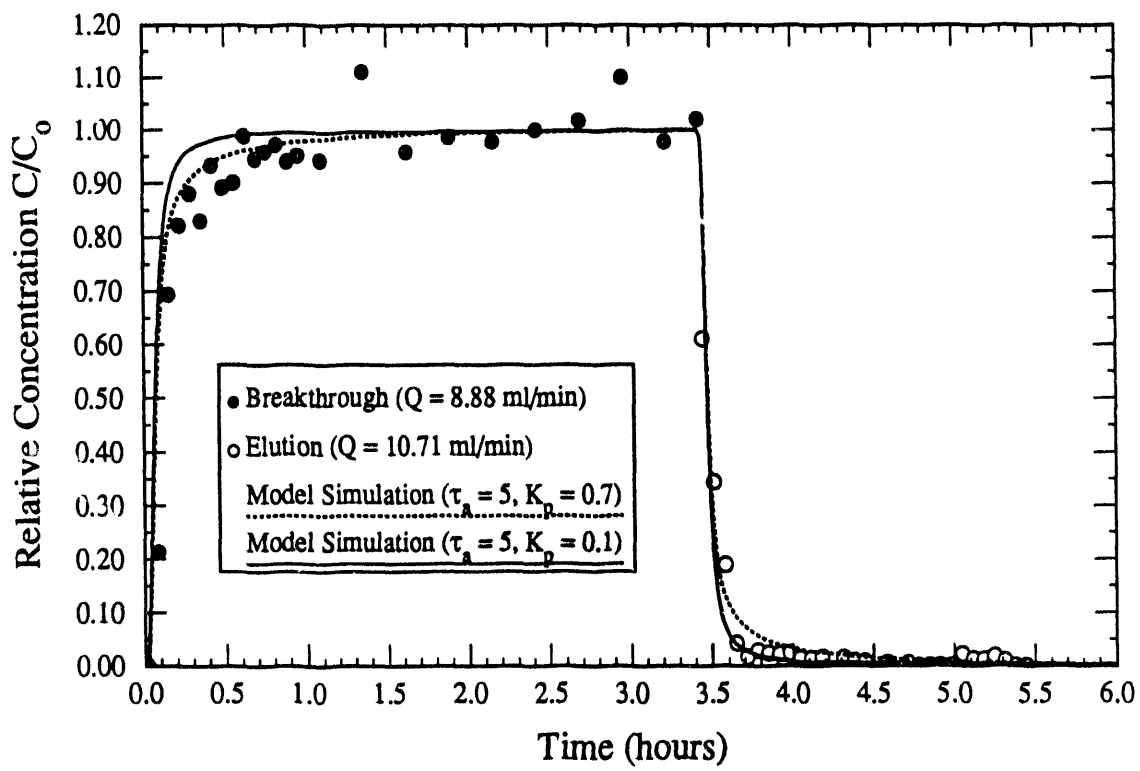

Figure 7: Model Simulation of TCE in 60°C Wet Minford Clay

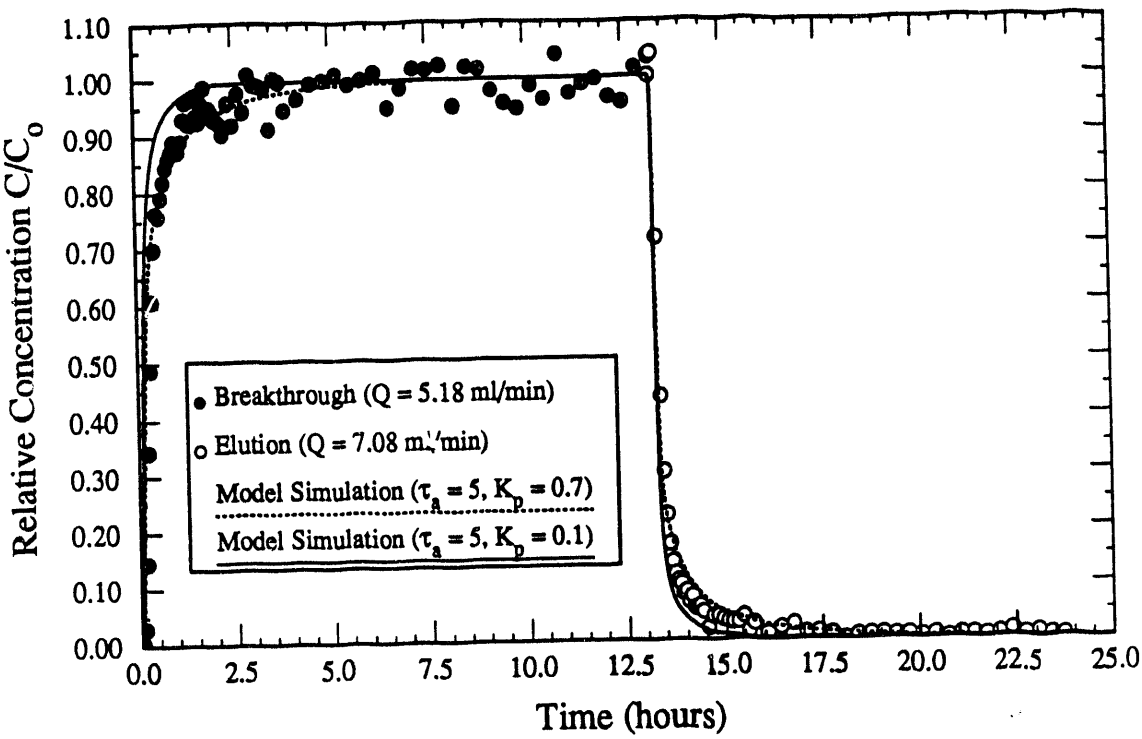

Figure 8: Model Simulation of TCE in 20°C Wet X-231B Clay

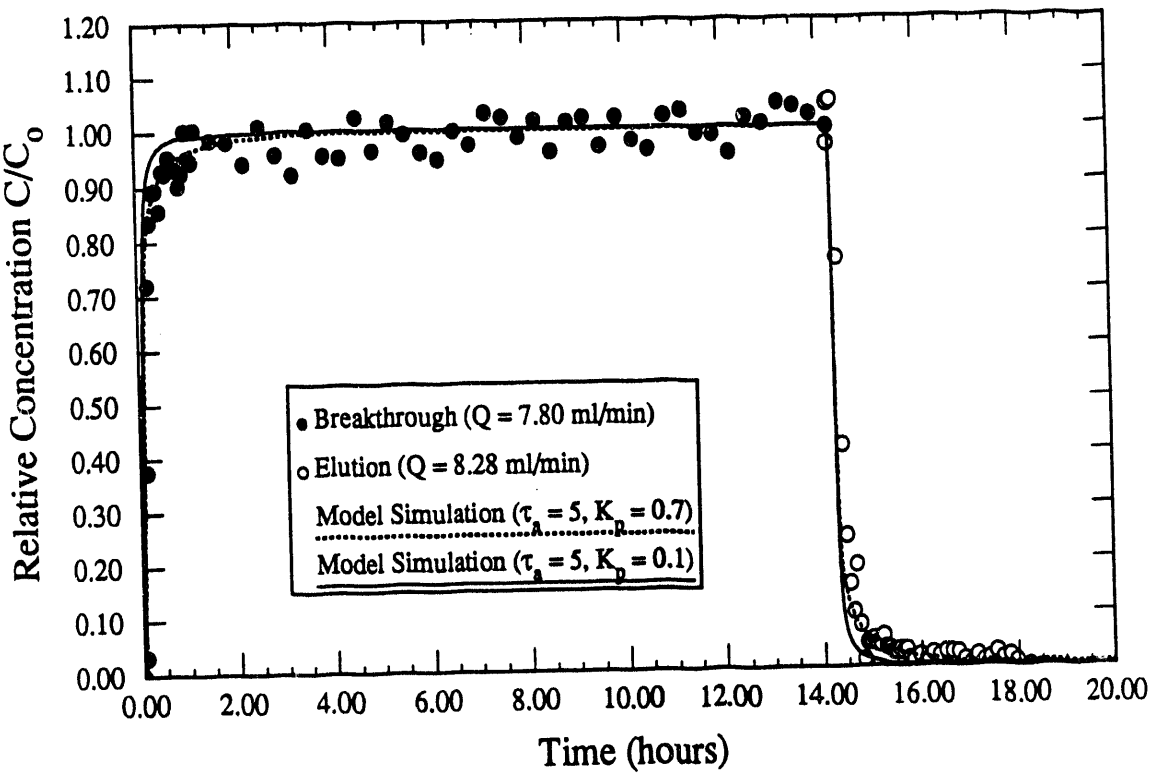

Figure 9: Model Simulation of TCE in 40°C Wet X-231B Clay

REFERENCES

Ashworth, R. A., G. B. Howe, M.E. Mullins, and T. N. Rogers, "Air-Water Partitioning Coefficients of Organics in Dilute Aqueous Solutions,", *J. Haz. Mat.*, 18:25-36, 1988.

Gierke J. S. and C. Wang, Modeling Thermally-Enhanced Vapor Extraction Coupled with *In Situ* Mixing for Remediation of Organically-Contaminated, Fine Grained Soils, Final Report to Oak Ridge National Laboratory, Contract No. 19X-SUJ598V, April 12, 1993.

Gierke J. S., N. J. Hutzler, and J. C. Crittenden, "Modeling the Movement of Volatile Organic Chemicals in Columns of Unsaturated Soil", *Water Resour. Res.*, 26:1529-1547, 1990.

Gierke J. S., N. J. Hutzler, and D. B. McKenzie, "Vapor Transport in Unsaturated Soil Columns: Implications for Vapor Extraction," *Water Resour. Res.*, 28:323-335, 1992.

Gierke, J. S., O. M. Reyes, and R. L. Siegrist, "Modeling Volatile Organic Chemical Removal by *In Situ* Soil Mixing/Steam Stripping," Proc. Conf. on Solving Ground Water Problems with Models, Assoc. of Ground Water Scientists and Engineers, Dallas, Texas, February 1992..

Gierke, J. S., C. Wang, O. R. West, and R. L. Siegrist, "Mixed Region Vapor Stripping in Fine-Textured Soils: 3. Modeling," in preparation, 1993.

Hassett, J. J., W. L. Banwart, and R. A. Griffin, "Correlation of Compound Properties with Sorption Characteristics of Nonpolar Compounds by Soils and Sediments: Concepts and Limitations," in *Environmental and Solid Wastes Characterization, Treatment, and Disposal*, Chapter 15, C.W. Francis, S.I. Auerbach, and V.A. Jacobs, eds., Butterworths, Boston, 161-179, 1983.

Millington, R. J., "Gas diffusion in Porous Media", *Science*, 130:100-102, 1959.

Sherwood, T. K., R. L. Pigford, and C. R. Wilke, *Mass Transfer*, McGraw-Hill, New York, 1975.

Siegrist, R. L., M. I. Morris, O. R. West, D. D. Gates, D. A. Pickering et al., "Field Evaluation of In Situ Treatment by Physicochemical Processes," Proc. Waste Management '93, U.S. Department of Energy, Tucson, Arizona, March 1993a.

Siegrist, R. L., O. R. West, and J. S. Gierke, "Mixed Region Vapor Stripping in Fine-Textured Soils: 2. Results of Field Pilot Test," in preparation, 1993b.

West, O. R., R. L. Siegrist, S. W. Schmunk, and J. S. Gierke, "Mixed Region Vapor Stripping in Fine-Textured Soils: 1. Laboratory Treatibility,"in preparation, 1993.

Wilke, C. R., and C. Y. Lee, "Estimation of Diffusion Coefficients for Gases and Vapors," *Ind. Eng. Chem.*, 47:1253-1257, 1955.

Weber, W. J., T. C. Voice, M. Pirbazari, G. E. Hunt, and D. M. Ulanoff, "Sorption of Hydrophobic Compounds by Sediments and Suspended Solids in Aquatic Systems II: Methods and Pilot Compound Results," *Water Research*, 1982.

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BIOGRAPHICAL SKETCHES

Michael D. Carpenter was awarded a B.S. degree in Civil Engineering in 1992 from Michigan Technological University, Houghton, and is now a M.S. candidate in Geological Engineering at Michigan Tech. Presently he is a graduate research assistant conducting soil column experiments that simulate vapor extraction in physically-mixed clay soils. His research and professional interests involve remediation techniques for contaminated soils, especially innovative techniques for low-permeability soils.

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Dr. Gierke obtained a Ph.D. degree in Environmental Engineering from Michigan Technological University, Houghton. He has been an Assistant Professor of Geological and Environmental Engineering at Michigan Tech since graduating in 1990. Dr. Gierke recently received a U.S. Department of Energy Environmental Restoration and Waste Management Junior Faculty Award for his research and teaching activities related to soil remediation. He teaches courses in hydrogeology, ground water engineering, contaminant transport, soil remediation, and environmental engineering. His current areas of research involve permeability changes in clay soils resulting from contamination by organic liquids and the remediation of organic contamination from clays using *in situ* techniques such as thermally-enhanced vapor extraction coupled with mixing or fracturing.

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