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Experimental determination of hydrodynamic dispersion coefficients for heavy metals using compacted clay

M. ZEKI CAMUR & HASAN YAZICIGIL

Department of Geological Engineering, Middle East Technical University, 06531 Ankara, Turkey

e-mail: mzeki@metu.edu.tr

Abstract Mass transport of ions through the Ankara clay liner, which was prepared under three different compaction conditions, was studied experimentally on the basis of sorption, advection and hydrodynamic dispersion processes. Under optimum compaction conditions, effective porosity and hydraulic conductivity of the material were 0.32 and 0.13–0.26 × 10^{-8} cm s^{-1}, respectively. Effective diffusion coefficients of Cd, Cl, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb and Zn ions were, respectively, 2.54, 9.51, 2.22, 2.85, 2.22, 7.93, 2.54, 3.08, 1.59, 3.17 and 2.54 (× 10^{-6}) cm^2 s^{-1}. Two materials, prepared using half of the optimum water content but optimum energy conditions (II), and optimum water content but half of the optimum energy conditions (III), have effective porosities of 0.35 and 0.40, respectively. Hydraulic conductivities of these materials were 3.1–4.38 × 10^{-8} cm s^{-1} and 916–1057 × 10^{-8} cm s^{-1}. Dispersivities were 0.96 cm and 2.0 cm in materials II and III, respectively.

Key words Ankara clay; clay liner; diffusion; dispersivity; sorption; waste disposal site

INTRODUCTION

The suitability of a clay liner to control advective contaminant transport has been conventionally evaluated on the basis of hydraulic conductivity. Previous work, however, indicates that chemical diffusion is another important transport process in such liners that has to be taken into consideration (for a summary see Rowe, 1994). The purpose of this study was to determine the impact of advective, dispersive and diffusive transport on liners that were compacted under three different conditions: I. optimum energy and water content, II. optimum energy but half of the optimum water content and III. optimum water content but half of the optimum energy. These conditions have been selected to show the adverse effects of improper handling of liner design in the field. The Ankara clay was used as a liner material in the investigation.

CHARACTERISTICS OF ANKARA CLAY

Reddish-brown mudstone layers in the Upper Pliocene sediments around the Ankara plain, Turkey are called "Ankara clay" (Birand, 1963). The approximate mineral composition of the Ankara clay is 37% calcite, 32% quartz, 6% feldspar, 12% smectite, 10.5% illite, 2.5% chlorite and kaolinite minerals. Standard geotechnical experiments show that the particle size distribution of the material is 50% clay, 34%

silt, 11% sand and 5% gravel, and it has a liquid limit of 73 and plastic limit of 29. It is a high plasticity inorganic clay (CH) according to the Casagrande classification. The specific gravity of the material is 2.71 kg dm^{-3}. The optimum compaction of the material can be achieved under conditions of 32% water content and 1.41 g cm^{-3} dry density (ρ_b). On the basis of compaction tests, the optimum energy but half of the optimum water content compaction condition corresponds to 1.38 g cm^{-3} dry density and 16% water content. The optimum water content but half of the optimum energy compaction condition corresponds to 1.21 g cm^{-3} dry density and 32% water content.

MASS TRANSPORT

Contaminant transport through clay liners (and soils) can be modelled using the advection–dispersion equation which, for a one-dimensional condition, can be expressed using the linear sorption assumption as:

$$\partial c/\partial t = (1/(1 + \rho_b K_d/n_e))\, D_h\, (\partial^2 c/\partial z^2) - v_s\, (\partial c/\partial z)$$

where c is ion concentration at a given depth z and time t, ρ_b is bulk dry density of the soil, K_d is distribution or partitioning coefficient of any given ion, n_e is effective porosity, D_h is hydrodynamic dispersion coefficient, v_s is seepage velocity ($= v_a/n_e$), v_a is advective (Darcy) velocity. The equation can be used to calibrate the hydrodynamic dispersion coefficient for an ion if the ion concentration distribution, effective porosity, seepage velocity, dry density and distribution coefficient are known at a given time and space scale (as in the case of experiments performed in this study) (Rowe *et al.*, 1988). The hydrodynamic dispersion coefficient is often expressed as the sum of the effective diffusion coefficient and the mechanical dispersion coefficient ($D_h = D_e + D_m$).

Previous studies indicate that the hydrodynamic dispersion coefficient can be regarded as an effective diffusion coefficient under the very low seepage velocity conditions that are observed in properly constructed clay liners. In other words, diffusion is the dominant mass transport process in liner materials that have been constructed under optimum conditions (Gillham & Cherry, 1982; Rowe *et al.*, 1988).

DATA EVALUATION

Three column experiments were carried out. In Column I, the Ankara clay was compacted into the lower part of the column under optimum energy and water content conditions. This experiment was carried out for 374 days. The solution started to leak into the collection bottle after 168 days. Based on the data collected, the advective velocity, hydraulic conductivity and effective porosity (volumetric water content) were calculated as 0.78×10^{-8} cm s^{-1}, 0.26×10^{-8} cm s^{-1}, and 0.35, respectively. In Column II, the material was compacted under conditions of optimum energy but half of the optimum water content. The experiment was carried out for 21.93 days. The solution started to leak into the collection bottle on the third day. The advective velocity, hydraulic conductivity and effective porosity (volumetric water content) were calculated as 12.68×10^{-8} cm s^{-1}, 4.40×10^{-8} cm s^{-1}, and 0.35, respectively. In Column III, the material was compacted under conditions of optimum water content but half of

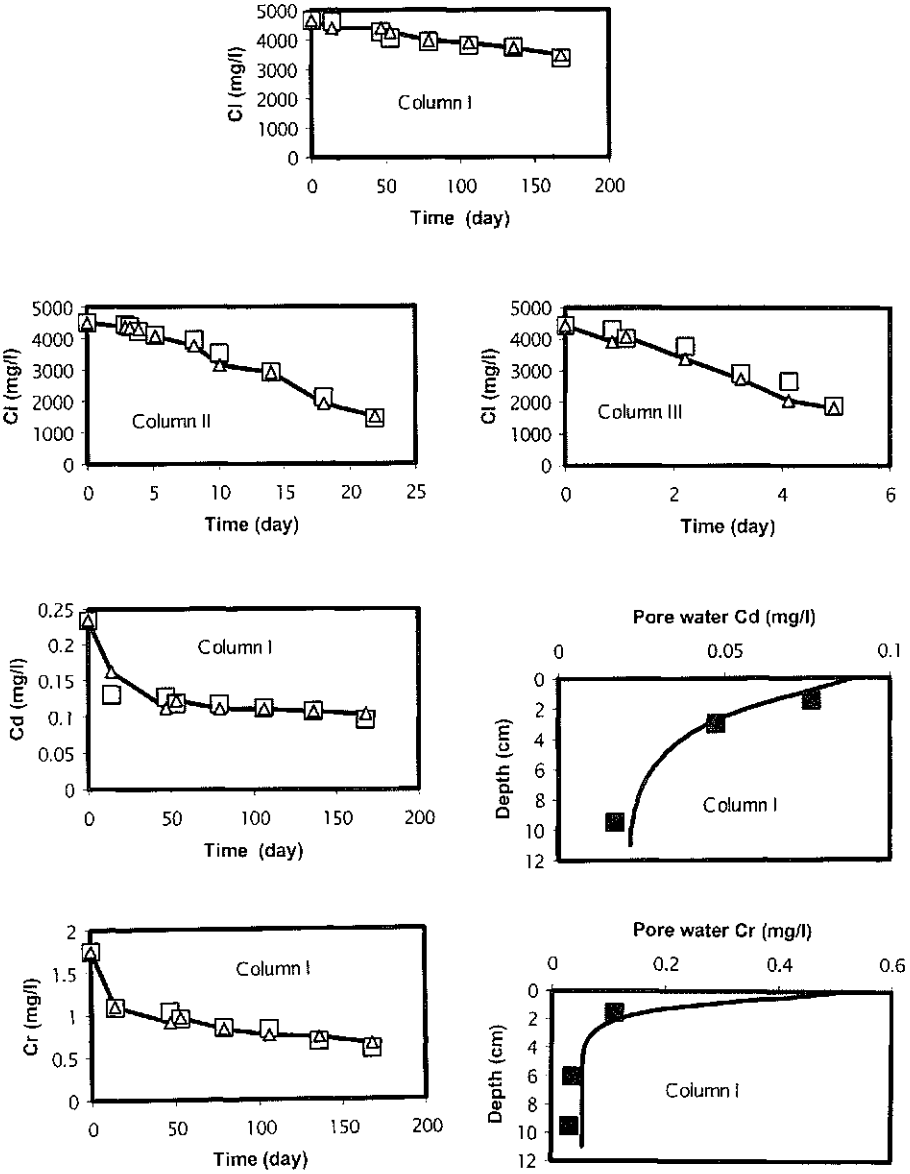

Fig. 1 Comparison of the experimental (square) and theoretical (triangle, line) concentrations both in the reservoir and in the pore water (at day 320.74) for various experiments.

the optimum energy. The experiment was carried out for 4.96 days. The solution started to leak into the collection bottle on the first day. The advective velocity, hydraulic conductivity and effective porosity were 3171 × 10^{-8} cm s^{-1}, 1057 × 10^{-8} cm s^{-1}, and 0.41, respectively. Hydraulic conductivity and effective porosity values for three conditions were also estimated independently using standard geotechnical tests; the results were very close to the values given above.

The mass transfer equation was solved for different values of D_h for each ion until a match was obtained between observed and theoretical concentrations in the source solution as a function of time using known ρ_b, v_s, n_e, K_d, and initial source solution concentrations. Freundlich nonlinear sorption isotherms established through sorption experiments were used to calculate equivalent linear distribution coefficients by an iterative technique (Rowe *et al.*, 1994). The mass transfer equation was solved using the POLLUTE software of Rowe *et al.* (1994). A finite mass top boundary condition was used in the calculations (Rowe *et al.*, 1994). A zero flux bottom boundary condition was adapted for cases where no effluent flow occurred into the collection bottle. In the case of effluent flow conditions, the bottom boundary was specified as fixed outflow.

The effective diffusion coefficients determined (assuming $D_h \approx D_e$) using the results of the Column I experiment (representing a nearly pure diffusion test) for Cl, Cd, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb and Zn ions are 9.51, 2.54, 2.22, 2.85, 2.22, 7.93, 2.54, 3.08, 1.59, 3.17, 2.54 × 10^{-6} cm^2 s^{-1}, respectively. Theoretical concentrations calculated using some of these effective diffusion coefficients are compared with the corresponding experimental concentrations in Fig. 1, which reveals correlation coefficients of between 0.95 and 0.99. Because the amount of pore water extracted from each compacted clay section was very little, it was not possible to obtain concentration estimates for all the ions; only those that were measured are shown in the figure.

The hydrodynamic dispersion coefficients determined, D_h, ($= D_e + D_m$) for Cl were 9.83×10^{-6} cm^2 s^{-1} for Column II material and 146.8×10^{-6} cm^2 s^{-1} for Column III material. Theoretical Cl concentrations in the reservoir calculated using these hydrodynamic dispersion coefficients are compared with the experimentally measured values in Fig. 1. Mechanical dispersion, dispersivity and seepage velocity relations ($D_m = \alpha v_s$) suggest 0.96 cm and 2.0 cm dispersivity values for Column II and III materials, respectively, based on a D_e value of 9.51×10^{-6} cm^2 s^{-1} for Cl determined earlier from Column I data collected under optimum conditions.

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