

Electro-Kinetic Flow Barriers in Compacted Clay

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Double liner systems are now required for new hazardous waste landfills and impoundments to prevent groundwater contamination caused by leachate. However, uncertainty always exists about the longevity of the synthetic flexible membrane liner, and the compacted clay components of the liner system may release some seepage in time under a sustained hydraulic head. The mechanisms of contaminant retention by clay minerals are not fully understood, and the attenuation capacity of any containment system is finite. In addition, diffusion through the clay liner under a concentration gradient may increase the rate of contaminant migration into the environment above that owing to advection alone. Electro-kinetic counterflow may be an effective measure to stop the migration of contaminants under a hydraulic gradient. An electro-kinetic fluid flow barrier can be created by the continuous or periodic application of an electrical gradient across a compacted clay liner. A coupled flow theory to describe the simultaneous flows of water, electricity, and contaminant ions under the influences of hydraulic, electrical, and chemical gradients has been developed by using the formalism of the thermodynamics of irreversible processes. An experimental testing program demonstrated the existence of electro-osmotic flow in partly saturated compacted clay and provided a basis to evaluate the validity of the theoretical predictions. An electrical gradient may move some inorganic species in soils much more effectively than hydraulic gradient. An electro-kinetic flow barrier halted the migration of the cation but accelerated that of the anion under laboratory testing conditions.

In spite of intense efforts at waste minimization, recycling, and alternative forms of waste disposal, landfills and impoundments will continue to play a major role in environmental protection.

The U.S. EPA issued regulations and performance standards for liner systems as a part of the 1984 RCRA Amendments. Guidelines for the design, construction and operation of liner systems were promulgated in 1985 (1) to control groundwater contamination caused by those disposal facilities. A composite double liner system with leachate collection systems above and between liners is required for most disposal facilities. Those liners contain both synthetic flexible membrane layers (FML) and compacted clay layers. A recently published Technical Resource document (2) provides extensive information and data about clays and their role in the system.

Unfortunately, the longevity of the FML is uncertain, and the FML, and the compacted clay component of the liner, may ultimately release some seepage under the influence of

a sustained hydraulic head. The mechanisms for retention of contaminants by clay minerals are not fully understood, and the attenuation capacity of the liner is finite. In addition, diffusion through the clay liner under the influence of a concentration gradient may increase the rate of contaminant migration into the environment. An electro-kinetically induced counterflow has been proposed as a means to stop the migration of contaminants.

Electro-kinetic phenomena in clay are reviewed in this paper to establish the fundamental principles of electro-kinetic flow barriers. Theoretical analysis and experimental evaluation of electro-kinetic flow barriers to contaminant transport through compacted clay are described. Other potential applications of electro-kinetics for hazardous waste site remediation are also noted in the hope that they may stimulate future research.

ELECTRO-KINETIC PHENOMENA IN CLAY

The surfaces of clay particles are normally negative charged because of isomorphous substitutions and the presence of broken bonds. Adsorbed cations for electrical neutrality form diffuse double layers on the surfaces of clay particles when they are placed in water (3,4). The electro-kinetic properties of clay are determined principally by the structure of the diffuse double layer on the wet clay surfaces.

Several electro-kinetic phenomena arise in clay when there are couplings between hydraulic and direct current electrical driving forces and flows. Those phenomena can broadly be classified into two pairs by the driving forces causing the relative movement between the liquid and the solid phases. The first pair consists of electro-osmosis and electrophoresis, where the liquid or the solid phase moves relative to the other under the influence of an imposed electrical potential. The second pair consists of streaming potential and migration or sedimentation potential, where the liquid or the solid phase moves relative to the other under the influence of hydraulic or gravity force and thus inducing an electrical potential. Those four electro-kinetic phenomena in clay are presented in Figure 1. Detailed descriptions of these phenomena are given by Mitchell (3) and van Olphen (4).

POTENTIAL USES OF ELECTRO-KINETICS FOR HAZARDOUS WASTE SITE REMEDIATION

Electro-kinetics may be useful for hazardous waste containment or site remediation or both in several ways. Each of these ways is briefly described next.

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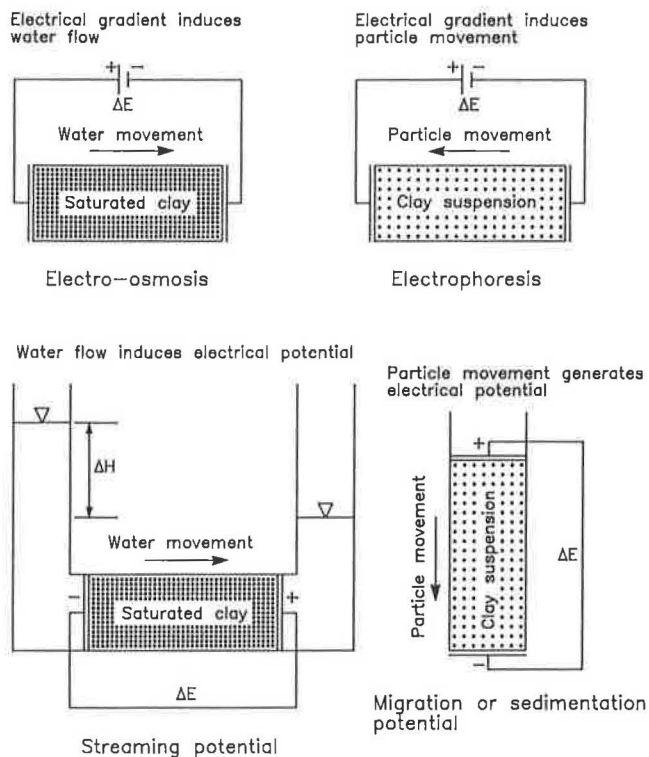


FIGURE 1 Electro-kinetic phenomena in clay.
[Adapted from Mitchell (3).]

Electro-Kinetic Flow Barrier to Contaminant Transport

The periodic or continuous application of an electrical gradient across a low permeability compacted clay liner of a hazardous waste landfill in the direction indicated in Figure 2 to inhibit any outward migration of hazardous constituents is denoted as electro-kinetic flow barrier. The contaminant migration is opposed by the combined effects of electro-osmosis and the effective ionic mobility of contaminant ions in compacted clay under the influence of the imposed electric field.

The in-place saturated hydraulic conductivity k_h of the compacted clay component of a liner system for a hazardous waste landfill must be 1×10^{-7} cm/sec or less to fulfill the requirements of the Hazardous and Solid Waste Amendments (HSWA) of 1984 (1). The coefficient of electro-osmotic permeability, k_e , is a soil property that indicates the hydraulic flow velocity through soil under a unit electrical gradient (i.e. 1 V/cm) and is generally in the range of 1×10^{-5} cm²/V sec to 10×10^{-5} cm²/V sec for most soils and is relatively independent of soil type (3). Hydraulic flow induced by a small electrical gradient in such a system should be able to balance that induced by a large hydraulic gradient. Hence, a small DC electrical gradient applied continuously or periodically in the direction indicated in Figure 2 may stop the advection component of contaminant migration.

The movement of contaminants by hydrodynamic dispersion and advection also may be resisted by an electrical gradient. Molecular diffusion in fine-grained soils, which are the soil types in which electro-kinetics are most likely to be effective,

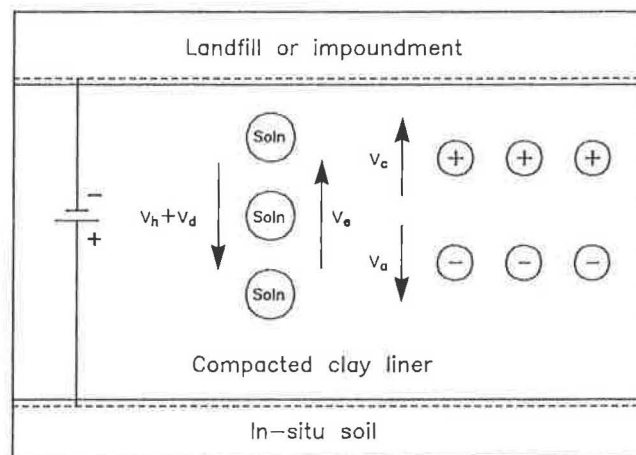


FIGURE 2 Concept of electro-kinetic flow barrier.

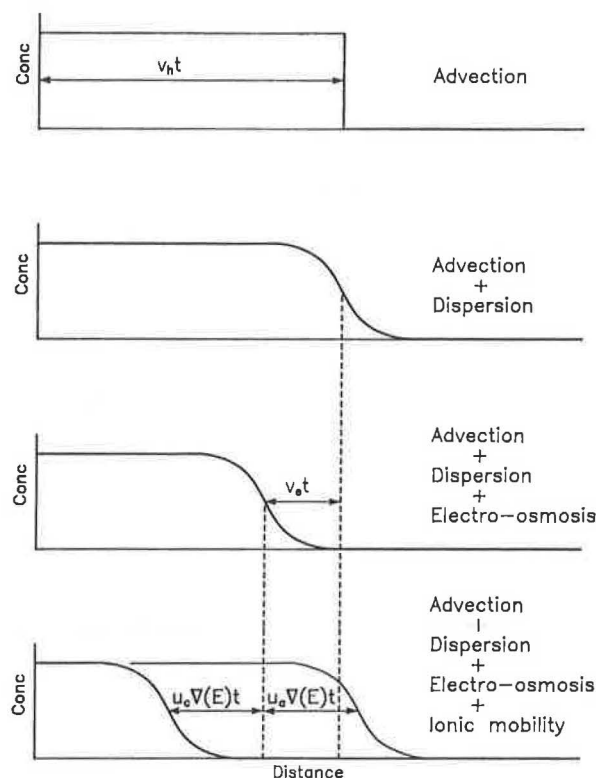


FIGURE 3 Movements of cations and anions under the influences of hydraulic, electrical, and chemical gradients.

can be expected to be the dominant component of hydrodynamic dispersion. Ionic contaminants will move relative to the hydraulic flow under the influence of the imposed electrical gradient. However, the directions and velocities of the ionic migrations depend on the charges and the ionic mobilities of the cation and the anion. Figure 3 illustrates the movements of the cations and the anions under the influence of hydraulic, electrical, and chemical gradients in terms of concentration against distance at a certain time t . The hydraulic

flow velocities are v_h and v_e owing to the imposed hydraulic and electrical gradients, respectively. The effective ionic mobilities of the cation and the anion in soil (i.e., the velocities of the ions under the influence of a unit electric field) are u_c and u_a . The applied electrical potential across the soil is E . The theoretical analysis and experimental evaluation of the viability of the electro-kinetic flow barrier to contaminant transport through compacted clay are the main subjects of this paper.

Concentration, Dewatering, and Consolidation

It takes a long time for waste sludges, slimes, coal washeries, mine tailings, or polluted dredged materials to settle by gravity and to consolidate. The shortage of long-term disposal sites and the increasing demand for reuse of dump sites for some other purposes shortly after being filled necessitate techniques to accelerate the concentration, dewatering, and consolidation processes.

Electrophoresis and electro-osmosis may provide means to concentrate and dewater those fine-grained slurries. When an electric field is imposed on a slurry, suspended particles carrying negative charges will migrate toward the anode under the influence of the electric field (Figure 4). The densified sediments at the anode can be removed periodically for further treatment or ultimate disposal without much difficulty. After the sediment has been densified sufficiently and the particle mobility has been reduced, further dewatering and consolidation can be achieved by electro-osmosis. Different procedures of applying those electro-kinetic techniques to densify and dewater coal waste slurry were outlined by Sprute and Kelsh (5), whose laboratory and field test results also indicated that a 100-acre by 110-ft-deep impoundment of coal waste sludge can be effectively consolidated by these electro-kinetic techniques. Moreover, the successes of electro-osmosis in dewatering polluted dredged materials and coal washery slimes were demonstrated in small scale experiments (6–8). However, attempts to dewater phosphate slimes in Florida have been only moderately successful.

Electro-Kinetic Injection

Electro-osmosis was successfully applied in lieu of injection pressure to cause bentonite suspension to move in controlled direction at an accelerated velocity through fine-grained soils

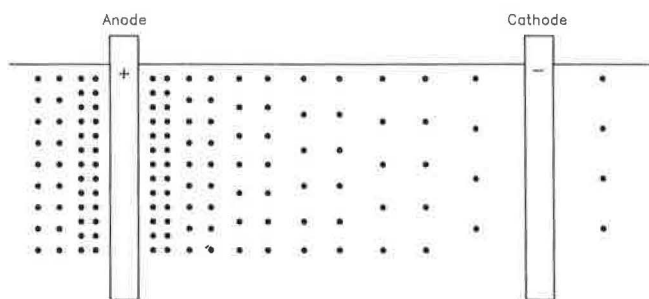


FIGURE 4 Densification of negatively charged particles from dilute suspension by electrophoresis.

(9). The bentonite suspension was injected from perforated steel tubular anodes into the soils toward the cathodes to seal off a building substructure from water percolation. Similarly, it may be possible to inject other chemical grouts to form a barrier in situ to mitigate contaminant migration and thus confine the contaminants within known boundaries.

Electro-kinetic injection might be used to inject cleanup chemicals into contaminated soils to release adsorbed hazardous materials from the surfaces of soil particles, thus facilitating subsequent removal by an appropriate method. Other chemicals may react with the toxics in situ to form harmless compounds or to fix the toxics on the surfaces of soil particles and render them immobile.

Electro-Kinetic Extraction

When an electric field is imposed on a wet soil mass, ionic migrations take place in directions dictated by the charges of the ions. The anions move toward the anode and the cations move toward the cathode (Figure 5). The soil pore fluid moves toward the cathode because of electro-osmosis. The combined effects of electro-osmosis and ionic migration under the influence of an imposed electric field may provide an effective means for removing contaminants from soils.

Some factors affecting the effectiveness of electro-kinetics in contaminant removal were studied by Hamnett (10), whose experimental results on silica sand and by using carbon electrodes indicate the high potential for removing inorganic contaminants from soils by electro-kinetics. The possibility for movement of nonpolar organics through soil by electro-osmosis remains essentially unexplored.

Electrochemical Effects in In Situ Cleanup

A number of electrochemical effects other than electro-osmosis, electrophoresis, and ionic migration may develop when an electric field is imposed on a wet soil mass or clay suspension, such as ion diffusion, ion exchange, development of osmotic and pH gradients, desiccation owing to heat generation at the electrodes, mineral decomposition, precipitation of salts and secondary mineral, electrolysis, hydrolysis, oxidation, reduction, physical and chemical adsorption, and soil fabric changes.

Contaminants may be transformed into inert forms by precipitation of salts and secondary minerals and by chelation and may be removed from the soil by electrolysis, hydrolysis, or redox reactions. Hamnett (10) reported that the chloride

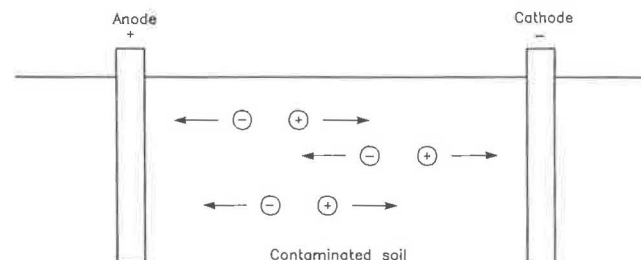


FIGURE 5 Electro-kinetic extraction of ionic pollutants.

ions in silica sand evolved as chlorine gas at the anode as a result of electrolysis. The pH at the cathode becomes higher and that at the anode becomes lower owing to the electrolysis of water at the electrodes. Segall et al. (11) reported that the highly alkaline water at the cathode could desorb organics, pesticides, and heavy metals from the surfaces of soil particles and thus facilitated removal from soil by electro-osmosis.

THEORETICAL ANALYSIS OF ELECTRO-KINETIC FLOW BARRIERS

The theoretical formulation is only outlined here. The complete development is given by Yeung (12). Contaminant migration through a compacted clay liner equipped with an electro-kinetic flow barrier involves several coupled simultaneous flows (i.e., water, electricity, and ions under the influences of hydraulic, electrical, and chemical gradients). Those transport processes are formulated by the formalism of the thermodynamics of irreversible processes to give a quantitative description of the phenomenological coefficients (13–16).

By the assumptions of the thermodynamics of irreversible processes, the flows or fluxes J_i are linear and homogeneous functions of the gradients or driving forces X_i . That is, any flux or flow J_i is related to the gradients or driving forces by

$$J_i = \sum_{j=1}^n L_{ij} X_j \quad (i = 1, 2, \dots, n) \quad (1)$$

where the phenomenological coefficients L_{ij} are independent of the driving forces. The L_{ii} are the conductivity coefficients for direct flows, and the L_{ij} ($i \neq j$) are called coupling coefficients, which quantify the cross phenomena (3). The coupled flows that can occur under the influences of hydraulic, thermal, electrical, and chemical gradients are given in Table 1. Moreover, the matrix of phenomenological coefficients L_{ij} is symmetric; that is,

$$L_{ij} = L_{ji} \quad (i, j = 1, 2, \dots, n) \quad (2)$$

provided a proper choice is made for the fluxes J_i and driving forces X_i (13). Those identities are called the Onsager reciprocal relations (14,15). The proper choice has to be formulated from the local balance equations of mass, energy, and momentum (16).

Assuming the contaminant consists of an ionic salt that dissociates into one cation and one anion, the driving forces are identified to be the hydraulic gradient $\nabla(-P)$, the electrical gradient $\nabla(-E)$, the concentration dependent parts of the chemical gradients of the cation $\nabla(\mu_c^c)$, and of the anion $\nabla(\mu_a^c)$. The fluxes are the volume flow rate of the solution per unit area J_v , the electric current density I , the diffusional flow rate of the cation J_c^d , and of the anion J_a^d per unit area relative to the flow of water. The diffusional flows are related to the absolute flows by

$$J_i = J_i^d + \frac{c_i}{c_w} J_w \quad (3)$$

TABLE 1 COUPLED AND DIRECT-FLOW PHENOMENA
[adapted from Mitchell (3)]

| Flow J | Gradient X | | | |
|------------------|---------------------------------------|---------------------------------------|------------------------------------|-----------------------------------|
| | Hydraulic | Thermal | Electrical | Chemical |
| Fluid | Hydraulic conduction (Darcy's Law) | Thermo-osmosis | Electro-osmosis | Normal osmosis |
| Heat | Isothermal heat transfer | Thermal conduction (Fourier's law) | Peltier effect | Dufour effect |
| Electric current | Streaming potential | Thermo-electricity | Electric conduction (Ohm's law) | Diffusion and membrane potentials |
| Ion | Streaming current | Soret effect | Electrophoresis | Diffusion (Fick's law) |

where c_i is the concentration of ion i and c_w is the concentration of water. Hence, the set of phenomenological equations relating the four flows and the four driving forces is

$$J_v = L_{11}\nabla(-P) + L_{12}\nabla(-E) + L_{13}\nabla(-\mu_c^e) + L_{14}\nabla(-\mu_a^e) \quad (4a)$$

$$I = L_{21}\nabla(-P) + L_{22}\nabla(-E) + L_{23}\nabla(-\mu_c^e) + L_{24}\nabla(-\mu_a^e) \quad (4b)$$

$$J_c^d = L_{31}\nabla(-P) + L_{32}\nabla(-E) + L_{33}\nabla(-\mu_c^e) + L_{34}\nabla(-\mu_a^e) \quad (4c)$$

$$J_a^d = L_{41}\nabla(-P) + L_{42}\nabla(-E) + L_{43}\nabla(-\mu_c^e) + L_{44}\nabla(-\mu_a^e) \quad (4d)$$

Those equations contain four conductivity coefficients, L_{ii} as defined next, and 12 coupling coefficients. Those phenomenological coefficients are not independent. As a result of the Onsager reciprocal relations,

$$L_{12} = L_{21} \quad (5a)$$

$$L_{13} = L_{31} \quad (5b)$$

$$L_{14} = L_{41} \quad (5c)$$

$$L_{23} = L_{32} \quad (5d)$$

$$L_{24} = L_{42} \quad (5e)$$

$$L_{34} = L_{43} \quad (5f)$$

Hence, there are only 10 independent coefficients characterizing the system. If any three of the driving forces can be set to zero in different experiments, then the quantities of flows are determined by a single driving force. The ratios of the measured quantities of flows to this force give the L_{ij} . However, it is not always possible or convenient to perform experiments with only one driving force. Instead, it is often more convenient to set two forces and one flow to zero and to evaluate the appropriate L_{ij} by solution of the simultaneous equations that represent the actual test conditions.

Considering the testing conditions used for the measurements of hydraulic conductivity, electro-osmotic permeability, electrical conductivity, osmotic efficiency, effective diffusivities, and the effective ionic mobilities, and assuming the solution is dilute with no interaction between the cation and the anion, the L_{ij} s were determined to be (12)

$$L_{11} = \frac{k_h}{\gamma_w n} + \frac{L_{12}L_{21}}{L_{22}} \quad (6a)$$

$$L_{12} = L_{21} = \frac{k_e}{n} \quad (6b)$$

$$L_{13} = L_{31} = \frac{-\omega c_c k_h}{\gamma_w n} + \frac{L_{12}L_{23}}{L_{22}} \quad (6c)$$

$$L_{14} = L_{41} = \frac{-\omega c_a k_h}{\gamma_w n} + \frac{L_{12}L_{24}}{L_{22}} \quad (6d)$$

$$L_{22} = \frac{\kappa}{n} \quad (6e)$$

$$L_{23} = L_{32} = c_c u_c \quad (6f)$$

$$L_{24} = L_{42} = -c_a u_a \quad (6g)$$

$$L_{33} = \frac{D_c c_c}{RT} \quad (6g)$$

$$L_{34} = L_{43} = 0 \quad (6h)$$

$$L_{44} = \frac{D_a c_a}{RT} \quad (6i)$$

where

k_h = the hydraulic conductivity,

k_e = the electro-osmotic permeability,

κ = the bulk electrical conductivity of soil,

ω = the reflection coefficient (the ratio of the measured osmotic pressure to the theoretical value),

γ_w = the unit weight of water,

c_c = the concentration of cation,

c_a = the concentration of anion,

u_c = the effective ionic mobility of cation,

u_a = the effective ionic mobility of anion,

D_c = the effective diffusivity of cation,

D_a = the effective diffusivity of anion,

n = the porosity of soil,

R = the universal gas constant, and

T = the absolute temperature.

The contaminant flows relative to the soil are of more significance than the diffusional flows relative to water. Combining Equations 3 and 4 gives the flow equations for cations and anions under the influences of hydraulic, electrical, and chemical gradients:

$$J_c = (L_{31} + c_c L_{11})\gamma_w \nabla(-h) + (L_{32} + c_c L_{12})\nabla(-E) + (L_{33} + c_c L_{13})\frac{RT}{c_c}\nabla(-c_c) + (L_{34} + c_c L_{14})\frac{RT}{c_a}\nabla(-c_a) \quad (7a)$$

$$J_a = (L_{41} + c_a L_{11})\gamma_w \nabla(-h) + (L_{42} + c_a L_{12})\nabla(-E) + (L_{43} + c_a L_{13})\frac{RT}{c_c}\nabla(-c_c) + (L_{44} + c_a L_{14})\frac{RT}{c_a}\nabla(-c_a) \quad (7b)$$

where $\nabla(-h)$ is the hydraulic gradient (dimensionless). Applying the principle of conservation of mass for steady flow, the governing equation for the concentration of species i is

$$\frac{\partial c_i}{\partial t} = -\nabla \cdot J_i - G_i \quad (8)$$

where G_i is a source-sink term denoting the removal rate of species i per unit volume. Solution of this equation gives concentration of species i as a function of time and position.

Special cases of the general coupled flow theory were compared with existing solutions describing the phenomena for consistency (12), such as the diffusion potential equation, the advection dispersion equation, the van't Hoff equation, and the chemical osmosis and ultrafiltration equations. Those comparisons indicate that the developed theory is general and incorporates all flow phenomena as special cases.

A one-dimensional computer model was developed to solve Equation 8 by finite differences as a function of time and position. The electrical and hydraulic gradients are assumed constant. However, the time and position dependencies of the chemical gradients are taken into account. The program allows input of all the required parameters and the application of periodic or continuous electrical gradients. When no externally applied electric field exists, the computer simulation converges to the analytical solution given by Ogata and Banks (17) for contaminant transport by advection and dispersion.

EXPERIMENTAL EVALUATION OF THE THEORY

A laboratory testing program was developed to establish the effectiveness of electro-osmosis in driving water through both partially saturated and fully saturated compacted clay, to evaluate the validity of the theoretically developed equations, and to establish the viability of the electro-kinetic flow barrier concept.

Because the experimental apparatus required for this laboratory testing program could not be adapted from conventional soil testing equipment, a new apparatus was designed, fabricated, and assembled and contains two sets of fixed wall permeameters with five identical permeameters in each set. One set of permeameters is equipped with electrodes, and the other serves as controls to compare the efficiency of the electro-kinetic flow barrier. The schematic diagram of the experimental apparatus is depicted in Figure 6. The compacted clay samples are 1.4 in. in diameter and 4 in. in length. All samples are permeated under identical hydraulic gra-

dients. Each permeameter is equipped with independent measuring devices for inflow and outflow volumes. The voltage across each sample and the electric current passing through can be monitored independently. The voltage measurement electrodes are separated from the electric current supply electrodes so that any adverse effects on voltage measurements arising from electrode reactions during the electro-kinetic process are eliminated. The current anodes are made of platinum mesh to minimize electrode reactions, and the other electrodes are made of stainless steel mesh for economic reasons.

The soil used in this laboratory test program is a gray brown silty clay of moderate plasticity (Unified Soil Classification CH), comes from Livermore, California, and has been used to construct the compacted clay liner of a landfill at Altamont (it is referred to as Altamont soil throughout this paper). The maximum dry density is 110 pcf, and the optimum water content is 17.4 percent as determined by the modified Proctor compaction test. The liquid limit, plastic limit and plasticity index of the soil are 52, 27 and 25 percent, respectively.

Five samples were prepared to establish the effectiveness of electro-osmosis as a means of water transport by kneading compaction at different moisture contents into the permeameters equipped with electrodes. The samples were saturated to different degrees of saturations using back pressures of 1 kg/cm² up to 5 kg/cm² applied in five steps. Different electrical gradients were applied to the samples at each saturation stage, and the respective volume flow rates of water were measured to determine the coefficients of electro-osmotic permeability.

Ten uniform replicate samples were compacted to evaluate the viability of an electro-kinetic flow barrier. All the samples were fully saturated with tap water and then were permeated with sodium chloride solution under identical hydraulic gradients. A periodic electrical gradient of 1 V/cm was applied for 1 hr/day to the group of permeameters equipped with electrodes. One sample from each group was dismantled from the system at an interval of 5 days. Each sample was then sectioned into eight pieces, and complete chemical analyses were performed on the pore fluid extracted from each piece.

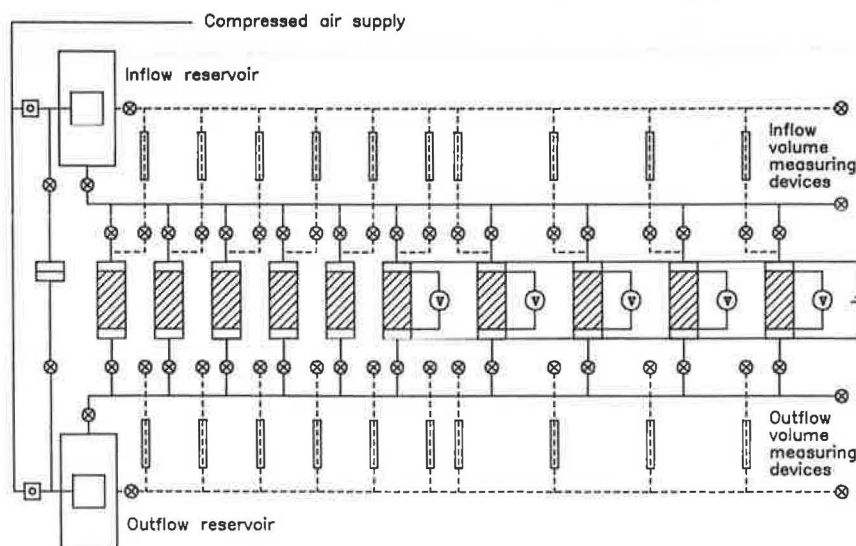


FIGURE 6 Schematic diagram of the experimental apparatus.

RESULTS AND DISCUSSION

The measured coefficients of electro-osmotic permeability of Altamont clay at different stages of back-pressure saturation are plotted against compacted dry densities and compaction moisture contents in Figures 7 and 8, respectively. Here, k_e is within the range of 1×10^{-5} cm²/V sec to 7×10^{-5} cm²/V sec. The decrease in measured k_e at later stages of back-pressure saturation may be due to the growth of micro-organisms that block flow channels through the samples after prolonged permeation. The measured hydraulic conductivities k_h are in the range of 1×10^{-7} cm/sec to 1×10^{-10} cm/sec, depending on the compaction water content and density, and are decreased with time even though the degrees of saturation were increased by the increase of back pressure. The growth of micro-organisms in the samples was evident

after careful examination of the samples at the end of the test. Nonetheless, the experimental results demonstrate the existence of electro-osmotic flow in both partially saturated and fully saturated compacted clay. The k_e measured is in the range of that for most saturated soils studied in earlier investigations (i.e., 1×10^{-5} cm²/V sec to 10×10^{-5} cm²/V sec).

The replicate samples for the electro-kinetic flow barrier study were compacted wet of optimum to 90 percent relative compaction. The hydraulic conductivities of those samples were measured to be on the order of 1×10^{-9} cm/sec. The coefficients of electro-osmotic permeability were measured to be 2×10^{-5} cm²/V sec. The diffusion coefficient of NaCl was measured in a separate experiment on similar samples to be 3×10^{-6} cm²/sec under conditions of standard temperature and pressure. The periodic application of an electro-kinetic flow barrier to the compacted clay samples indicated that the

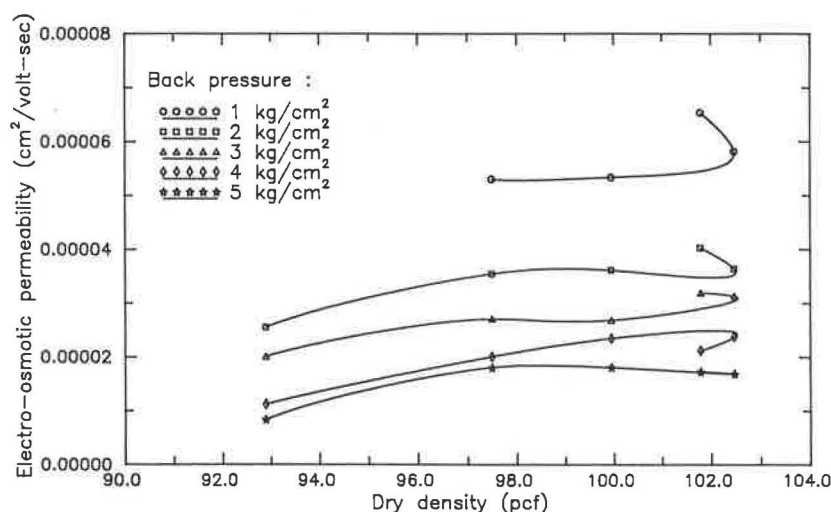


FIGURE 7 The relationship between electro-osmotic permeability and dry density for compacted Altamont clay.

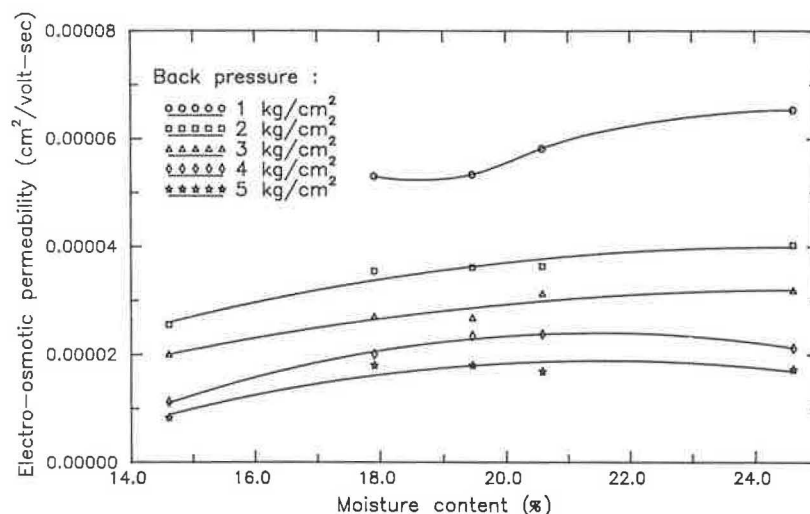


FIGURE 8 The relationship between electro-osmotic permeability and compaction moisture content for Altamont clay.

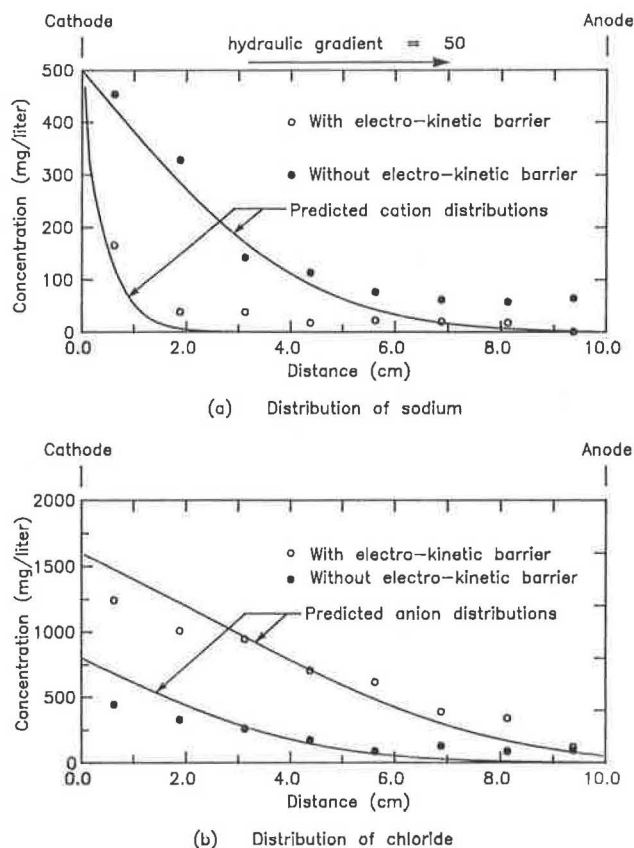


FIGURE 9 Distributions of contaminants after 20 days. Continuous application of hydraulic gradient and periodic (1 hr/day) application of electrical gradient.

migration of sodium ions was halted and the migration of chloride ions was accelerated. In this case, the ionic mobility of the chloride ions exceeded the electro-osmotic counterflow and resulted in a net migration of chloride ions toward the anode. However, the electrical gradient provided a very effective flow barrier to the migration of the cation.

The distributions of contaminants (NaCl) after 20 days of permeation is presented in Figure 9. The curves give the computer model predictions by using the measured parameters as input. The measured concentration profiles are observed to be in good agreement with the predicted profiles given by the theory.

PRACTICAL APPLICATION

The results from this continuing research indicate that electro-osmosis can stop advective and dispersive flows through compacted clay. The cathode would be installed on the landfill side of a clay liner when applied to a landfill. Transport of contaminants by those mechanisms would be prevented by maintaining a small net inward flow (i.e., a greater inward electro-osmotic flow than outward hydraulic flow).

However, the results also show that ionic transport in the electric field would cause migration of anions to the anode underneath the liner. Should those anions pose a risk to the environment, then a collection system would be required for their removal.

Analysis indicates that for values of hydraulic conductivity and electro-osmotic permeability typical of those for compacted clay liner materials (i.e., $k_h \leq 1 \times 10^{-7}$ cm/sec and $k_e \approx 5 \times 10^{-5}$ cm²/V sec) the required sustained DC voltage across a liner of typical thickness (i.e., 3 ft) would be quite low (of the order of a few tenths of a volt). Thus, problems resulting from gas and heat generation and cracking often associated with electro-osmosis when used for clay consolidation may be minor. Because both the voltage and the current density would be low, the power costs would be low.

CONCLUSIONS

1. The existence of electro-osmotic flow in partially saturated and fully saturated compacted clay of the type used in waste landfill liner systems was demonstrated experimentally.

2. The coefficients of electro-osmotic permeability of compacted Altamont clay were measured to be in the range of 1×10^{-5} cm²/V sec to 7×10^{-5} cm²/V sec. Those values are in the range of values for most of soils (3).

3. An electro-kinetic flow barrier such as the one depicted in Figure 2 halted the migration of the cation but accelerated that of the anion under laboratory testing conditions.

4. The developed coupled flow theory reasonably predicted the migration of the contaminant ions under the influences of the hydraulic, electrical, and chemical gradients.

5. An electrical gradient may move some inorganic species in soils much more effectively than a hydraulic gradient.

ACKNOWLEDGMENTS

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