

# A Study of Coupled Electric/Hydraulic Flow in Kaolinite

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Results of a laboratory investigation on the effects of electro-osmosis on the permeability of kaolinite clay are presented. Application of an electric potential to the kaolinite clay increased the permeability of the clay and created a pH gradient across the sample. With application of combined electric and hydraulic gradients, electric gradients were found to contribute significantly to discharges across the sample at low hydraulic gradients. Results presented will enhance understanding as to the feasibility of using electro-osmosis to decontaminate fine-grained soils.

Electro-osmosis is the process by which water flows through a soil mass in response to the application of an electric potential and is the result of the exchangeable nature of the adsorbed cations in clay particles and the dipolar nature of the water molecules. Although the principles of electro-osmosis are more than a century old (1), the applications of the process are quite recent. Since its first application for soil stabilization (2), electro-osmosis has been successfully employed in tasks such as dewatering (3), consolidation (4), and as an aid in pile driving (5).

In principle, soil stabilization or dewatering is accomplished by applying electric current to electrodes driven in the soil mass. As a result of electric treatment, inhomogeneities of ionic concentration develop, and pH changes, and lead to the development of nonuniform voltage gradients and resulting pore water pressures. Esrig (4) studied the effects of electrode geometry on pore water pressures and found that the pore water pressure at a certain point is related to the voltage at that point. Similar studies by other investigators (5-7) indicate a linear relationship between electro-osmotic flow and electric gradients and significant variations of coefficient of electro-osmotic permeability and variations in water content. Olsen (8) found that with increasing overburden pressures in clayey soils, osmotic and electro-osmotic permeabilities play a greater role in controlling flow than does hydraulic permeability. Subsequent studies concentrated on numerical solutions of the governing differential equation for combined electrokinetic and hydrodynamic flow (9,10).

Recent studies focused on electrochemical effects associated with the process of electro-osmosis. Nemec (11), in a study of pH changes in electrochemical cells, found that electrochemical effects in soils are enhanced and controlled by the strong pH gradients developed in the electric potential field and primarily is due to the electrolysis of water. Possible

electrochemical effects include ion exchange, alteration of soil minerals, changes in soil fabric, electrolytic introduction of new species from the electrode decomposition products or external injections, and development of chemical gradients in soil. The pH gradients developed by electro-osmosis affect the solubility of metallic ions (such as iron, magnesium, calcium, and aluminum) and, therefore, control the extent and rate of electrolytic transfer of ions into the soil. Renaud and Probstein (12), in their numerical simulations by using double-layer theory, clearly showed the strength of electro-osmosis in diverting groundwater flow from a potentially hazardous waste site by development of pore water pressure gradients in the soil. The potential use of electro-osmosis to decontaminate fine-grained soils is indicated in those studies.

In light of those developments, an experimental approach was used in the present study to assess relative magnitudes of hydraulic and electro-osmotic permeabilities under application of hydraulic or electric gradients or both and to study the extent of pH changes during the electro-osmotic process. Results are believed to aid in evaluating the feasibility of using electro-osmosis to decontaminate fine-grained soils.

## EXPERIMENTAL SETUP

The electro-osmotic cell (Figure 1) used in the experiment consisted of three 6-in.-diameter chambers made of Plexiglas. The center chamber, 6 in. long, was used to house the soil sample. Each of the two 4-in.-long end chambers contained an opening for pH electrodes with calomel reference and a drainage valve and external burette for measuring the hydraulic gradient. The voids in the two end chambers were filled with crushed stone to exert a confining pressure on the ends of the sample. End plates (8 in.  $\times$  8 in.  $\times$  1/2 in.) were used to seal the outside chambers and to house the circular graphite plates (6 in.  $\times$  1/4 in.), which were used as electrodes.

An LA 300 LAMBDA power supply was used, and Fluke 75 multimeters were also used to measure both voltage and current across the sample. An Expandable Ion-Analyzer EA 940 by Orion Research was used in conjunction with the pH electrodes to determine pH values throughout the experiment.

Tests were conducted on a kaolinite sample, because kaolinite is the least active of the clay minerals with a low colloidal activity; therefore, kaolinite provides a conservative indication of the importance of electro-osmosis in soils. The slurry was prepared, poured into the Plexiglas mold, and then dynamically compacted at its optimum moisture content. [The optimum moisture content and the maximum dry density as

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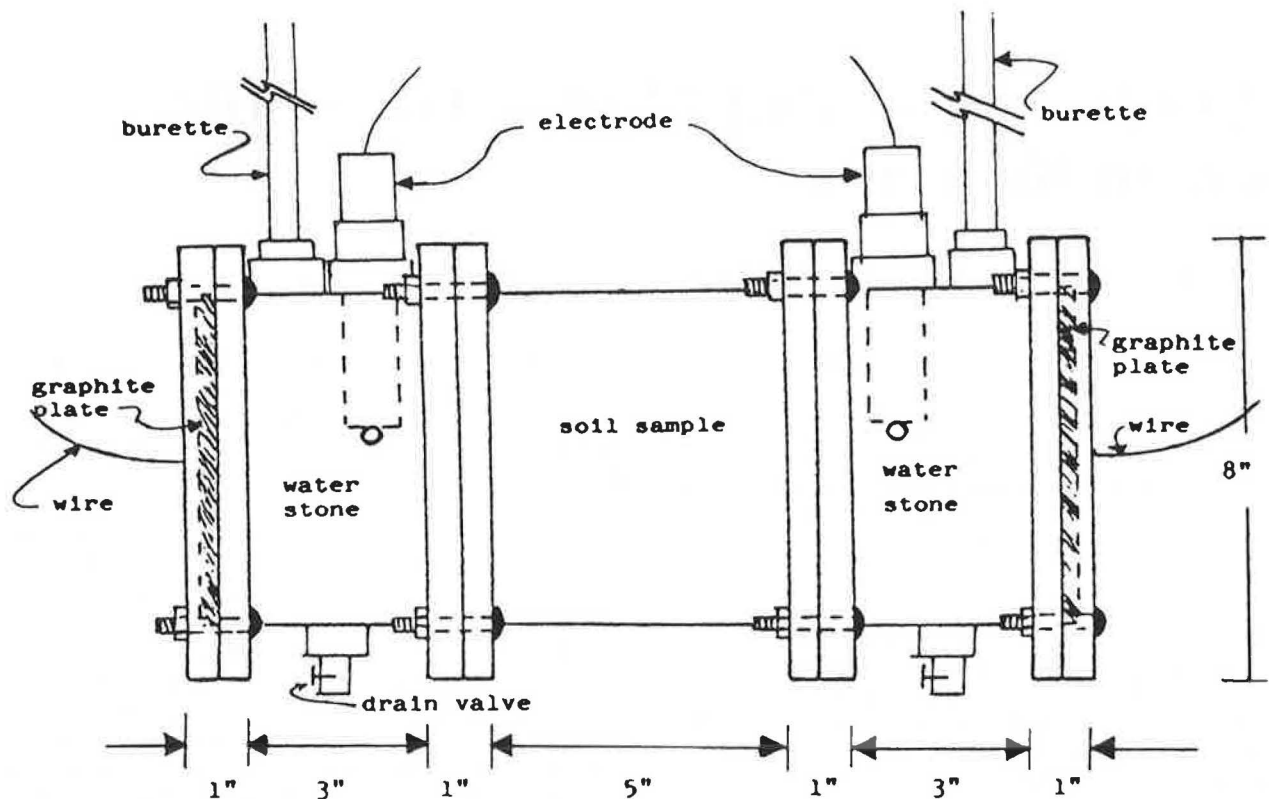


FIGURE 1 Experimental setup (cell description).

determined by the modified Proctor test (ASTM D1557-78) were found to be 23.5 percent and 93.6 pcf, respectively.] The sample was saturated with a back pressure of 3 psi and a hydraulic head of 40 cm. Permeability of the sample was computed to be  $2 \times 10^{-7}$  cm/sec, using the Falling Head method. A flexible wall permeability test was conducted on another kaolinite sample with the same moisture content and dry density to establish the permeability value further and resulted in values of conductivity equal to  $5 \times 10^{-7}$  cm/sec. Those values agree closely with those reported in the literature for kaolinite.

With hydraulic conductivity values established, an electric potential of 20 V was directed to the graphite plates. As a result of hydrolysis, hydrogen bubbles began to appear almost immediately at the cathode. Even at a potential of 5 V, hydrolysis remained a problem and thus made burette readings less reliable. Consequently, volume flux was measured at the anode side of the sample where electrolysis reactions were less significant. The electrical conductivity of the soil is given by the equation

$$K_e = q/(i_e \times A)$$

where

- $q$  = flow passing through the sample as measured at the anode side,
- $i_e$  = electrical gradient equal to the voltage across the sample divided by its length, and
- $A$  = cross-sectional area of the sample.

Further testing of the sample included application of combined hydraulic and electric gradients. Electric potential created electric gradient, and burette levels were manipulated to create hydraulic gradient. The pH/reference electrodes in conjunction with the ion analyzer were used to monitor the pH of the cathode and anode cell waters periodically.

## DISCUSSION OF RESULTS

### Hydraulic Gradient Versus Permeability

The hydraulic permeability was first monitored as the hydraulic gradient was allowed to change. To validate those results, flexible wall tests were conducted at various gradients. Figure 2 presents the results of both testing methods. It can be noticed in Figure 2 that a linear extrapolation of flexible wall test results agrees fairly well with the results obtained from the cell test and that a linear relationship between hydraulic gradient and permeability within the hydraulic gradient ranges tested in flexible wall tests is implied. The permeability, however, remained constant under lower gradients.

### Individual Application of Electric and Hydraulic Gradients

The kaolinite soil specimen was monitored for changes in discharge across the sample in response to time of application of electric and hydraulic gradients. Figure 3 presents discharges versus time when the sample was subjected individ-

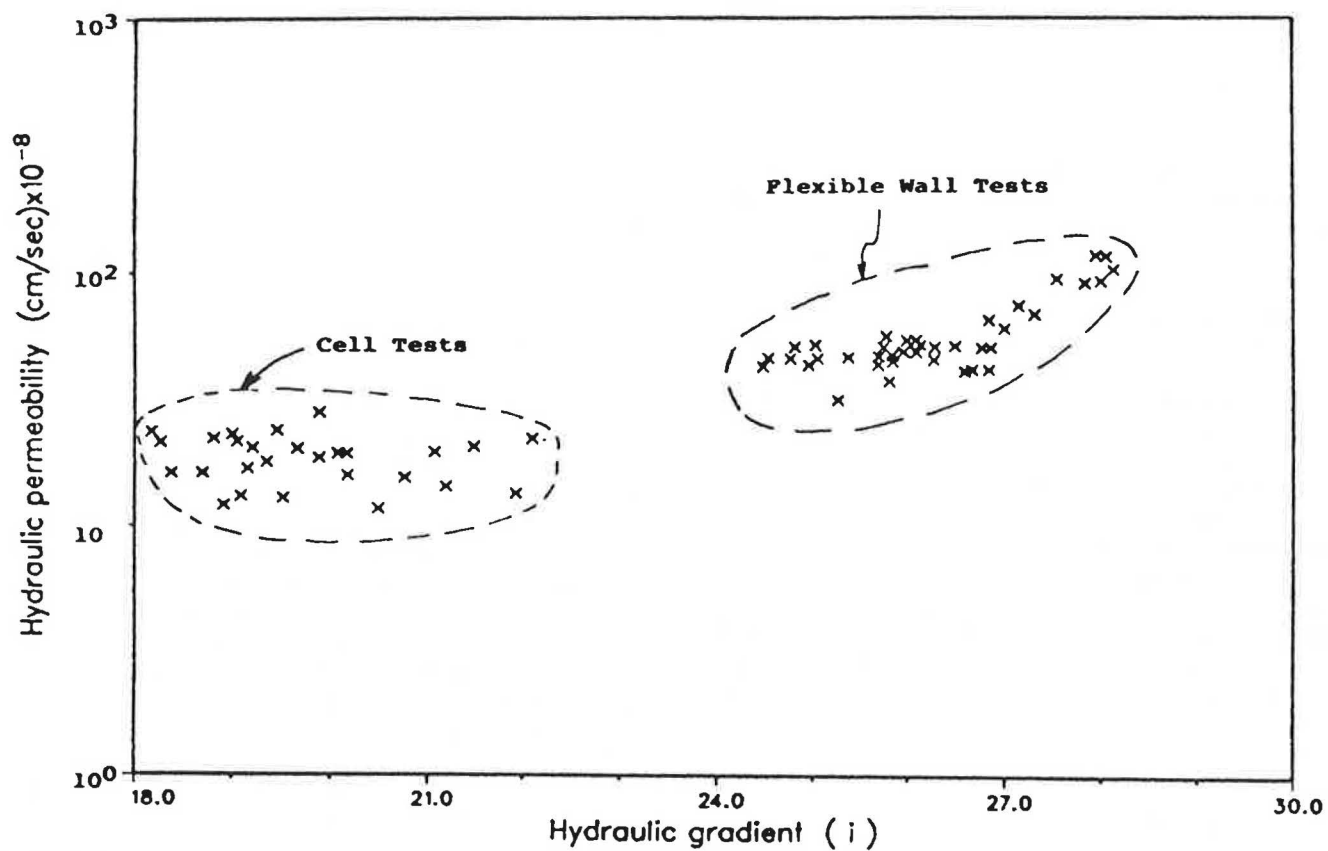


FIGURE 2 Variation of hydraulic permeability with hydraulic gradient.

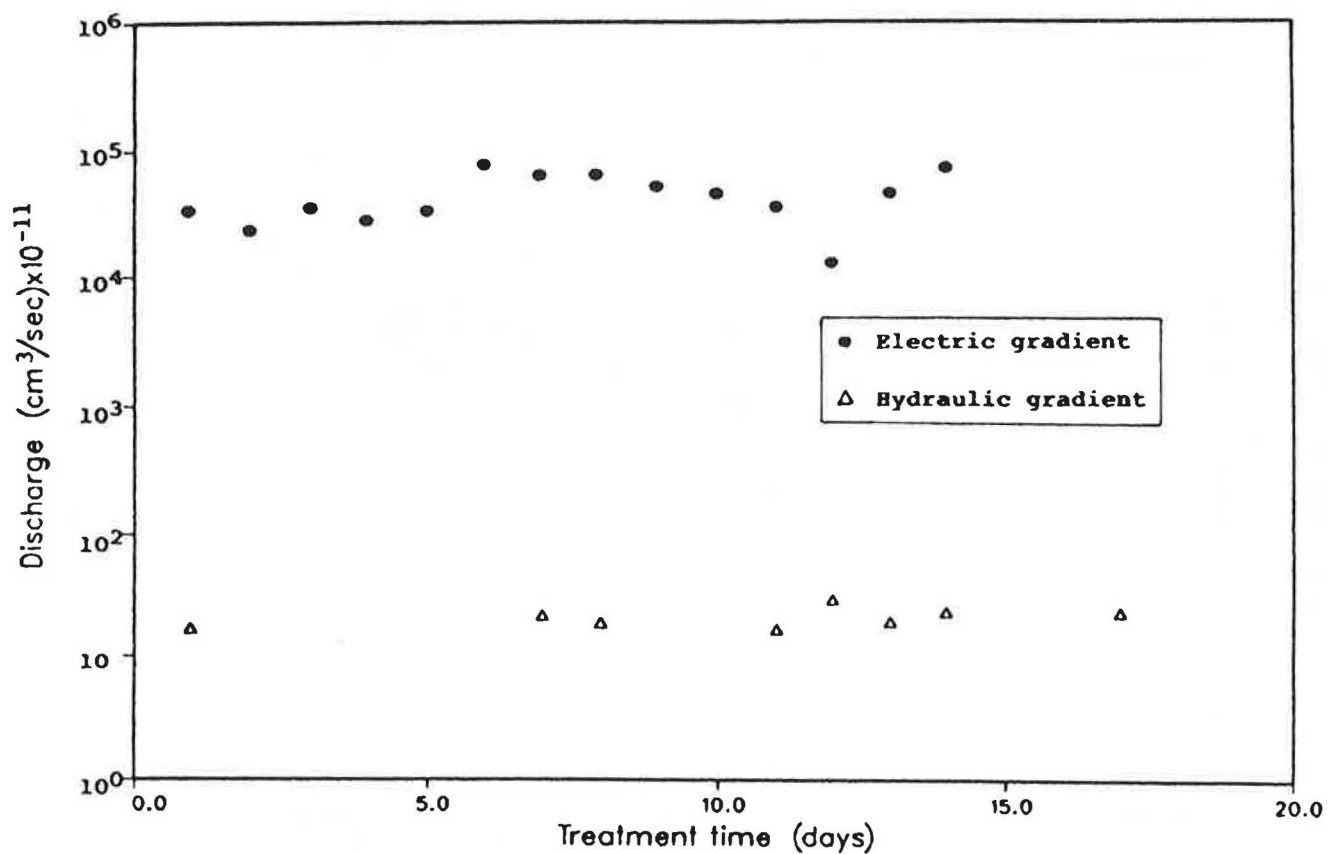


FIGURE 3 Time-dependent discharges caused by electric gradient (0.0025 volts/cm) and hydraulic gradient (20).

ually to hydraulic and electric gradients. As can be seen, an average hydraulic gradient of 20 resulted in discharges on the order of  $10^{-10}$  cm<sup>3</sup>/sec, and an electric gradient of 0.0025 V/cm yielded discharges on the order of  $10^{-7}$  cm<sup>3</sup>/sec. Discharges owing to hydraulic gradient did not indicate any significant fluctuations with time. However, noticeable fluctuations existed in discharges caused by electric gradients and are attributed to nonuniform spatial orientation of moisture gradients in the soil sample. Similar observations were made by Nemec (11), who noticed that in the initial phases of treatment moisture minima develop near anode and cathode and moisture maxima develop near the center of the sample. With elapsing treatment time, Nemec observed the moisture gradients becoming much sharper and their spatial orientation tending to be more uniform. Figure 3 also indicates sudden increases in discharges because of electric gradient at the end of 6 days and 12 days. Those increases with the progression of electro-osmotic treatment may be attributed to the cation exchange capacity of the clay. Clay particles immersed in a liquid partially dissociate the ions adsorbed to the clay and thus make them available for ionic conductivity. Therefore, the increase in discharge may be a result of the time necessary for ions to dissociate from clay particles and enhance conductivity.

#### Combined Application of Electric and Hydraulic Gradients

Figure 4 presents discharges resulting from the combined application of hydraulic gradients and an electric gradient of

0.0025 V/cm. There is a significant increase in discharges, from  $7 \times 10^{-7}$  cm<sup>3</sup>/sec to  $6 \times 10^{-6}$  cm<sup>3</sup>/sec as the hydraulic gradient is increased from 0 to 4. Assuming the increase in discharges is purely due to hydraulic gradients, application of a constant electric potential increased the discharges across the sample by  $7 \times 10^{-7}$  cm<sup>3</sup>/sec. The contribution to discharge by electric gradient is computed to be 70 percent at a hydraulic gradient of 1 and 14 percent at a hydraulic gradient of 4, which undermines the significant contribution of electro-osmosis to the permeability characteristics of soils at low hydraulic gradients.

#### pH Changes During Electro-Osmosis

The pH at the anode and cathode were monitored throughout the experiment. As was expected, the pH of the distilled water decreased at the anode and increased at the cathode. Figures 5 and 6 demonstrate pH changes under two scenarios. Figure 5 represents when the cells were filled with distilled water and an electric field was applied immediately. The pH at the anode decreased from 7 to values close to 5, and the pH at the cathode increased to values approaching 10. Figure 6 represents when the pH of the distilled water was allowed to reach that of kaolinite, which was found to be 5.2, and then the electric potential was applied. The pH at the cathode approached a value of 10, and the pH at the anode increased to approximately 7.

It is worthy to study those results in light of Nemec's observations (11). Nemec noticed a highly nonuniform nature of pH gradients between anode and cathode. His experiments

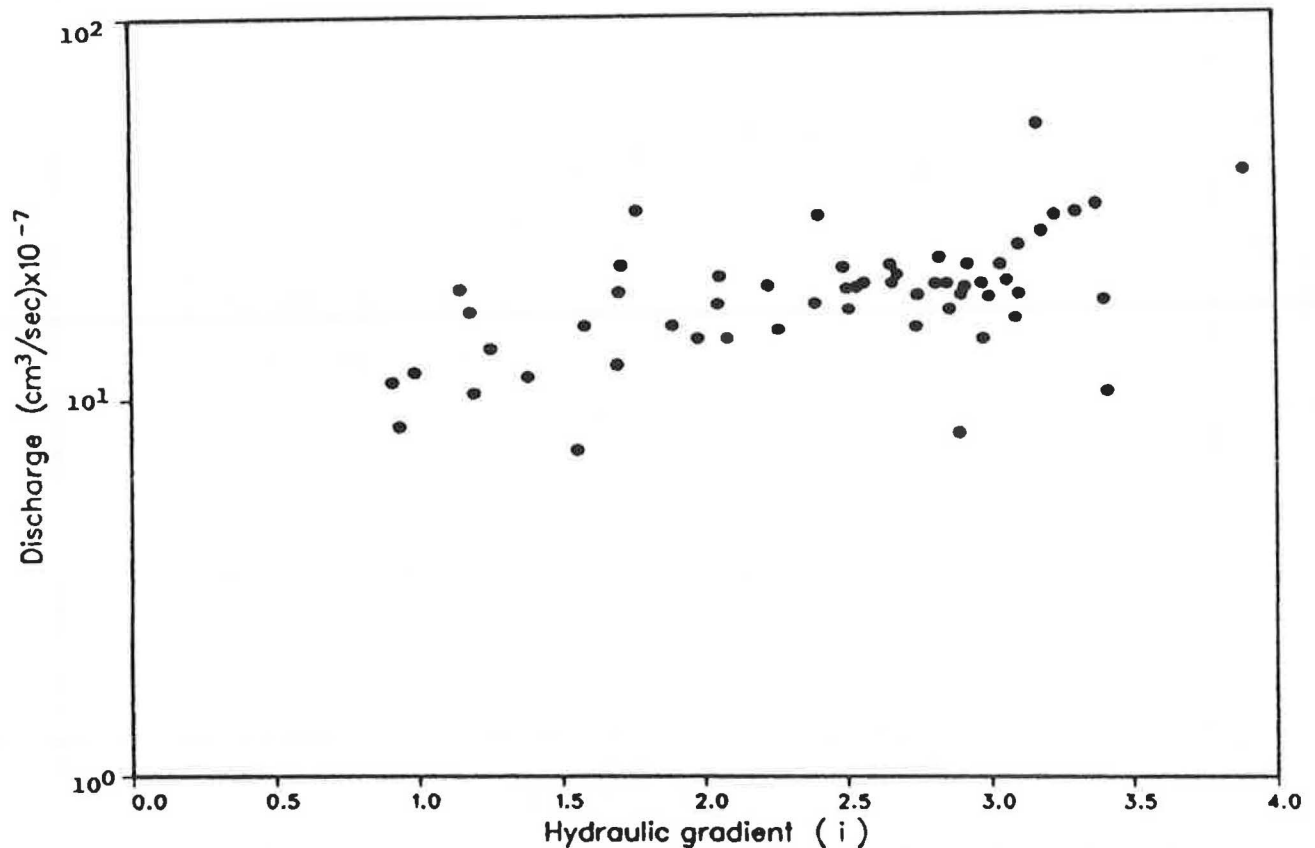


FIGURE 4 Variation of discharges with hydraulic gradient combined with an electric gradient of 0.0025 volts/cm.

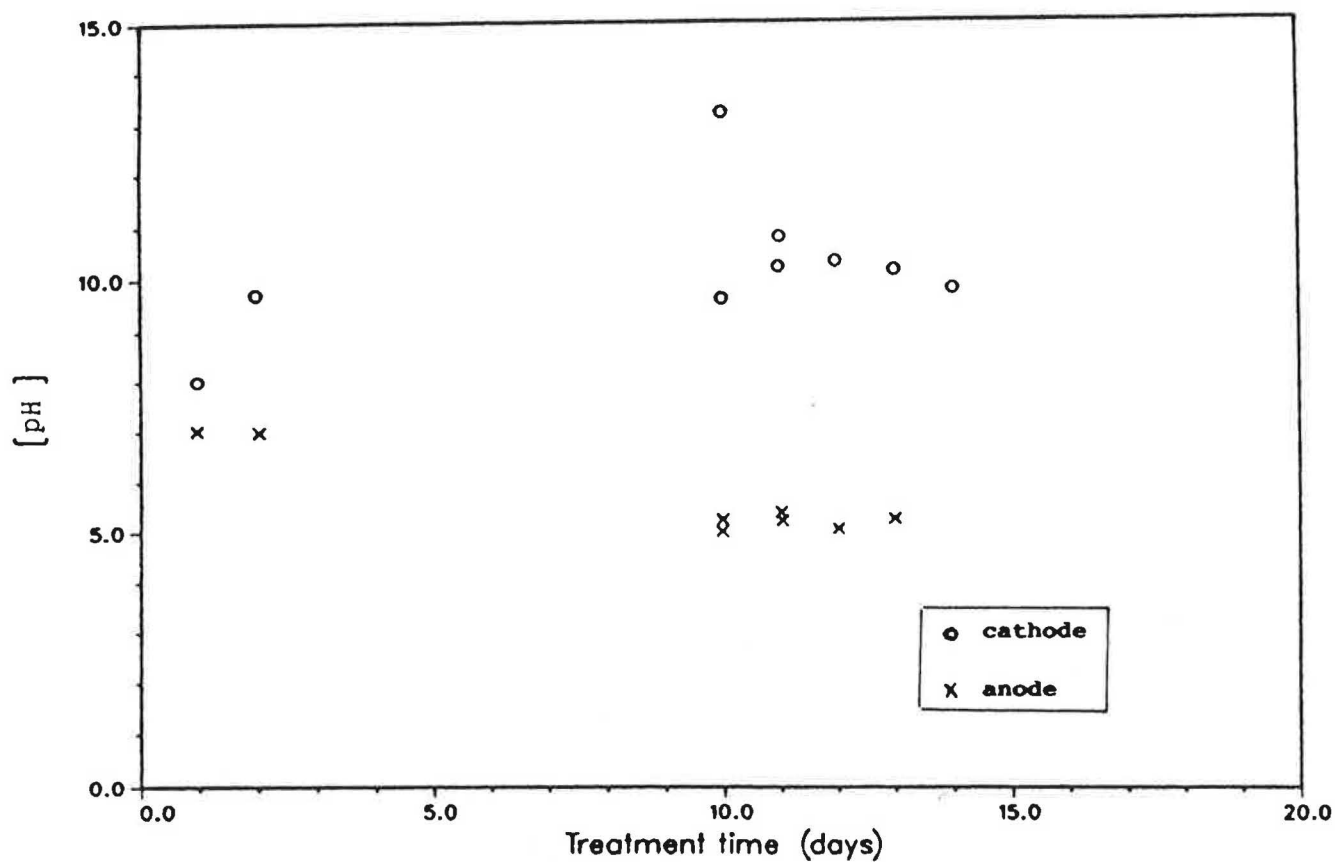


FIGURE 5 Time-dependent variation of pH caused by instantaneous application of electric potential.

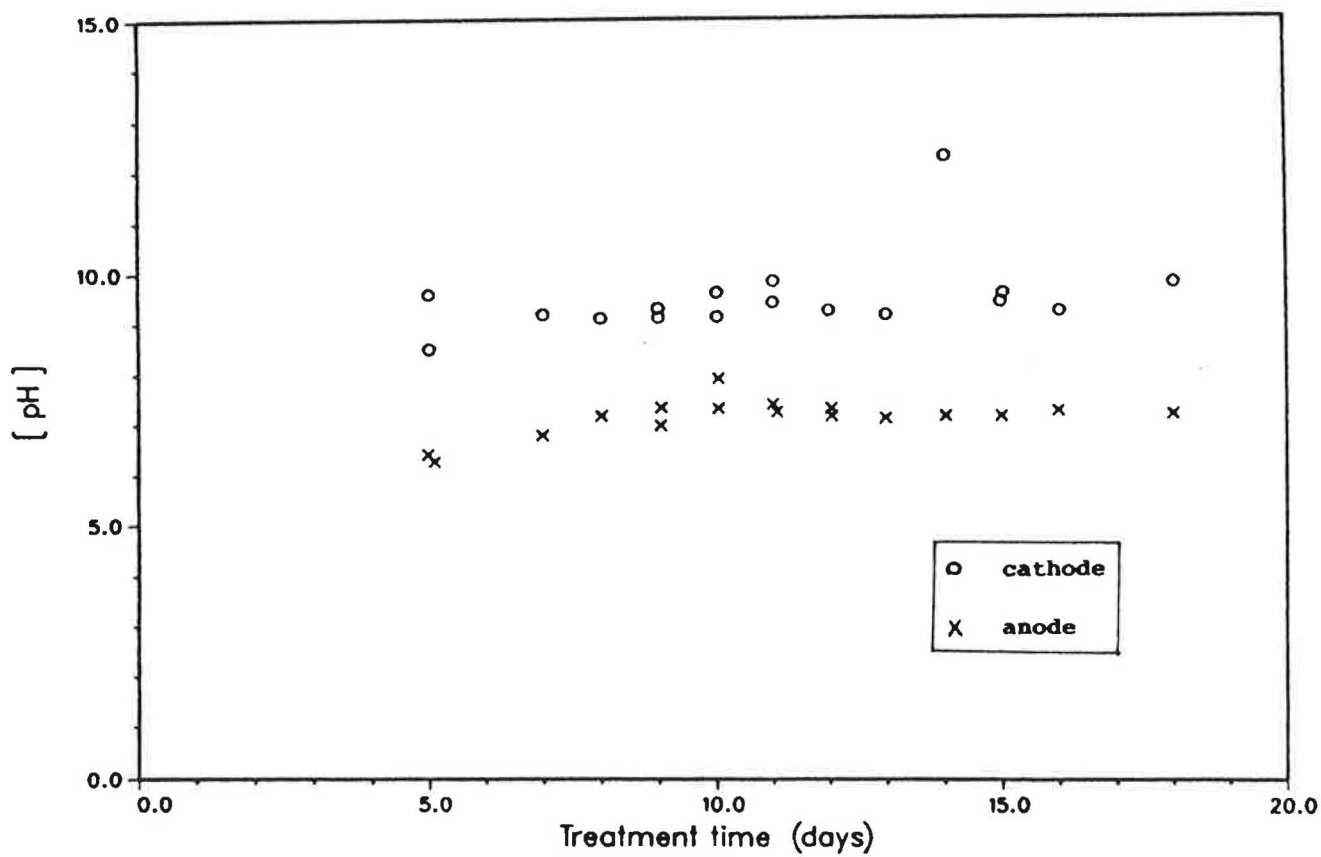


FIGURE 6 Time-dependent variation of pH caused by delayed application of electric potential.

indicated that in a period of 168 hr the pH at the cathode increased consistently from an initial value of 5.23 to 8.99 and the pH at the anode decreased oscillatorily to 4.83. The pH behavior at cathode is generally accepted to be governed by clay deflocculation and hydrogen ion adsorption, but pH behavior at anode is controlled by many electrochemical factors. Kaolinite displays anion-adsorption capacity in acid (anodic) environment. Dissolution of iron at the anode and also presence of amorphous noncrystalline compounds in the soil suspension enhance the anion-exchange capacity of acid soils. All those factors, together with the electrode processes (such as formation of gas bubbles), are thought to produce the changing pattern of pH behavior at anode in Nemec's experiments and in the present experiments.

Results suggest that additional observations in various soils are required for a general interpretation of pH changes during electro-osmotic treatment. Further research is needed to understand fully electrolysis reactions at the electrodes and the degree of transport of the ions caused by their size, mobility, and exchange capacities. The success of electro-osmosis in the decontamination effort of any soil is dependent on the electrochemical nature of the soil and its constituents. Whether or not contaminated soils would release adsorbed pollutants to electro-osmotically driven water is a subject of potential importance.

#### ACKNOWLEDGMENTS

This research was partially supported by the Hazardous Substance Management Research Center. The center is a consortium of five New Jersey universities and an advanced technology center of the New Jersey Commission on Science and Technology.

#### REFERENCES

1. F. F. Reuss. *Memoires Society Imp Naturalistes*, Moscou 2, 1809, pp. 327.
2. L. Casagrande. *Review of Past and Current Work on Electroosmotic Stabilization of Soils*. Harvard Soil Mechanics Series 45, Cambridge, Mass., 1957.
3. C. A. Fetzner. Electro-Osmotic Stabilization of West Branch Dam. *Journal of Soil Mechanics and Foundations Division*, ASCE, 1967, pp. 85–106.
4. M. I. Esrig. Pore Pressures, Consolidation, and Electrokinetics. *Journal of Soil Mechanics and Foundations Division*, ASCE, 1968, pp. 899–920.
5. J. K. Mitchell. In-Place Treatment of Foundation Soils. *Journal of Soil Mechanics and Foundations Division*, ASCE, 1970, pp. 73–107.
6. M. Grey. Fundamental Aspects of Electro-Osmosis in Soils. *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM6, 1967, pp. 209–230.
7. D. V. Morris, S. F. Hillis, and J. A. Caldwell. Improvement of Sensitive Silty Clay by Electro-Osmosis. *Canadian Geotechnical Journal*, Vol. 22, 1985, pp. 17–24.
8. H. W. Olsen. Liquid Movement Through Kaolinite Under Hydraulic, Electric, and Osmotic Gradients. *American Association of Petroleum Geologists*, Vol. 56, 1972, pp. 2022–2028.
9. R. W. Lewis, C. Humpheson, and J. C. Bruch. Applications of Electro-Osmosis to Ground-Water Flow Problems. *Journal of Ground Water*, Vol. 13, 1975, pp. 484–491.
10. J. Bruch. *Electroosmosis in Ground-Water Pollution Control*. Technical Report N.S.F., University of California, Santa Barbara, 1976.
11. H. T. Nemec. Environmental pH Changes in Electrochemical Cell During Electro-Osmotic Stabilization of Soils. *Studia Geotechnica et Mechanica*, Vol. 5, 1983, pp. 13–38.
12. P. C. Renaud and R. F. Probst. Electro-Osmotic Control of Hazardous Wastes. *Journal of Physicochemical Hydrology*, Vol. 9, 1987, pp. 345–360.

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*Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.*