

Electrokinetic Soil Processing in Waste Remediation and Treatment: Synthesis of Available Data

YALCIN B. ACAR AND JIHAD HAMED

Electrokinetic soil processing is an innovative in situ technique to remove contaminants from soils and groundwater. The process is an alternative to conventional processes, with significant economic and technical advantages. This paper provides a comprehensive review of the literature on electrokinetic soil processing. The fundamentals of electrokinetic phenomena in soils and their potential use in waste management are presented. A synthesis of available data on the technique is presented. Engineering implications regarding the current-voltage regime, duration energy requirements, and soil contaminant characteristics are provided. This review indicates that the process can be used efficiently to remove ions from saturated soil deposits.

The need to remove contaminants from soil and groundwater, the high cost of current remediation techniques (\$50 to \$1,500 per cubic yard of soil), and limited resources lead to an everlasting strife to find new, innovative, and cost-effective in situ techniques for removal or separation of contaminants from soils.

The electrokinetic phenomena in soils are envisioned to be useful for removal or separation of organic and inorganic contaminants and radionuclides; for barriers and leak detection systems in clay liners; for diversion schemes for waste plumes; for injection of grouts, microorganisms, and nutrients into subsoil strata; and for in situ generation of hydrogen peroxide for remediation (1–5).

In the last five decades since its first application and use (6), the mechanics of consolidation by electroosmosis has been extensively investigated by geotechnical engineers. However, studies investigating removal of ions from soils by the electrokinetic phenomena are limited, possibly because of insufficient understanding of the electrochemistry associated with the process. The need to use the process in removal and separation of contaminants necessitates a good understanding of electrochemistry and its relation to mechanical behavior. Recent studies at Louisiana State University provided a better understanding of the electrochemistry and demonstrated that the acid front generated by electrolysis reaction at the anode advances and eventually flushes across the specimen by advection, migration, and diffusion (4,7). Hamed et al. (8) demonstrated that the movement of this acid front together with migration and advection of the cations and anions under electrical gradients constitute the mechanisms of removing contaminants from soils. The factors influencing the acid-base profile across the porous medium would significantly

affect the flow, the flow efficiency, and the extent of ion migration and removal in electrokinetic soil processing.

ELECTROKINETIC PHENOMENA IN SOILS

Coupling between electrical, chemical, and hydraulic gradients is responsible for different types of electrokinetic phenomena in soils. These phenomena include electroosmosis, electrophoresis, streaming potential, and sedimentation potential, as shown in Figure 1. Electroosmosis and electrophoresis are the movement of water and particles, respectively, caused by application of a small direct current. Streaming potential and sedimentation potential are the generation of a current by the movement of water under hydraulic potential and movement of particles under gravitational forces, respectively. The effect of coupling becomes more important in fine-grained soils with lower coefficients of permeability.

In electroosmosis, electrodes can be placed in an open- or closed-flow arrangement. Open-flow arrangement constitutes the case when an electrode is sufficiently permeable to admit ingress and egress of water. In the closed-flow arrangement, the electrode is not permeable or porous. Different electrode configurations (open or closed) result in substantial variations in the total matrix potentials across the soil specimen.

Figure 2 shows a schematic diagram of the matrix potentials (pressure head) developed in a soil specimen under constant current (or voltage) conditions. The matrix potential shown in Figure 2 represents the initial conditions and will change with time as the chemistry across the cell changes. In Case I of Figure 2, the water in a reservoir behind the anode would permeate through the soil to displace the pore fluid.

In Case II, where ingress of water is prevented at the anode, negative matrix potentials are generated in the soil, increasing the confining stress proportionally until equilibrium conditions are reached by the flow of water from the anode to the cathode. This arrangement has often been used by geotechnical engineers to consolidate soil deposits. In Case III, positive pore pressures are developed, reducing the confining stress, which may potentially lead to swelling. In Case IV, the matrix potential drops at the anode and increases at the cathode. The water level will rise in the cathode side and drop at the anode side.

The electroosmotic flow rate, q_e , is defined with an empirical relationship,

$$q_e = k_e i_e A = k_i I = \frac{k_e}{\sigma} I \quad (1)$$

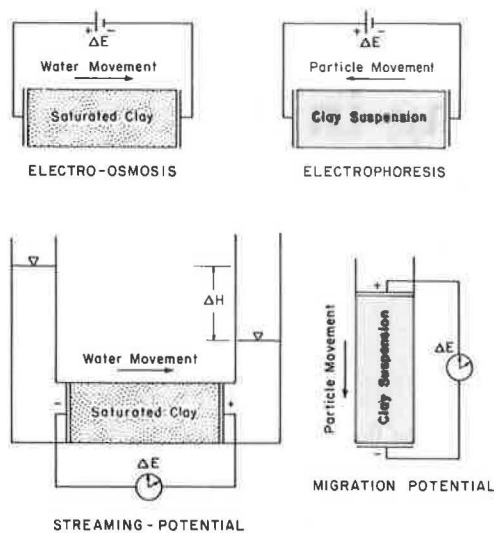


FIGURE 1 Electrokinetic phenomena in soils (9).

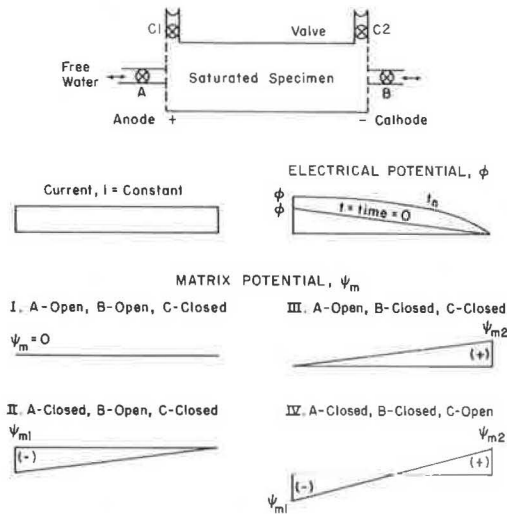


FIGURE 2 Schematic diagram of matrix potential generated with different electrode configurations (4).

where

- k_e = coefficient of electroosmotic permeability ($\text{cm}^2/\text{sec-V}$),
- k_i = electroosmotic water transport efficiency ($\text{cm}^3/\text{amp-sec}$),
- I = current (amp),
- σ = conductivity (siemens/cm),
- i_e = electrical potential gradient (V/cm), and
- A = cross-sectional area (cm^2).

Estimates of electroosmotic flow rates can be made using Equation 1. The values of k_e measured at earlier stages of processing (within hours) vary within one order of magnitude for all soils; 1×10^{-5} to 10×10^{-5} ($\text{cm}^2/\text{V-sec}$), the higher values being at higher water contents. Further processing results in decreases of k_e values.

Figure 3 shows a schematic diagram of one-dimensional laboratory tests in electrokinetic soil processing. The pre-

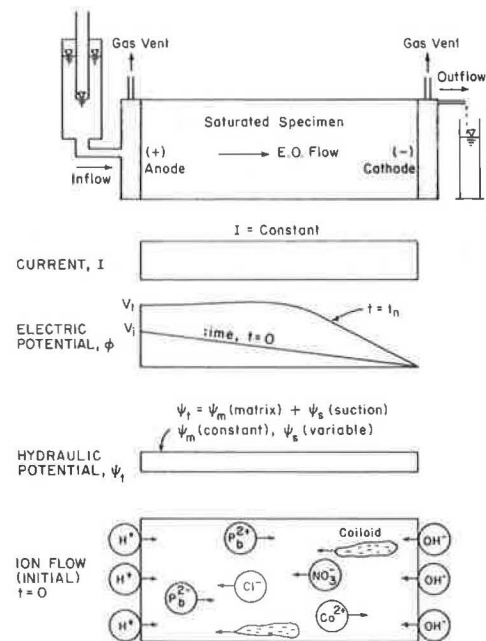


FIGURE 3 Schematic diagram of electrokinetic processing, ion flow, and comparison of flow in clays (8).

vailing electrical gradients and the ion flow are also depicted. A comparison of flow under electrical and hydraulic gradients in clays is also provided. The coefficient of electroosmotic permeability is independent of the size and distribution of pores (fabric) in the soil mass. However, hydraulic conductivity is most affected by the fabric. Therefore, hydraulic conductivity decreases by five to six orders of magnitude (10^{-3} to 10^{-8} cm/sec) from the fine sands to clays. Figure 3 indicates that under equal gradients, electrical potentials in fine-grained soils would result in three orders of magnitude larger flows than hydraulic potentials. Therefore, electroosmosis-induced flow can be considered to be an efficient pumping mechanism in saturated, low-permeability, fine-grained soil.

The efficiency and economics of electroosmotic dewatering is governed by the amount of water transferred per unit charge passed, which is quantified by electroosmotic water transport efficiency, k_i . The parameter k_i may vary from 0 to $1.2 \text{ cm}^3/\text{amp-sec}$, depending on the electrical conductivity of the porous medium. The conductivity changes with water content, cation exchange capacity, and free electrolyte content in the soil and also because of the prevailing chemistry during electrokinetic processing. An approach to quantifying this amount in soil-water-electrolyte systems is proposed by Gray and Mitchell (10). Their study indicated that electroosmotic efficiency decreases with a decrease in water content and an increase in activity of the soil. The electroosmotic dewatering efficiency is independent of variations in electrolyte concentration (sodium ion) for active clays, whereas an increase in electrolytes tends to decrease the efficiency in inactive clays.

Recent studies by Lockhart (11) substantiate the conclusions of Gray and Mitchell (9). The efficiency parameter k_i increased from 0.32 to $1.20 \text{ cm}^3/\text{amps-sec}$ with the decrease of NaCl and HCl concentrations from 10^{-1} to 10^{-3} M ; k_i decreased during an increase in electrical gradients, possibly because of a higher influx of H^+ ions (8). Lockhart (11) found

that a higher electroosmotic efficiency was recorded with H and Cu clays. The efficiency parameter k , changed in the order of $H > Cu > Al > Na > Ca$. Higher voltage gradients were required to initiate flow in Al clays.

POTENTIAL USES OF ELECTROKINETICS IN WASTE MANAGEMENT

The four electrode configurations described earlier could potentially be used in the following ways in waste disposal (4): (a) dewatering of waste sludge slimes, dredged spoil by first concentrating the solid particles using electrophoresis and subsequent consolidation by electroosmosis (2), (b) electroosmotic flow barriers (12), (c) leak detection systems for disposal facilities, (d) injection of grouts to form barriers, (e) provision of nutrients for biodegrading microcosm, (f) in situ generation of reactants such as hydrogen peroxide for cleanup or electrolysis of contaminants, and (g) decontamination of soils and groundwater. Figure 4 shows electrokinetic clay barriers, waste plume diversion schemes, and electroosmotic injection.

In situ remediation methods often necessitate the use of hydraulic charge and recharge wells to permeate the decontaminating liquid or stabilization agent through the soil deposit, or to provide nutrients for the biodegrading microcosm. Although such systems may effectively be used in highly permeable soils, they become inefficient and uneconomical in low-permeability silts and clayey deposits. Electrokinetic soil processing with open electrode configuration could also be used to achieve an efficient seepage and decontamination method in such soils.

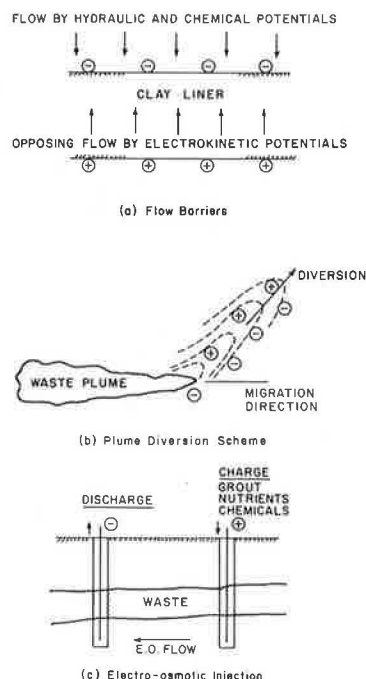


FIGURE 4 Schematic view of different applications of electrokinetic phenomena in remediation (7).

Removal of Contaminants by Electrokinetic Soil Processing

Upon application of low-level direct current (in the order of milliamperes per cm^2 of electrode area) to the saturated porous medium, the following processes occur:

1. The water in the immediate vicinity of electrodes is electrolyzed. An acid front is generated at the anode while a base front is created at the cathode. Acar et al. (4) formalized the development of these fronts. The pH will drop to below 2.0 at the anode and will increase to above 12.0 at the cathode.

2. The acid front will advance across the specimen in time towards the cathode by

- a. Advection of the pore fluid caused by the prevailing electroosmotic flow,
- b. Advection of the pore fluid caused by any hydraulic differences,
- c. Diffusion because of concentration gradients, and
- d. Migration because of the electrical gradients.

Development of these acid and base distributions and movement of ionic species are formalized by Acar et al. (7).

3. The migration, diffusion, and advection will also result in movement of cations and anions to respective electrodes in the porous medium (8,12).

4. The acid advancing across the specimen exchanges with adsorbed cations in the diffuse-double layer, resulting in their release into the pore fluid and advance towards the cathode by advection and diffusion (8).

5. In case the generation of the acid front is not controlled at the anode, the electrolyte concentration inside the porous medium will gradually increase, resulting in increased conductivity in the vicinity of the anode, decrease in electroosmotic flow (8), and a corresponding decrease in bulk flow movement by advection.

6. The anion depletion at the cathode region may lead to an increase in voltage and an increase in energy expenditure during the process. The chemistry at the anode and the cathode should ideally be controlled to achieve continued advection while providing sufficient H^+ ions for desorption of contaminants and solubilization of salts. This is possible either by decreasing the current to levels where pH is at a desirable level or by frequent flushing at both ends by a fluid of controlled pH and chemistry.

Synthesis of Available Data

Studies investigating removal of ions from soils by electroosmosis are rare, possibly because of difficulties in understanding the chemistry. Table 1 (13–20) provides a synthesis and analysis of laboratory studies that reported some form of data related to ion removal from soils. In an early study by Puri and Anand (13), leaching of Na^+ ions was detected in the effluent in electroosmotic consolidation. Puri (21) suggested that in electroosmosis monovalent ions will move faster than divalent ions because of the former's higher dissociation from the clay surface. It is also noted that movement of ions was low at low water contents and significantly increases by an increase in water content.

Jacobs and Mortland (14) demonstrated that Na^+ , K^+ , Mg^{++} , and Ca^{++} ions can be leached out of Wyoming ben-

TABLE 1 ANALYSIS OF LABORATORY DATA REPORTED FOR REMOVAL OF CHEMICALS BY ELECTROKINETICS

| Soil Type/ Chemical | Concentration ($\mu\text{g/g}$) | | Current Density and/or Voltage (mA/cm^2) or [V/cm] | Duration (hr) | Charge $\frac{\text{amp-hr}}{\text{m}^3}$ | Energy kWh/m^3 | Remarks |
|---|--|---|--|----------------------------------|--|---------------------------------|--|
| | Initial | Final | | | | | |
| 1. Puri and Anand (13) High pH Soil - Na^+ | N/A | N/A | 9.3-14.9 [20.0] | 8 (inter- mittent) | N/A | N/A | A Buchner funnel was used in testing. The diameter was 18 in. Cathode is circular brass plate. Anode consists of five cylindrical bars arranged symmetrically along the circumference. Na normality of percolate increased up to 0.6 N. The effluent was 90% NaOH, 10% Na_2CO_3 . |
| 2. Jacobs and Mortland (14) 5% Bentonite/95% Sand Na-Ca Na-Ca-Mg Na-K Na Ca K | .59/.57 .44/.3/.4 .65/.41 0.78-1.11 0.86-1.0 0.79 | 0.0/(N/A) 0.0/(N/A) 0.0/(N/A) 0.0 .26-0.30 0.0 | 0.32-0.64 [N/A] | 10-140 | 2-20 | N/A | 1-D tests. Cylindrical specimens ($D = 0.75$ in., $L = 1$ in.). Circular platinum electrodes. Rate of removal of monovalent ions were directly related to the amount remaining in the specimens. The rate of removal was in the order of $\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$. Na^+ was removed more efficiently than all other ions. Tests were discontinued when most Na^+ was removed. Concentrations reported are in symmetry units which is described as normalized concentrations. |
| 3. Krizek, et al. (15) Slurry/Sediment No. 1 - Na K Ca $\text{NH}_4\text{-N}$ No. 2 - Na K Ca $\text{NH}_4\text{-N}$ | 320 7 65 138 360 15 340 172 | 330 290 640 320 205 160 5800 456 | [0.5] [1.0] | 150 150 | N/A N/A | 20 65 | Slurries ($w = 100 - 142\%$) from discharge pipes and contaminated bottom sediments are tested. Cylindrical 1-D consolidation tests ($D = 14$ cm, $L = 25$ cm). The concentrations are the initial and final effluent values. |
| 4. Hammett (16) Silica Sand - NaCl Heavy Clay | 3% | N/A | 6.25-16.25 [0.6] | 12-20 | N/A | N/A | A 3-D laboratory model. 35 cm by 8 cm, with 5 cm depth. Carbon rods were used as electrodes. After 12 hours, concentration at anode was a third of the cathode side. The data shows movement of ions to respective electrodes. |
| 5. Runnels and Larson (17) Silty Sand - Cu(II) | 617 | 290-543 | 0.01-0.05 [.165] | 24-72 | N/A | N/A | 1-D tests. Cylindrical specimens ($D = 0.75$ in., $L = 6$ in.). Square platinum electrodes (1 in 2). Quartz sand washed with HCl to remove impurities. |
| 6. Renaud and Probst (3) Kaolinite - Acetic Acid | 0.5-1.3 | N/A | 1.47 [1.16] | 6.7 | 328 | 11.5 | 1-D cylindrical specimens. 30 cm in length, 8 cm in width, and 5 cm in depth. Tests were conducted to assess electro-osmotic water transport efficiency. Efficiency increased with increasing concentration of acetic acid. |
| 7. Thompson (18) Ottawa Sand SiO_2 flour Cu (NO_3) $_2$ | 0.01 N | N/A | N/A [25] | 336 | N/A | | A tubular, 3 section test set-up is used. The middle section contained the chemical in solution, the other two sections contained the soil specimen, and contaminant movement into the cathode section was monitored. Transport was a function of pH of the soil. |
| 8. Lageman (19) Peat Pb Cu Pottery Clay - Cu Fine Clayey Sand - Cd | 9000 600 1000 275 | 2400 200 100 40 | N/A N/A N/A N/A | N/A N/A N/A N/A | N/A N/A N/A N/A | 101 101 25 198 | Details of experiments are not available. From a presentation by Lageman (1990), it is understood that 1-D tests are conducted with rectangular electrodes. The pore fluid at anode/cathode compartment was flushed with a conditioning fluid intermittently in order to control the chemistry at the electrodes and sustain the advection in decontamination. |

(continued on next page)

TABLE 1 (continued)

| Soil Type/ Chemical | Concentration ($\mu\text{g/g}$) | | Current Density and/or Voltage (mA/cm^2) or [V/cm] | Duration (hr) | Charge $\frac{\text{amp-hr}}{\text{m}^3}$ | Energy kWh/m^3 | Remarks |
|----------------------------|--|---|---|------------------|--|-----------------------------------|---|
| | Initial | Final | | | | | |
| 8. Lageman (19) (cont.) | | | | | | | |
| Clay - As | 300 | 30 | N/A | N/A | N/A | 207 | |
| Fine Clayey Sand | | | | | | | |
| Cd | 319 | <1 | N/A | N/A | N/A | 54 | |
| Cr | 221 | 20 | | | | | |
| Ni | 227 | 34 | | | | | |
| Pb | 638 | 230 | | | | | |
| Hg | 334 | 110 | | | | | |
| Cu | 570 | 50 | | | | | |
| Zn | 937 | 180 | | | | | |
| River Sludge | | | | | | | |
| Cd | 10 | 5 | N/A | N/A | N/A | 180 | |
| Cu | 143 | 41 | | | | | |
| Pb | 172 | 80 | | | | | |
| Ni | 56 | 5 | | | | | |
| Zn | 901 | 54 | | | | | |
| Cr | 72 | 26 | | | | | |
| Hg | 0.50 | 0.20 | | | | | |
| As | 13 | 4.4 | | | | | |
| 9. Banerjee, et al. (20) | | | | | | | |
| Silty/Silty Clay - Cr | 2460 2156 870 704 642 532 234 148 | 22 12 50 19 22 37 3 10 | N/A [0.1-1.0] | 24-168 | N/A | N/A | Eight cylindrical 1-D tests were conducted on specimens brought from the field ($D = 5.1$ cm, $L = 2.5$ cm to 6.7 cm). Electrodes used were Ni-Cu wire mesh. Hydraulic and electrical potentials were applied simultaneously in order to facilitate removal. |
| 10 Hamed, et al. (8) | | | | | | | |
| Georgia Kaolinite - Pb(II) | 118-145 | 7-40 | 0.037 [≤ 2.5] | 100-1285 | 362-2345 | 29-60 | 1-D tests. Cylindrical specimens ($D = 4$ in., $L = 4$ in. and 8 in.). Circular graphite electrodes. Initial conductivity of specimens 75-86 $\mu\text{S}/\text{cm}$. Rose up to 1000 $\mu\text{S}/\text{cm}$ at the anode, dropped to 22 $\mu\text{S}/\text{cm}$ at the cathode after the process. Pb(II) movement and electrochemistry across the specimens are reported. |
| 11 Mitchell and Yeung (12) | N/A | N/A | N/A | N/A | N/A | N/A | Investigated the feasibility of using electrokinetics to stop migration of contaminants. Electric field slowed down the migration of cations and increased the movement of anions. k_a did not display a marked change by an increase in backpressure, molding water content and dry density. |

tonite by electroosmosis. Figure 5 presents the amount of the ions removed versus the electroosmotic flow in bentonite-sand mixtures. Monovalent ions are removed at a faster rate.

Krizek et al. (15) found that the soluble ions content substantially increased in effluent in electroosmotic consolidation of polluted dredgings, while they also noted that heavy metals were not found in the effluent during electroosmosis. Hammet's tests demonstrated that Na^+ ions move toward the cathode, whereas Cl^- and SO_3^{2-} ions move toward the anode.

This study demonstrated that ions could be removed from soils by the process.

Shmakina (22) notes that the method has been used in the Soviet Union since the early 1970s as a method for concentrating metals and exploring for minerals in deep soil deposits. He mentioned its use in prospecting for Cu, Ni, Co, and Au. A porous ceramic probe with HNO_3 is placed at the cathode. This acid prevents precipitation of ions at the cathode. Placement of this acid probe is specifically necessary if the base

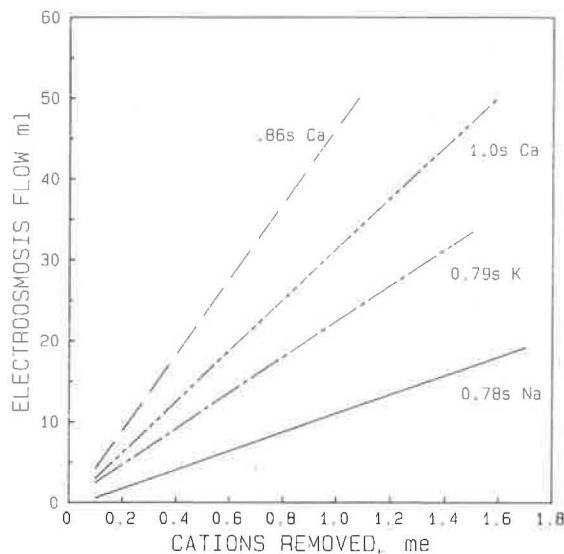


FIGURE 5 Cation removal versus electroosmotic flow (s represents symmetry units, an equivalent concentration) (14).

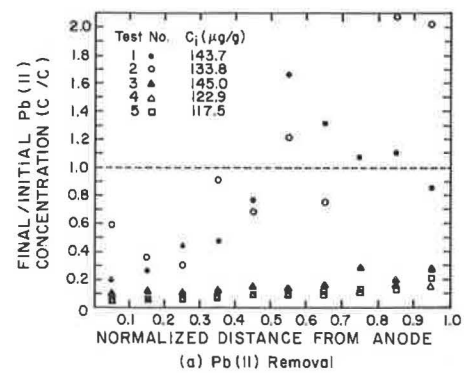
generated at the cathode is not neutralized. The migrating ions are extracted with this probe. The quantity of the extracted metal at the cathode and the rate of accumulation are correlated with the composition of the ore and the distance of the sampling locations to the ores.

The potential of the technique in waste remediation resulted in initiation of several recent studies. Runnels and Larson (17) have investigated the potential use of electromigration to remove contaminants from groundwater. The amount of copper removed increased with processing time (total charge passed). However, the current efficiency decreased as the processing time increased, possibly because of the increase in conductivity as noted by Hamed et al. (8).

Renauld and Probststein (3) investigated the change in the electroosmotic water transport efficiency of kaolinite specimens loaded with acetic acid and sodium chloride. This study indicated that the current efficiency increased with higher concentrations of this weak, organic acid. This implies that when the deposit is contaminated with organic acids, the efficiency of electrokinetic soil processing may increase.

A better understanding of the chemistry in electrokinetic soil processing is achieved by studies at Louisiana State University. Putnam (23) investigated the development of acid/base distributions in electroosmosis. Acar et al. (4,24) present the theory for acid-base distributions in electroosmosis and compare the predictions of this model with the results of the tests conducted by Putnam (23). A good correlation was noted. This theory and the model presented by Acar et al. (24) describe the movement of different species in electrokinetics. The study demonstrates the movement of the acid front from the anode to the cathode by advection and diffusion and provides the fundamental basis of the chemistry developed during the process.

A comprehensive subsequent study on removal of Pb(II) from kaolinite is reported by Hamed et al. (8). Kaolinite specimens were loaded with Pb(II) at 118 to 145 $\mu\text{g/g}$ of dry kaolinite, below the cation exchange capacity of this mineral. As shown in Figure 6, electroosmosis removed 75 to 95 per-



(a) Pb(II) Removal

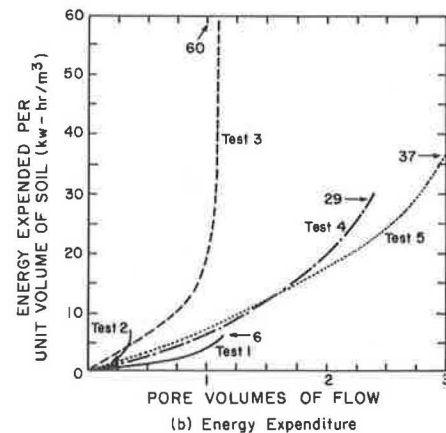


FIGURE 6 Pb(II) removal from kaolinite and corresponding energy expenditure (8).

cent of Pb(II) across the test specimens. The study clearly demonstrated that the removal was caused by migration and advection of the acid front generated at the anode by the primary electrolysis reaction. The energy used in the study to decontaminate the specimens was 29 to 60 kW-hr per cubic meter of soil processed. This study also demonstrates and explains the complicated electrochemistry associated with the process. An interesting finding of this study is electroplating of the removed Pb(II) at the carbon cathode.

Other laboratory studies conducted by Lageman (19) and Banerjee et al. (20) further substantiate the applicability of the technique to a wide range of contaminants and soils. High removal rates were achieved in soils contaminated with Cr, Cd, Ni, Pb, Hg, Cu, Zn, Hg, and As.

Although these laboratory studies display the feasibility of using electroosmosis to decontaminate soils, limited field studies are available. Table 2 presents a synthesis of field tests investigating or reporting some form of chemical removal from soils. Segall et al. (25) present the chemical characteristics of the water accumulated at the electrodes in electroosmotic dewatering of dredged soil. Their study indicated that

1. There was a significant increase in heavy metals and organic materials in electroosmosis effluent above that recorded in the original leachate. The concentrations of zinc, lead, mercury, and arsenic were especially high.

2. Total organic carbon content of the effluent was two orders of magnitude higher than the original leachate. It is postulated that highly alkaline conditions resulted in disso-

TABLE 2 SYNTHESIS OF FIELD DATA REPORTED FOR REMOVAL OF CHEMICALS BY ELECTROKINETICS

| Soil Type/ Chemical | Concentration ($\mu\text{g/g}$) | | Current Density and/or Voltage (mA/cm^2) or [V/cm] | Duration (hr) | Energy kWh/m^3 | Remarks |
|---|---|--|--|-----------------------------|----------------------------|---|
| | Initial | Final | | | | |
| 1. Puri and Anand (13) High pH Soil - NaOH | 4.8 | 2.8 | 1.35 [2.44] | 6 | N/A | An area of 4.5 m x 4.5 m was first trenched all around, 1.05 m in depth and 0.30 m in width. Anode and cathode were laid horizontally within this area. Anode was a shot of iron, 0.9 m x 1.8 m laid at top. Cathode was a perforated iron tube, 0.10 cm in diameter and 1.8 m long laid at 0.3 m depth. The concentrations reported are for the exchangeable Na in the top 7.5 cm of the soil. |
| 2. Case and Cutshall (26) Alluvial deposits - ^{90}Sr | 8 | 50 | 0.3 [0.05] | 5,352 | N/A | An area of 11 m by 5 m was investigated. 1.7 m stainless steel rods were driven in an arc-plus-center point array. The arc consisting of 25 anodes and a central cathode. The concentrations reported are for the effluent in a monitoring well. |
| 3. Segall, et al. (25) Dredged Material Cd, Zn, Pb, As, Fe Na K OH^- HCO_3^- Organic Nitrogen Ammonia Nitrogen TOC | <1 6150 350 0 0 4 67 3 | 0.2-20 16300 510 5950 979 15 128 2000 | [0.01-1.0] | N/A | N/A | Concentrations noted are for the effluent in electro-osmotic consolidation of dredged material compared to that of water leached specimens. The distance between electrodes is 3-5 m. |
| 4. Lageman (19) Sandy Clay - Zn Heavy Clay - As Dredged Sediment Pb Cu | 70-5120 90-385 340-500 35-1150 | 30-4470 20-240 90-300 15-580 | 0.8 [0.4-0.2] 0.4 [0.4-0.2] N/A | 1344 1200 430 | 287 270 N/A | An area of 15 m by 6 m studied. Contamination depth: 0.40 m. Temperature rose from 12°C to 40°C. Conductivity increased from 2000 $\mu\text{S/cm}$ to 4000 $\mu\text{S/cm}$. Voltage gradient decreased. 2 cathodes (vertical) at 0.5 m depth. 33 anodes (vertical), 3 rows at 1.0 m depth. Distances: cathode-anode = 1.5 m; anode-anode = 1.5 m. An area of 10 m by 10 m was studied within a depth of 2 m. Cathodes (vertical), 2 rows: 1 row at 0.5 m depth; 1 row at 1.5 m depth. 36 anodes (vertical), 3 rows at 2 m depth; 2 rows of 14; 1 row of 8. Distances: cathode-anode = 3 m; anode-anode = 1.5 m. Temperature rose from 7°C to 50°C. An area of 70 m by 3 m was studied to a depth of 0.2 m to 0.5 m. Cathode is laid horizontal, anode (vertical). Cathode-anode 3 m; anode-anode 2 m. |
| 5. Banerjee, et al. (20) Silt/Silty Clay - Cr | N/A | N/A | 2-4 [0.2-0.24] | <72 | N/A | Nine field experiments were conducted in an array of electrodes. Combined Hydraulic and electrical potentials were applied. Steel reinforcing bars were used and replaced after each experiment. The results are inconclusive. |

lution and release of the organic material. Pesticides came out at the cathode.

Case and Cutshall (26) described a field study for control of radionuclide migration in soil by application of DC current. This study demonstrates that it is possible to migrate radionuclides with the technique. Lageman (19) reported the re-

sults of field studies conducted in the Netherlands to decontaminate soils by electrokinetic soil processing. Figure 7 shows a schematic diagram of the reported field process. An electrode fluid conditioning and purification system is noted. The conditioning (such as buffering of the effluent to avoid precipitation of removed ions) is for the control of the influent-effluent chemistry, whereas purification (such as ion exchange

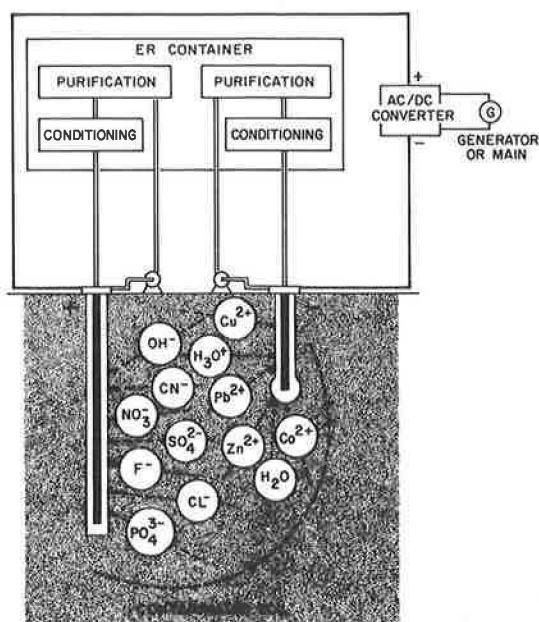


FIGURE 7 Schematic diagram of the field system reported by Lagemann (19).

resin columns) is for removing any excess ions in the effluent. A recent study investigating the application of the process to decontaminate a chromium site was reported by Banerjee et al. (20). The laboratory studies reported by Hamnet (16), Runnels and Larson (17), Lageman (19), and Hamed et al. (8) together with the pilot-scale field studies of Lageman (19) display the feasibility of using the process in site remediation. Further pilot-scale studies are necessary to improve the technology and establish the field remediation scheme for different site conditions and chemistry.

Engineering Implications

This review of the present state of knowledge on electrokinetic soil remediation resulted in the following implications:

1. Type of soil. The process results in movement of ions in sandy to clayey soils. It seems that there will not be any major restriction on the type of soil. High-water-content, low-activity soils at low-pore-fluid electrolyte concentrations will result in the most efficient conditions.
2. Type of contaminants. All available data are on ionic forms of inorganic cations, some radionuclides (e.g., ^{90}Sr), and acetic acid. Recent laboratory studies at Louisiana State University demonstrate that it is feasible to remove adsorbed phenol (1,000 ppm) from kaolinite by this technique. Furthermore, release of pesticides and increase in total organic carbon content in the effluent in electroosmotic consolidation indicate that the method has potential in removing organic contaminants. Data regarding acid-base distributions indicate that salts (such as PbO) may also dissolve and migrate because of the advancing acid front. However, there is no factual data to validate this hypothesis. Laboratory data demonstrate that while cations move towards the cathode, anions move towards the anode (8,12).

3. Concentration of contaminants. There exists factual data demonstrating removal at levels of up to 10,000 ppm of Cu(II) and 5,000 ppm of Pb(II) . As concentrations of contaminants (ionic) increase, removal should be mostly by migration as advection (electroosmotic flow) will substantially decrease. At lower concentrations, both advection and migration will be acting to remove the contaminants.

4. Mixture of contaminants. The data indicate that the process also works on a mixture of contaminants (19). The removal amount is related to both the concentration and the mobility of the specific ion under electrical gradients. Monovalent ions may be removed at a higher rate than higher valence ions.

5. Saturation. Mitchell and Yeung (12) present data regarding the effect of saturation on k_e , which did not change significantly in specimens compacted at different molding moisture contents. These data suggest that the process may be applicable in partially saturated soils.

6. Depths. The review of literature indicates that there should not be a depth limitation in the process beyond practical problems that may be encountered.

7. Type of electrodes. Inert electrodes such as graphite, carbon, or platinum should be used to avoid introducing secondary corrosion products into the soil mass. Open electrodes allow control of influent and effluent chemistry. It should be recognized that some ions will be electroplated on the cathode. Cost-effective electrodes need to be devised and manufactured.

8. Electrode configuration. The electrodes can be placed horizontally or vertically. The electrical potential gradients generated because of different electrode arrangements affect the flow conditions and hence the removal efficiency. The gradients significantly change by electrode configurations and the depth of individual electrodes relative to the counter electrode. A hexagonal network of electrodes with a central cathode and all electrodes at the same depth is hypothesized to be an efficient configuration. However, it is necessary to design the most efficient electrode configuration by considering the coupling of electrical, hydraulic, and chemical gradients.

9. Electrode spacing. Spacing will depend on the type and level of contamination and the selected current-voltage regime. A substantial decrease in efficiency of the process may result because of increases in temperature when higher voltage gradients are generated. A spacing that generates a potential gradient in the order of 1 V/cm is preferred. The electrode spacing generally is up to 3 m.

10. Current level. The current level reported is in the order of milliamperes per square centimeter of electrode area (0.01 to 1.0 mA/cm²). It can be varied to monitor the influent pH level at the anode and to control the rate of decontamination.

11. Duration. Process should be continued until the desired removal is achieved. The remediation duration is site specific. Acid front generated at the anode will advance to the cathode. In general, in fine-grained soils it is expected for the treatment to continue a number of months. When it is desired to reduce the duration by increasing the electrical potential gradient, the efficiency of the process decreases.

12. Effluent-influent chemistry. It is possible to control the efficiency by controlling the pH and the chemistry of the effluent and the influent. Two alternatives are available: (a) decreasing the current to a level where fewer H^+ ions are

generated, and (b) flushing the anode and cathode by a fluid of known chemistry.

13. Chemistry subsequent to the process. The porous medium becomes acidic on completion of the process. The medium returns to original conditions by diffusion of the acidic pore fluid to the surrounding medium. Cathode effluents may require postchemical treatments (such as ion exchange resin columns for inorganic contaminants) to achieve concentration of contaminants. Cathodes may necessitate treatment with acid to remove the electroplated contaminants, if found necessary.

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