Electroosmosis technology for soil remediation: laboratory results, field trial, and economic modeling

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Abstract

Laboratory experiments have demonstrated electroosmosis to be very effective for removing a water-soluble organic from low-permeability silty clay soil from a DuPont site in the eastern U.S. Concentrations were reduced below detection levels by electroosmotically driving 1.5 pore volumes of water through the soil. Neutralizing the fluid at the anode with lime or sodium hydroxide significantly increased the efficiency of the process. An in-situ field trial is under way. A simple economic analysis is presented, which estimates the cost of applying the technology for this application full-scale to be $78 m^{-3} ($63 per cubic yard) for a three-year remediation project. © 1997 Elsevier Science B.V.

Keywords: Electroosmosis technology; Field trial; Economic modeling

1. Introduction

A DuPont site in the eastern U.S. is contaminated with a proprietary water-soluble solvent used in a manufacturing operation until the early 1970's. Dissolved solvent is still present in the soil above the water table because of the low hydraulic conductivity of the soil (about 1×10^{-5} cm s^{-1}). The low conductivity also makes the soil not amenable to conventional means of in-situ remediation. Therefore, a laboratory and engineering analysis program was undertaken to determine whether electroosmosis might be a practical means of in-situ treatment.

Electroosmosis has been used for several decades to dewater and stabilize soft soils at construction sites [1]. More recently, many laboratory investigations have employed electroosmosis to remove organic species from clay, including phenol, acetic acid, gasoline, and trichloroethylene [2-5]. The similar technology of electromigration, suitable for removing charged contaminants such as heavy metals, has been applied in full-scale remediation projects in Europe [6].

2. Experimental methods

Laboratory experiments utilized 6-in.-wide Plexiglas tanks 18 in. long with an electrode compartment at each end (Fig. 1). Soil was packed to a depth of ≈ 4 in. A constant current of 40 mA was driven through the soil, representing 0.3 mA cm^{-2}.

The contaminant is a proprietary semivolatile, highly polar compound fully miscible with water. As it has little tendency to adsorb to soil, it is a good candidate for removal by electroosmosis. Its initial concentration in the soil was about 8 mg kg^{-1}. The initial soil pH was ≈ 10 owing to caustic spills that had previously occurred in the area from which the soil was taken. The soil comprised about 40% clay, 30% silt, and 30% sand.

In most experiments, the cathode compartment was a panel consisting of galvanized steel screen and a piece of corrugated plastic wrapped in a geotextile. The corrugated plastic provided a conduit so that effluent water could be easily siphoned from the top of the panel.

The anode compartment was either a cavity filled with coke particles or a panel consisting of an iridium-oxide-coated expanded titanium mesh sandwiched between two pieces of perforated corrugated plastic, then wrapped in a geotextile. This design keeps the electrode material separated from the soil so that base treatment can be as effective as possible in preventing the soil from becoming too acidic.

In all but one experiment, water with added caustic or lime was circulated through the anode compartment by pumping from an external reservoir to the bottom of the compartment and siphoning from the top to return the liquid to the reservoir. In the remaining experiment, the anode fluid was not neutralized. Instead, addition of water to the anode was controlled by a level probe.

Make-up water was typically added to the anode reservoir daily. Experiments in which NaOH was the sole neutralizing agent utilized a pH controller to maintain pH 10 with addition of a 6 N solution. In the experiments using lime (CaO) as a neutralizing agent, this was added daily along with the make-up water and supplementary NaOH, if desired.

The catholyte was not neutralized in any experiments. Effluent solution was continuously siphoned from the top of the cathode compartment. The pH and the concentrations
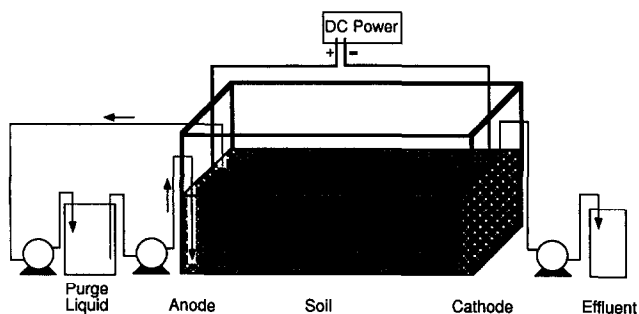

Fig. 1. Schematic diagram of the laboratory apparatus for electroosmosis experiments.

Table 1
Summary of experimental parameters

Soil dimensions		
	Length (distance between electrodes)	41 cm
	Depth	9 cm
	Width	15 cm
Current		40 mA
Current density		0.3 mA cm^{-2}
Applied potential		40–150 V
Potential gradient (avg)		1–4 V cm^{-1}
Electroosmotic flow rate (avg)		100–400 ml per day
Electroosmotic permeability (avg)		0.5–2.5 × 10^{-5} cm^2 V^{-1} s^{-1}

of contaminant, sodium, and calcium were measured for each collection period, typically daily. At the end of each experiment, soil samples were taken at five or ten locations between the anode and cathode to determine pH, moisture content, and contaminant concentration. The contaminant concentration was determined by GC/MS analysis with a detection limit of 0.5 ppm. Calcium and sodium concentrations were determined by ICP analysis.

A summary of the experimental parameters is provided in Table 1.

3. Experimental results

3.1. Flow rate

The lowest flow rate was observed in the experiment without pH control (Fig. 2). Neutralizing the anode with lime significantly improved the results. In both cases, the initial electroosmotic permeability was between 1×10^{-9} and 1.5×10^{-9} m^2 V^{-1} s^{-1}.
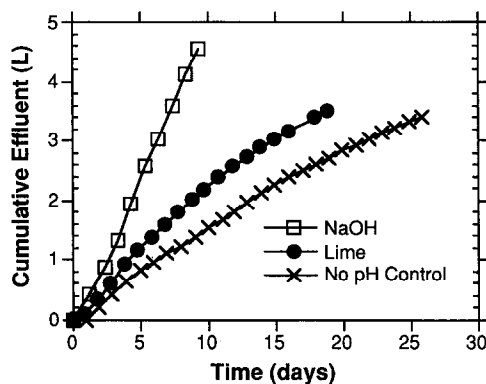

Fig. 2. Cumulative volume of effluent vs. time for three experiments utilizing different pH control strategies.

However, the flow rates dropped to about half their initial values by the time 1.5 pore volumes of flow had been driven through the soil.

In contrast, neutralizing with NaOH provided a consistently high flow rate throughout the experiment. The observed electroosmotic permeability was about 2.5×10^{-9} m^2 V^{-1} s^{-1}.

Not shown in Fig. 2 are the results of two experiments utilizing a mixture of NaOH and lime. Use of a 10% NaOH/90% lime mixture resulted in a nearly constant daily flow rate approximately equal to the initial performance of the 100% lime experiment. A 30% NaOH/70% lime mixture produced results almost identical with those for the 100% NaOH experiment.

Using 30% or more NaOH produced the highest electroosmotic flow rates, but also produced a high degree of soil swelling—approximately 20%, particularly near the anode. This could pose a problem in the field, so it might be desirable to restrict the amount of NaOH utilized. A conservative approach would be to use a 10% NaOH/90% lime mixture, providing a nearly constant electroosmotic permeability of 1.2×10^{-9} m^2 V^{-1} s^{-1}.

3.2. Contaminant removal

The contaminant concentration in the effluent fluid was initially around 50 ppm and remained approximately constant until about 1500 ml (0.75 pore volumes) of water had been collected as effluent. The concentration declined until it was undetectable after about 3000 ml of flow (1.5 pore volumes). This was found for all experiments, irrespective of flow rate. The cumulative amount of contaminant collected is plotted vs cumulative effluent volume in Fig. 3. After electroosmosis treatment, the soil contained no measurable contaminant.
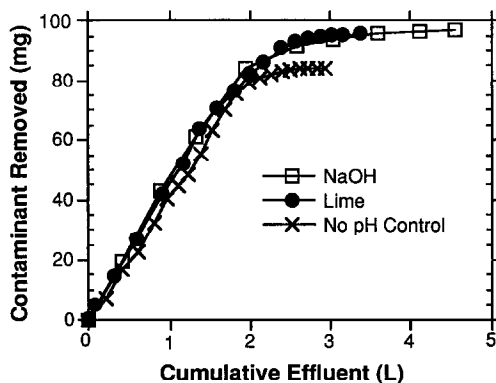

Fig. 3. Cumulative contaminant removed vs. cumulative volume of effluent collected for three experiments utilizing different pH control strategies.
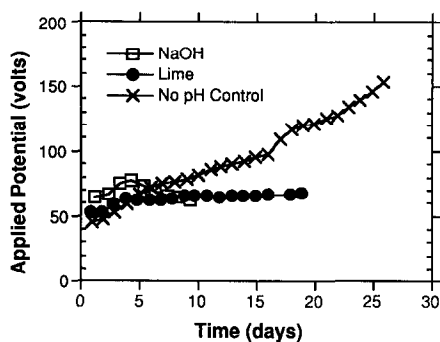
Fig. 4. Applied electrical potential vs. time for three experiments utilizing different pH control strategies. In all cases, the electrical current was maintained at 40 mA throughout the experiment.

3.3. Applied potential

All methods of pH control at the anode were successful in maintaining the applied potential in a fairly narrow range, corresponding to an overall electrical conductivity of about 0.02 S m^{-1}. However, without pH control, the electrical conductivity of the soil decreased throughout the experiment. By the end, the experiment was consuming twice the electrical power of the pH controlled experiments (Fig. 4).

3.4. Soil pH

Soil pH after electroosmosis was markedly affected by the pH control strategy (Fig. 5). Without neutralization at the anode, soil pH was between 3 and 5 throughout the soil except near the cathode, where the pH was about 11. Neutralizing the anode with lime increased the predominant soil pH to between 4 and 7, accounting for the higher flow rate in this experiment. Neutralizing with NaOH further increased the predominant soil pH to between 7 and 8, accounting for the still higher flow rate in this experiment. It is interesting that, even with anode neutralization, the predominant soil pH was significantly lower than the pH of 10–12 maintained in the water of the anode compartment.
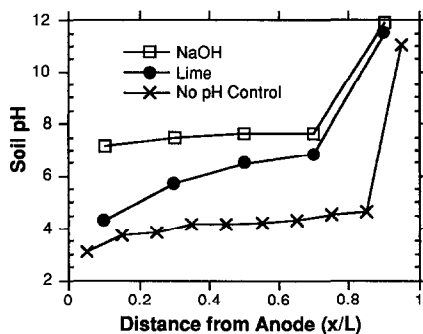

Fig. 5. Soil pH profile after electroosmosis treatment for three experiments.
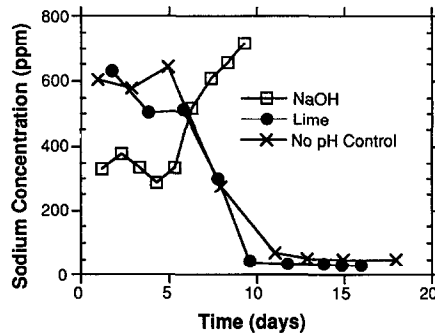
Fig. 6. Sodium concentration in effluent vs. time for three experiments.

3.5. Sodium and calcium in effluent

As one might expect, the experiments with no sodium replenishment showed the soil being depleted of sodium (Fig. 6). What is interesting is that breakthrough occurred at one pore volume of flow. Similarly, in the experiment that received sodium hydroxide at the anode, it took one pore volume of flow for the added sodium to reach the cathode. These results suggest that sodium was largely restricted to the double layer of the soil pores instead of being spread throughout the free pore water. Otherwise, one would expect sodium to have migrated much faster through the soil, since the ionic mobility of sodium, even correcting for tortuosity and porosity effects, is about ten times higher than the electroosmotic permeability [7].

Likewise, in the experiment with added lime, the calcium concentration in the effluent increased sharply after about one pore volume of flow (Fig. 7). Once again, this suggests that added calcium is confined to the double layer in the soil pores. Calcium removal in the experiment without pH control was slow and fairly constant. Adding sodium hydroxide completely stopped the removal of calcium from the soil, probably by virtue of the higher soil pH in that experiment.
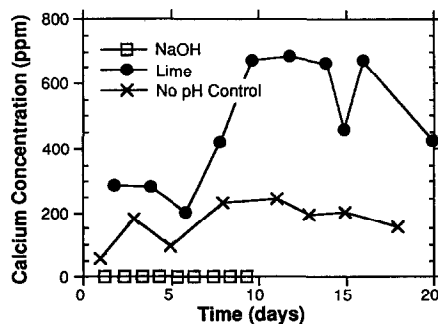

Fig. 7. Calcium concentration in effluent vs. time for three experiments.

4. Field trial

An in-situ field experiment will soon be fully operational in a 10-ft. by 30-ft. region of the contaminated area from which the soil for the laboratory experiments was taken. Electrode panels 18 in. wide, similar in design to those used in the laboratory experiments, have been inserted into the ground to an average depth of 14 feet. The 30-ft. row of anode panels consisted of 16 panels inserted side-by-side with an average gap of 5 inches between them. The 30-ft. row of cathode panels consisted of 15 panels with an average gap of 6 in.

The means of installing the electrode panels was similar to that for installing sheet pile. First, an expendable drive shoe was placed on a 20-ft. long hollow steel casing with outer dimensions of 4-in. × 21-in. The drive shoe prevented soil from entering the casing cavity while the casing was driven into the soil with a vibratory hammer. After driving to the desired depth, the hammer was unclamped from the top of the casing, and the electrode panel was inserted into the cavity. The hammer was then clamped onto the casing again and the casing pulled out of the ground, leaving the drive shoe and electrode panel behind.

DC power will be supplied by a rectifier capable of delivering 65 A at 120 V. The anode and cathode fluid reservoirs are 250-gallon tanks. A constant fluid level will be maintained in the anode panels by continuously pumping fluid from the anode tank to the bottom of the anode panels and siphoning off fluid from near the top of the panels, returning it to the anode tank. Fluid will be continuously pumped from near the top of the cathode panels to the cathode tank.

5. Scale-up considerations

It cannot be assumed that, on a per-soil-volume-basis, the electrical energy expended in a laboratory electroosmosis experiment on a contaminated soil will be representative of that required to remediate the actual site. That may or may not be true, as the following analysis indicates.

Consider the case where a large area is to be remediated using alternating rows of anodes and cathodes. Assuming steady state operation, uniform soil properties, and a uniform electric field within the treatment region, the power input per soil volume can be calculated for an anode-cathode pair to be

$$\frac{\text{Power}}{\text{Soil volume}} = \frac{(\Delta V)^2/R}{DXL} = \frac{\sigma(\Delta V)^2}{L^2} \tag{1}$$

where ΔV is the applied electrical potential, R is the electrical resistance between the anode row and the cathode row, σ is the soil electrical conductivity, D is the treatment depth, X is the length of the electrode row, and L is the anode–cathode separation distance. The electrical field energy per soil volume (E) is the product of the above expression and the duration T of the remediation project

$$E = \frac{\sigma(\Delta V)^2 T}{L^2} \tag{2}$$

The parameters ΔV, T, and L are not independent. An expression more helpful than Eq. (2) may be derived by considering how these parameters are related. The remediation time may be expressed as

$$T = \frac{\text{Required purge water volume}}{\text{Electroosmotic flow rate}} \tag{3}$$

For the soil between an individual anode–cathode row pair

$$\text{Required purge water volume} = \alpha nDXL \tag{4}$$

where α is the required number of pore volumes adequately to clean the soil and n is the soil porosity (v/v). The electroosmotic flow rate through the soil between an anode–cathode row pair is given by

$$Q = k_e DX(\Delta V)/L \tag{5}$$

where k_e is the electroosmotic permeability.

Combining Eqs. (3)–(5) yields an expression for the remediation time in terms of the applied voltage and the anode–cathode separation distance

$$T = \frac{\alpha nL^2}{k_e(\Delta V)} \tag{6}$$

This may be rearranged to express the required applied potential to complete the remediation project within the desired time

$$\Delta V = \frac{\alpha nL^2}{k_e T} \tag{7}$$

Combining Eqs. (2) and (7) yields an alternative expression for the amount of electrical field energy required to remediate a site

$$E = \frac{\sigma \alpha^2 n^2}{k_e^2} \left(\frac{L^2}{T} \right) \tag{8}$$

This expression helps to explain why the electrical field energy required for a field project may be very different from that measured in the laboratory. Presumably, the soil electrical conductivity (σ), required number of pore volumes (α), soil porosity (n), and electroosmotic permeability (k_e) will be the same in both cases. However, the remaining parameters—the anode–cathode separation distance (L) and the project duration (T)—will almost certainly be much larger in the field application. Eq. (8) teaches that, unless the ratio L^2/T is preserved, the energy expenditure will be different.

6. Cost modeling

The goal of the economic analysis presented here is to determine the anode–cathode separation distance that minimizes the cost of a remediation project. This analysis is limited to cases where the remediation of a large area is to be accomplished by means of alternating rows of vertical anodes and cathodes.

For present purposes, the costs of an electroosmotic remediation project are divided into two categories: those costs that are significantly affected by the anode–cathode separation distance and those that are not. The two major costs that are affected by the anode–cathode spacing are electricity and the electrode system. The electricity cost is affected because, for a given remediation time, the anode–cathode spacing will determine the magnitude of the applied potential required to accomplish the remediation project. This effect is shown in Eq. (8). The electrode system cost is affected simply because the number of electrodes varies inversely with the anode–cathode spacing. Other costs—for the rectifier and power control system, the fluid handling system, treating the contaminant after removing it from the soil, mobilizing electrode installation equipment, supervision, maintenance, etc.—are treated as fixed costs in this analysis. The magnitude of these costs will vary with each remediation project, but may be expected to be in the vicinity of \$15 per cubic meter of soil (\$11 per cubic yard).

The cost of electricity may be expressed as

$$C_e = P_e E \tag{9}$$

where C_e is the electrical energy cost per soil volume and P_e is the price of electricity.

Combining Eqs. (8) and (9) yields

$$C_e = \frac{P_e \sigma \alpha^2 n^2 L^2}{k_e^2 T} \tag{10}$$

When electrodes in the form of panels or trenches are to be used, the number of electrodes will vary inversely with the anode–cathode separation distance. Therefore, the cost of the electrode system (exclusive of mobilization costs) can be approximated as

$$C_E = P_E / L \tag{11}$$

where P_E is the average cost per area of a planar electrode and its installation.

Combining Eqs. (10) and (11) yields the sum of the electricity and electrode costs per soil volume for electroosmotic soil remediation using planar electrodes

$$C_e + C_E = \frac{P_e \sigma \alpha^2 n^2 L^2}{k_e^2 T} + \frac{P_E}{L} \tag{12}$$

To minimize this sum, the expression is differentiated with respect to L and set to zero, yielding an expression that can be solved to find the optimum anode–cathode spacing

$$L = \left[\frac{P_E k_e^2 T}{2 P_e \sigma \alpha^2 n^2} \right]^{1/3} \tag{13}$$

Substituting Eq. (13) into Eq. (7) yields the optimum applied potential

$$\Delta V = \left[\frac{P_E^2 k_e}{4 P_e^2 \sigma^2 \alpha n T} \right]^{1/3} \tag{14}$$
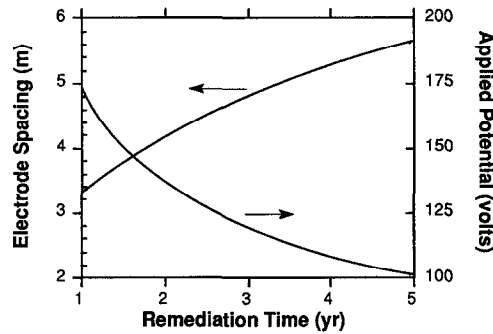
Fig. 8. The effect of the remediation time on the optimum electrode spacing and applied potential.

The resulting cost of electricity and electrodes is found by combining Eqs. (12) and (13)

$$C_e + C_E = \left(\frac{27}{4}\right)^{1/3}\left[\frac{P_E^2 P_e \sigma \alpha^2 n^2}{k_e^2 T}\right]^{1/3} \qquad (15)$$

The laboratory experiments provide the following set of parameter values for the application under study: $k_e = 1.2 \times 10^{-9}$ m^2 V^{-1} s^{-1}; $\sigma = 0.025$ S m^{-1}; $n = 0.36$; $\alpha = 1.5$. The cost of materials and installation for the electrode panels, exclusive of the fixed cost of equipment mobilization, was about \$200 m^{-2}. The cost of electricity at the site is \$0.05 kWh^{-1}. With these values for P_E and P_e, the optimum electrode spacing increases from 3.3 m for a 1 year remediation project to 5.6 m for a 5 year project (Fig. 8). The optimum applied potential decreases from 173 V for a 1 year project to 101 V for a 5 year project (Fig. 8). Assuming fixed costs of \$15 m^{-3}, the total remediation cost decreases from \$106 m^{-3} for a 1 year project to \$68 m^{-3} for a 5 year project (Fig. 9). The fixed costs include the cost of lime and/or caustic for neutralizing the anode compartment. In the above examples, the charge input required is 3500 A h m^{-3}, so the amount of base needed is 130 eq m^{-3}. At 18–40 g eq^{-1}, the maximum amount of base required would be 12 lb m^{-3}. At \$0.05 lb^{-1}, the cost of caustic and lime would be less than \$0.60 m^{-3}.
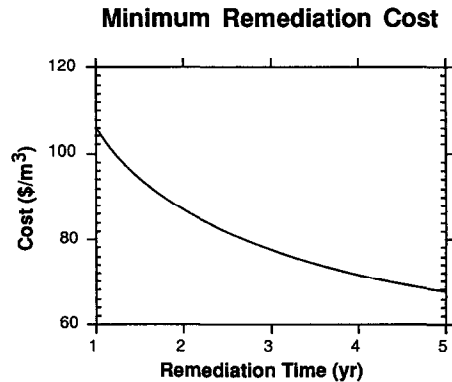
Minimum Remediation Cost

Fig. 9. The effect of the remediation time on total cost.

7. Conclusions

Electroosmosis is an effective process for removing water-soluble organics from clay-rich soils, particularly when the anode is properly buffered. When key parameters determined from laboratory experiments are combined with the desired remediation time and the prices of required supplies and services, a simple methodology can be followed to determine the anode–cathode spacing and the applied electrical potential that will minimize the cost of the project. With sufficient time to accomplish the project, it appears that the costs can be favorable compared with the costs of excavation and ex situ treatment.

8. Symbols

α	Required number of soil pore volumes
σ	Soil electrical conductivity
ΔV	Applied electrical potential
C_e	Cost of electricity
C_E	Cost of a planar electrode system
D	Treatment region depth
k_e	Electroosmotic permeability
L	Anode–cathode spacing
P_e	Price of electricity
P_E	Price of planar electrodes
Q	Flow rate
T	Remediation time
X	Treatment region width
Y	Treatment region length

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