

# Influence of current density and pH on electrokinetics

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## Abstract

Two series of electrokinetic experiments have been conducted on kaolinite to study the effects of current density and influent pH on electrokinetic processing. In the first series, eleven tests were conducted at different current densities ranging from 0.123 mA/cm<sup>2</sup> (10 mA) to 0.615 mA/cm<sup>2</sup> (50 mA) using distilled water as the influent. In the second series, ten tests were conducted with constant current densities of 0.123 mA/cm<sup>2</sup> (10 mA) and at different influent pH of 2, 4, 8, 10 and 12. In all cases, the soil was initially mixed with the influent. Results from the first series showed that the flow rate increases as the current density increases. On the other hand, increasing the current density reduced the time needed for the acid front generated at the anode to reach the cathode. In tests with different influent pH, results indicated a gradual increase in electro-osmotic flow between pH of 2 to 10 and a sharp increase from 10 to 12. We also noticed that pH of the cathode compartment increased at the early stage of testing and then started to decrease with time for tests with influent pH ranging from 2 to 10. At the same time, the flow rate started to decrease with time. However, this was not the case for tests with influent pH of 12. The pH of the cathode compartment remained high and the flow rate was constant throughout the testing period. Increasing current density resulted in a slight increase in the energy expenditure for the same number of pore volume. However, increasing the influent pH resulted in a large reduction of the energy expenditure for the same number of pore volume. All tests have been duplicated and similar results were achieved. © 1997 Elsevier Science B.V.

*Keywords:* Kaolinite; Current density; Influent pH

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## 1. Introduction

As management of hazardous materials gains increased attention in the United States, new and more effective technologies are being sought to immobilize and/or destroy the wastes, either in situ for previously disposed wastes or at the waste generation site.

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Remediation of contaminated soils and groundwater at present is an expensive proposition. Electrokinetic remediation is one of the most promising methods and has been shown to be quite effective in removing both organic and inorganic contaminants.

Studies investigating removal of ions from soils by electro-osmosis are rare, possibly due to difficulties in understanding the chemistry. A comprehensive study on removal of Pb(II) from kaolinite is reported by Hamed et al. (1991). The study clearly demonstrated that the removal was due to migration and advection of the acid front generated at the anode by the primary electrolysis reaction. This study also demonstrates and explains the complicated electrochemistry associated with the process. An interesting finding of this study is electroplating of heavy metals at the carbon cathode.

Further studies involving removal of Cd(II) and Cr(III) by Hamed (1990) show similar results. Other laboratory studies conducted by Lageman (1989) further substantiate the applicability of the technique to a wide range of inorganic contaminants and soils.

A study by Bruell et al. (1992) has shown that removal of benzene and toluene from clay by electrokinetics is possible. They also conclude that it appears to be a viable remediation technology for removal of gasoline range hydrocarbons and chlorinated solvents from fine grained soils. Under the influence of an applied DC voltage, metal cations migrate to the cathode, and the water molecules are dragged with them (Mitchell, 1976). Thus, the dissolved organic compounds in water will also be expected to migrate to the cathode under the influence of the electric field. Reduction of water at the cathode would result in the simultaneous evolution of hydrogen gas and formation of hydroxyl ions. Thus, an increase in the pH should be anticipated at the cathode.

Further study (Probstein and Shapiro, 1990) demonstrated the potential of the technology in removing organic compounds from contaminated soils. Probstein and Hicks (1993) report high removal rates of phenol and acetic acid from kaolinite, up to 95%. They report that acetic acid removal deviated from linearity due to transient behavior in zeta potential, electric field distribution, or both. A lower flow rate for acetic acid compared to phenol is due to the acidic environment (low pH). The acidic environment neutralizes the negative charge on the soil leading to a lower electro-osmotic flow. Acar et al. (1992) have also reported phenol removal of 85–95% from kaolinite.

Case and Cutshall (1979) describe a field study for control of radionuclide migration in soil by application of DC current. It was demonstrated that it is possible to migrate radionuclides by electrokinetic soil processing.

Other bench-scale laboratory data demonstrate the feasibility of removing Pb, Cr, Cd, Ni, Cu, Zn, As, phenol, TCE and BTEX compounds from fine grained soils. The details of the process and available results are presented by Hamed (1990) and Acar and Hamed (1991).

All the studies have suggested or shown that electrokinetic remediation is most effective with some form of enhancement to aid removal of contaminants. Metal removal in particular is seen to be severely hindered by the pH variation in the soil which develops upon application of an electric field. Precipitation of metals in the soil at moderately alkaline pH is reported. Pamukcu and Wittle (1992) report that Cd, Co, Ni and Sr all show this trend, although Sr did start depleting from the cathode region upon further processing time.

Jacobs et al. (1994) have studied the feasibility of removing zinc from kaolinite by rinsing the cathode compartment to reduce the diffusion of hydroxyl ions into the soil. They show that even this simple rinsing method can result in an almost complete removal of Zn from the soil. Eykholt and Daniel (1994) report that for kaolinite contaminated with copper, the chemistry of the system (mainly pH) affects its electrokinetic response. Electrokinetic flow is highest for higher pH in the case when kaolinite does not have any contaminant. Eykholt (1992) also reports that flow reversal can occur when the pH of the cathode compartment is reduced substantially. Acar and Alshawabkeh (1993) have stated that zeta potential decreases linearly with the logarithm of the pH of the soil medium which results in reduction of electro-osmotic flow. They also report that at high initial ionic conductivity or low initial soil pH, very little electro-osmotic flow occurs.

A review of all laboratory studies has indicated the importance of pH on the removal of organic and inorganic contaminant from soil. Some of the enhancement techniques deal with controlling the pH at the cathode compartment to improve the removal efficiency of ions from soil by electrokinetics. But none of these studies focus on the pH of the soil or the pH of the influent. Therefore, part of this study focuses on the effect of soil pH and the pH of the influent in the electrokinetic process.

Electrokinetic processing is time consuming. All bench-scale studies reported were conducted for several days or several weeks to remove contaminants from soil. The second part of this paper focuses on the study of the effects of current density on electrokinetic processing and the energy associated with it.

Two sets of experiments have been conducted to study the effects of current density and pH of the influent on electro-osmotic flow. The basic goal of the two sets of experiments was to understand the electro-osmotic process in soils, and thus no contaminants were used. This ensured that no complication arose due to soil-contaminant interactions. Zeta potential for kaolinite at various pH is also measured and compares well with previous results.

## 2. Methodology

This study aimed to relate the electro-osmotic process in kaolinite with the current applied and pH of the solution supplied at the anode. The kaolinite specimens were prepared in circular tubes and current was applied between the two ends by means of graphite electrodes.

### 2.1. Kaolinite

The soil chosen for this study is the commercially available air floated kaolinite clay, RC-32 from the Thiele Kaolin Company (Wrens, GA). 85% of the RC-32 particles are finer than 2 microns and the pH of the soil at 20% solids is 5.2. These and other properties and characteristics of the soil can be found in Bhadra, 1996.

## 2.2. Experiments

Two separate sets of experiments have been conducted. One was to determine the effect of current on the electro-osmotic process and the other was to study the effect of pH of the influent on electro-osmosis.

- Tests at various constant currents. Different constant currents were used to apply the electric field to the soil specimen. The influent was distilled water. Constant currents of 10, 15, 20, 25, 30 and 50 mA were applied to the specimens, corresponding to current densities of 0.123, 0.185, 0.247, 0.308, 0.370 and 0.615 mA/cm<sup>2</sup> respectively.
- Tests at various influent pH. For this second set of tests, the pH of the influent was varied. The constant current used for all tests of the second set was 10 mA. The influent pH tested was at pH of 2, 4, 8, 10 and 12.

The dimensions of the specimens, duration of tests, current density, pH, number of pore volumes, flow, and other parameters are presented in Table 1.

Secondary temperature effects have been reported to decrease the efficiency of electro-osmotic flow when the current density is greater than 5 mA/cm<sup>2</sup> (Gray, 1970). Therefore, current density used in all tests was below 5 mA/cm<sup>2</sup>. All tests were stopped after the pH of the effluent decreased, indicating that the acid front generated at the anode had reached the cathode compartment.

## 2.3. Electro-osmosis cells

Cells were made of plexiglass tubes 10.16 cm (4 in.) in diameter and 10.16 cm long. Small holes that allowed wires to be inserted into the soil specimen were drilled at regular intervals along the plexiglass tube. Caps at the two ends were made of plexiglass plates. The caps had circular cuts in them to hold the electrode and the plexiglass tube snug. Various holes cut into the caps allowed for electrolysis gas products to escape and for flow to take place. The end reservoirs in the caps had capacity of 110 ml, and holes were drilled above them in the caps to allow venting of gaseous electrolysis products. The electrodes were of graphite, cut to fit in the cap and perforated with holes to allow flow. The electrodes were held in place by the end caps that were held tight against the soil specimen by means of threaded rods with bolts.

## 2.4. Sample preparation

In the laboratory, kaolinite soil specimens were compacted at the optimum moisture content in the plexiglass cylinders. For the first set of experiments where different constant currents were used, kaolinite was mixed with distilled water at its optimum moisture content. For the second set of tests, run with influents at various pH, kaolinite was mixed with the same solution as the influent for compaction.

## 2.5. Influent preparation

For the first set of experiments, the influent supplied was pure distilled water. For the second set, the influents supplied were at different pH values. These pH solutions were

Table 1  
Testing summary

Parameters	Test No.									
	CC 10		CC 15		CC 20		CC 25		CC 30	
	a	b	a	b	a	b	a	b	a	b
Current (mA)	10	10	15	15	20	20	25	25	30	30
Current density (mA/cm <sup>2</sup> )	0.123	0.123	0.185	0.185	0.247	0.247	0.308	0.308	0.37	0.37
Duration (days)	18.84	18.84	8.06	8.06	13.12	13.17	14.28	14.25	7.42	4.96
Porosity	0.44	0.44	0.45	0.45	0.45	0.45	0.46	0.46	0.44	0.45
Pore volume (ml)	363.3	361.4	373.6	373.6	369	368.6	379.6	376.6	361.8	368.8
Total flow (ml)	936	803	519	592	1089	819	1555	1430	1030	709
No. of pore vol.	2.58	2.22	1.41	1.61	2.95	2.22	4.1	3.77	2.85	1.92
Flow rate (ml/h)	2.07	1.78	2.68	3.06	3.46	2.59	4.54	4.18	5.78	5.96
S (%) <sup>a</sup>	82.3	81.7	88.6	88	85	85.4	91	89.9	82.1	83.8
Max. Ke ( $\times 10^{-5}$ ) <sup>b</sup>	1.2	1	1.2	1.2	1.5	1.2	1.3	1.25	2	2.3
Max. Ki <sup>c</sup>	0.07	0.065	0.06	0.085	0.065	0.06	0.065	0.065	0.06	0.07

Parameters	Test No.									
	pH 2		pH 4		pH 8		pH 10		pH 12	
	a	b	a	b	a	b	a	b	a	b
Influent pH	2	2	4	4	8	8	10	10	12	12
Current (mA)	10	10	10	10	10	10	10	10	10	10
Current density (mA/cm <sup>2</sup> )	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123
Duration (days)	24.7	21	22	22	14.9	14.9	24.7	21	18.1	18.1
Porosity	0.46	0.46	0.47	0.47	0.48	0.48	0.46	0.47	0.47	0.47
Pore volume (ml)	379.4	380.8	387.3	385.3	392.1	398.6	380.7	384.2	389.4	389.9
Total flow (ml)	625	512	681	686	597	766	1253	1029	3465	3236
No. of pore vol.	1.65	1.34	1.76	1.78	1.52	1.92	3.29	2.68	8.9	8.3
Flow rate (ml/h)	1.05	1.02	1.29	1.30	1.68	2.14	2.11	2.04	7.98	7.45
S (%) <sup>a</sup>	89.1	93.2	93.05	92	94.8	98	90.9	94.6	94.8	93.7
Max. Ke ( $\times 10^{-6}$ )	2.6	6	2.5	3	1.4	4	4	3.5	18	24
Max. Ki <sup>3</sup>	0.08	0.075	0.1	0.11	0.1	0.14	0.1	0.12	0.3	0.34

<sup>a</sup> Degree of saturation.

<sup>b</sup> Maximum electro-osmotic permeability (cm<sup>2</sup>/Vs).

<sup>c</sup> Maximum electro-osmotic water transport efficiency (cm<sup>3</sup>/amps).

prepared by adding either hydrochloric acid (for influents with pH less than 7) or sodium hydroxide (for influent with pH greater than 7) to distilled water until the desired pH was reached.

## 2.6. Testing procedure

A filter paper was placed between the soil specimen and the graphite electrode to prevent the soil particles from clogging the tubes and the end reservoirs. Graphite electrode was used to prevent corrosion and introduction of secondary corrosion products.

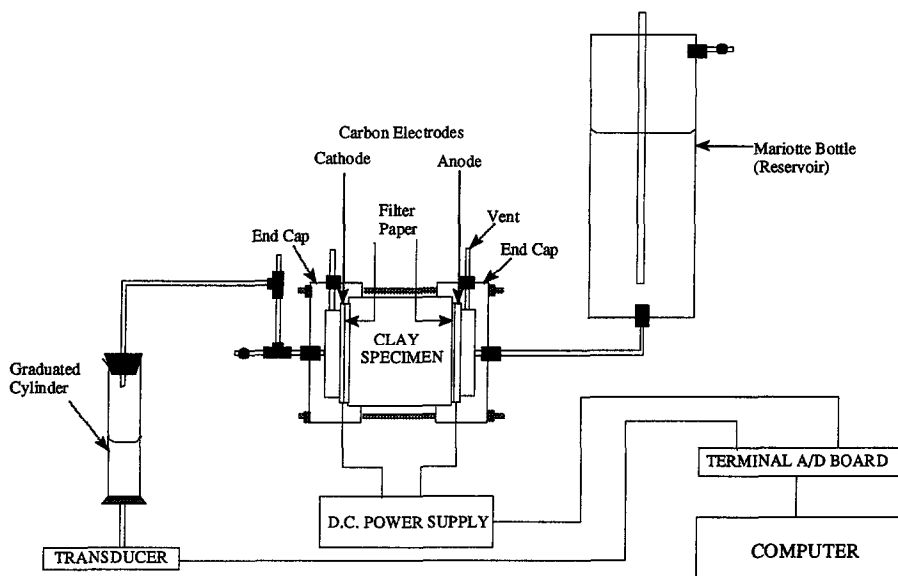


Fig. 1. Schematic view of the experimental setup.

The constructed setup that was used to run the electrokinetic tests is shown in Fig. 1. A Mariotte bottle was used to supply the influent at the anode to minimize a hydraulic gradient and a graduated cylinder collects the flow at the cathode. A pressure transducer is attached to the graduated cylinder at the cathode to monitor electro-osmotic flow. A Validyne DP15 variable reluctance differential pressure transducer was used in conjunction with a CD280 multichannel carrier demodulator.

All experiments were run in the constant DC current mode to keep the net rates of electrolysis reactions constant and minimize complicated current boundary conditions. The DC power supply used was either the Hewlett Packard HP E3612A (capable of 0–60 V at 0–0.5 A or 0–120 V at 0–0.25 A) or HP 6035 A (capable of 0–500 V at 0–5 A). The changing voltage and the flow were constantly monitored by means of a data acquisition board in a computer. Besides monitoring flow and voltage, the effluent pH and conductivity at the cathode was recorded manually by means of Cole-Parmer Chemcadet pH meter Model 5986-60 and Jenway 4020 conductivity meter respectively. Wires, tipped with inert silver epoxy and inserted in the soil specimen at various intervals also allowed measurement of voltages at different locations in the specimen.

#### 2.6.1. Data acquisition system

The data acquisition system for this study consisted of a CompuAdd 386/25 MHz and/or a Zenith 386/20 MHz computer installed with an analog-to-digital (A/D) data acquisition board and a data acquisition software. Keithley Metrabytes data acquisition board, DAS-20 was used with LabTech Notebook data acquisition software. The data acquisition board, DAS-20 is capable of either 8 differential or 16 single-ended analog inputs, but has been used in the differential mode.

Standard Proctor compaction tests were conducted to find the optimum moisture content for RC-32 kaolinite. The basic goal of these experiments was to understand the electro-osmotic process in soils, and thus no contaminants were used. Besides these tests, measurements of zeta potential of kaolinite at different pH values were accomplished by means of a zeta-meter manufactured by Zeta-Meter (New York).

### 3. Analysis of results

Table 1 summarizes all the tests conducted in this study. Two different sets of tests were used. The first set of tests conducted was to study the effects of current density on electro-osmotic flow, electric potential, energy, and pH at the cathode. The second set of tests was conducted to study the effect of initial pH and influent pH on the process. The methodologies for all these tests have been described in Section 2.

All tests were continued until pH levels at the cathode compartment decreased to relatively steady values. The authors believe that the decrease in pH values across the soil specimen resulted from the advancement of the acid front generated at the anode toward the cathode.

#### 3.1. Flow

Several tests were conducted to study the effects of a low current density and pH of the influent on electrokinetic soil processing. Fig. 2 presents the electro-osmotic flow in time at different current densities. It is clear that tests with higher current densities have higher flow rates. For example, the test at  $0.37 \text{ mA/cm}^2$  (30 mA) produced a total flow of 750 ml in five days while the test at  $0.123 \text{ mA/cm}^2$  (10 mA) produced about 750 ml in 15 day. Results from these tests indicate that flow rate is clearly dependent on the current applied. This is as expected since energy expenditure is higher for higher currents. Electro-osmotic flow and electromigration are important for movement of contaminants when decontaminating soils by electrokinetics. In case of the tests

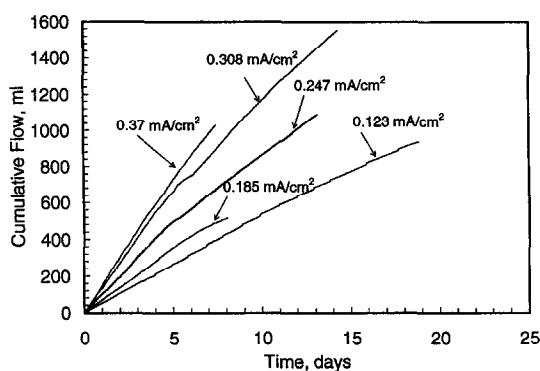


Fig. 2. Cumulative flow vs. time for tests with different current densities and distilled water as influent.

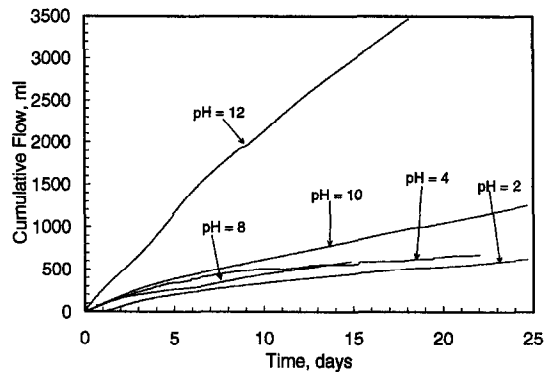


Fig. 3. Cumulative flow vs. time at different influent pH with constant current density of  $0.123 \text{ mA/cm}^2$ .

conducted here, it is the advection (electro-osmosis) and migration (ion movement due to electric field) terms that transport the  $\text{H}^+$  ions from the anode to the cathode. Electro-osmosis and electromigration is more at higher currents and thus the acid front will move to the cathode faster at higher currents. This has reduced the processing time for the tests.

Fig. 3 shows the effect of influent pH on electro-osmotic flow. There is a gradual change in the flow rate between pH of 2 and 10, but between pH of 10 and 12 there is a sharp increase. Comparison between tests at pH of 10 and 12 shows that the flow for a period of 10 days is 500 ml and 2000 ml respectively. The results indicate that for kaolinite, electro-osmotic flow is favored by high values of influent pH.

The average flow rate for the varying constant current cases run with distilled water as influent and for the constant current cases run with different influent pH has been calculated. Fig. 4 shows the average flow rate versus current density and can be represented by the following equation:

$$q = 35.416i_a^2 - 2.3332i_a + 1.8588 \quad (0.123 \leq i_a \leq 0.617) \quad (1)$$

where  $q$  is the average flow rate (ml/h) and  $i_a$  is the current density ( $\text{mA/cm}^2$ ). This

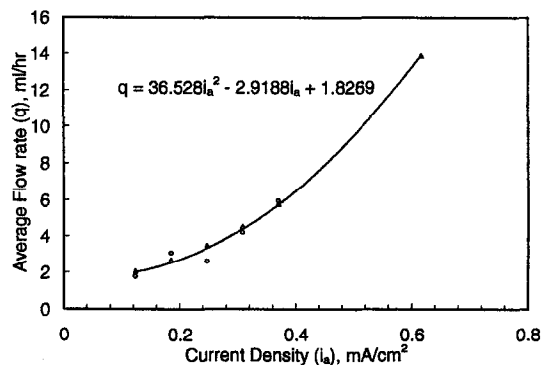


Fig. 4. Average flow rate vs. different current densities for tests with distilled water as influent.



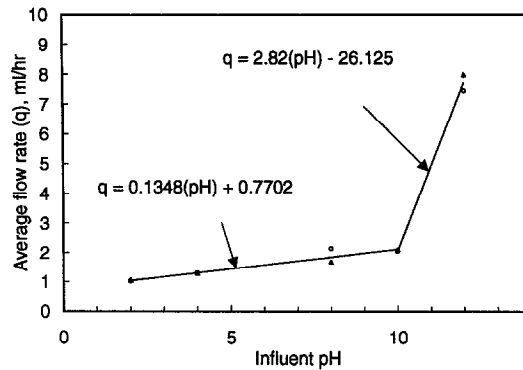


Fig. 5. Average flow rate vs. influent pH for tests with constant current density of 0.123 mA/cm<sup>2</sup>.

equation has been obtained for current density values ranging from 0.123 mA/cm<sup>2</sup> (10 mA) to 0.615 mA/cm<sup>2</sup> (50 mA) and may not be valid outside that range.

Fig. 5 shows the average flow rate versus pH for tests run at constant current density value of 0.123 mA/cm<sup>2</sup> (10 mA) with different influent pH values. Due to the extreme difference in flow rate after pH of 10, the following two equations are suggested for obtaining the electro-osmotic flow rates:

$$\begin{aligned} q &= 0.1255 \times \text{pH} + 0.7795 & \text{for } 2 \leq \text{pH} \leq 10 \\ q &= 2.935 \times \text{pH} - 27.24 & \text{for } 10 < \text{pH} \leq 12 \end{aligned} \quad (2)$$

These two equations cannot be generalized to include cases other than for the constant current values used. However, the sharp increase in the flow rate after a certain pH can be expected in all cases. The trend of higher electro-osmotic flow at higher pH is as expected. The magnitude of zeta potential of kaolinite at higher pH is larger. This will result in higher electro-osmotic flow.

### 3.2. Electrical potential gradient

Fig. 6 shows the changing voltage across the cell with time for different constant current tests with distilled water as influent. The voltage quickly reaches a high value for tests conducted at higher currents. While it took 19 days for the test conducted at current density of 0.123 mA/cm<sup>2</sup> (10 mA) to reach a maximum value of 2 V/cm, it took only 7 days for the test run at 0.37 mA/cm<sup>2</sup> (30 mA) to reach its peak value of 10 V/cm. Furthermore, the peak potential values ranged from 2–4 V/cm for constant current values of 10–20 mA but increased sharply for higher currents.

Fig. 7 presents the electric potential gradient across the electrodes for different influent pH during the course of these tests. All tests show an increase in the voltage gradient at early stages, but a nearly constant value is reached later. The maximum value ranged between 4 to 6 V/cm for all tests. It seems that the influent pH does not affect the electric potential across the electrodes.

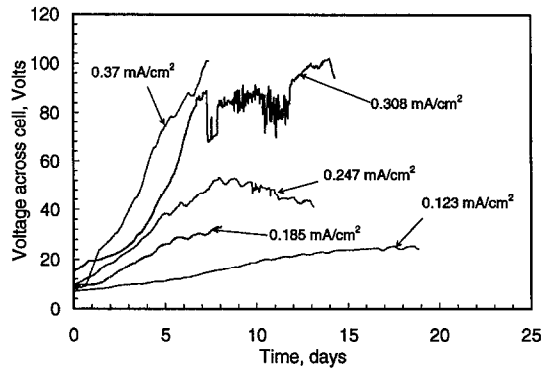


Fig. 6. Electrical potential across the cell vs. time for tests with different current densities and distilled water as influent.

### 3.3. pH and conductivity

Fig. 8 presents pH versus time at different current. It is clear that once the pH in the alkaline cathodic end starts dropping, the flow rate starts to decrease as well. One of the reasons could be the acidic environment of the whole cell (Hamed, 1990). Electrolysis in the anode and cathode ends produce an acidic and alkaline environment, respectively. The alkaline cathodic end is gradually neutralized by the acid front that is moving with the flow from the anode. This change is reflected in the changing pH of the cathode compartment as shown in Fig. 8. In the case of higher current, the electrokinetic process was much faster in neutralizing the base at the cathode because the flow rate was much higher. This is seen by comparing the cathode pH variation with time as shown in Fig. 8. The pH at the cathode drops earlier for higher currents than for lower currents.

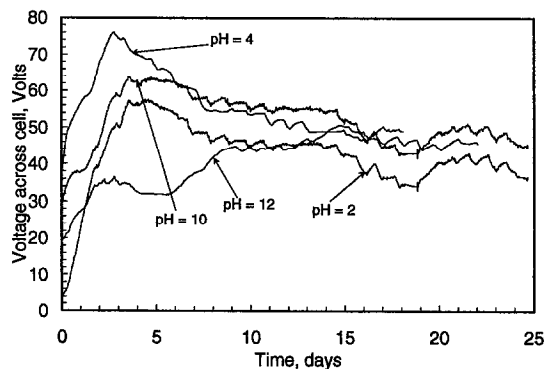


Fig. 7. Electrical potential across the cell vs. time for tests with different influent pH at a constant current density of  $0.123 \text{ mA/cm}^2$ .

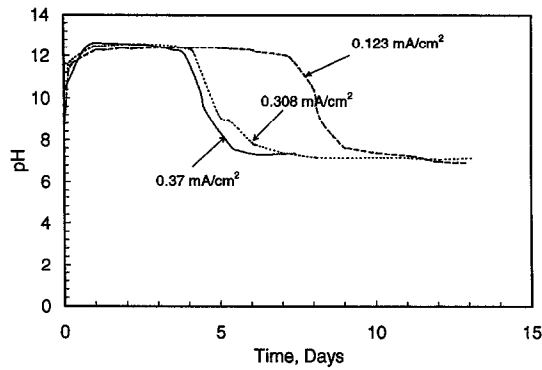


Fig. 8. The pH of cathode compartment for tests run with distilled water at different current densities.

### 3.4. Conductivity

The electrical conductivity phenomena arise from the movement of ions or electrons through a conducting system under the influence of an electric field ( $E$ ). Conductivity is measured in siemens (mhos) per distance between the measurement points in a medium. Conductivity rises from a very low value ( $\sim 1 \mu\text{s/cm}$ ) for deionized, distilled water to several orders of magnitude higher for a fluid containing electrolytes, depending on their type and concentration.

In all these tests, a conductivity meter was used to measure the conductivity of fluid at the cathode compartment at different times. Conductivity values are sensitive indicators of  $\text{H}^+$ ,  $\text{OH}^-$  and other ions if they exceed the pore fluid ionic concentrations. Since these tests were conducted without addition of any contaminant, the major ionic constituents are considered to be the  $\text{H}^+$  and  $\text{OH}^-$  ions, although ions such as  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Mg}^{2+}$  etc. present in kaolinite will leach out. This premise is supported by Fig. 9 showing the variation of conductivity at the cathode compartment with time. The conductivity starts dropping about the same time as the pH, indicating that the conductivity is most probably a function of the  $\text{H}^+$  and  $\text{OH}^-$  ions and that other ions are minor constituents.

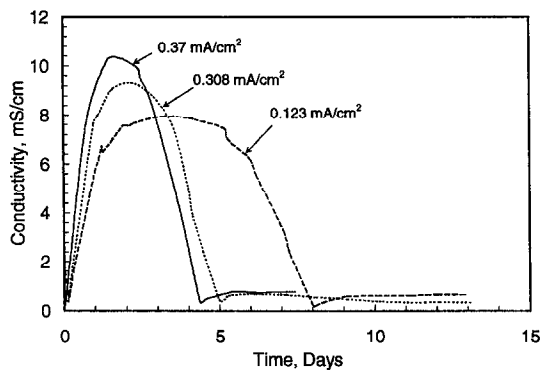


Fig. 9. Conductivity of cathode compartment for tests run with distilled water at different current densities.

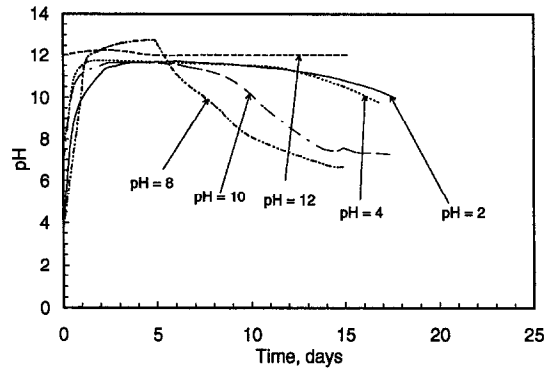


Fig. 10. The pH of cathode compartment for tests run with various influent pH at a constant current density of  $0.123 \text{ mA/cm}^2$ .

Fig. 10 presents the variation of pH at the cathode compartment versus time for different influent pH at a constant current of  $10 \text{ mA}$  ( $0.123 \text{ mA/cm}^2$ ). Fig. 10 shows that for test with influent pH of 12, the pH of the cathode compartment remains constant and the flow rate is very high. The continuous supply of influent pH of 12 will neutralize the acid front generated at the anode resulting in a higher pH at the anode compartment. Therefore, the acid front generated at the anode will not travel along the specimen. Consequently, the pH at the cathode compartment will not drop and the flow rate will remain high as shown in Fig. 3. Fig. 10 also shows that the acid front generated at the anode will travel faster for tests with influent pH of 8 and 10 than for tests with influent pH of 2 and 4. The tests with lower influent pH have lower flow rate than tests with higher pH, resulting in a slower movement of  $\text{H}^+$  ions toward the cathode by advection.

Fig. 11 shows the conductivity versus time for different influent pH. All tests show an increase in conductivity in early stages of testing, probably as a result of increasing

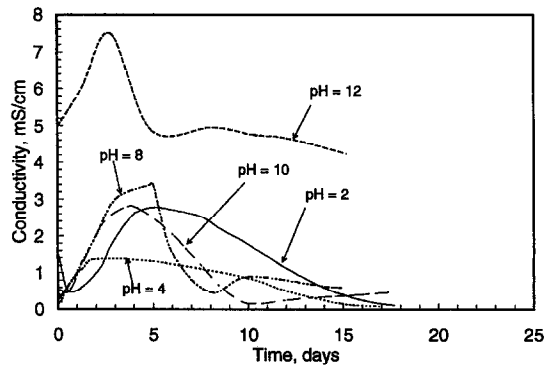


Fig. 11. Conductivity of cathode compartment for tests run with various influent pH at a constant current density of  $0.123 \text{ mA/cm}^2$ .

pH of the cathode compartment. As the  $H^+$  ions travel toward the cathode, the conductivity decreases to a very low value and remains nearly constant after that. However, tests with influent pH of 12 behaved differently. The conductivity remains high because the acid front generated at the anode compartment did not reach the cathode for the reason stated above. Figs. 10 and 11 show that the conductivity drops down whenever there is a decrease in the cathode pH.

### 3.5. Variation of electrical potential in the soil

For the tests conducted in this study, measurements have been taken of electric potential at different locations in the soil specimen. Measurements initially (soon after current is applied to the soil specimen) show a linear increase in the potential values across the cell from the cathode to the anode. Thus, it can be concluded that the resistance throughout the cell is initially the same. This linear increase in potential at the beginning stages soon changes to one where the increase is highest near the cathode and linear from that portion onwards. This change shows that the resistance of the soil close to the cathode increases as the electrokinetic process continues. This phenomena results in an overall increase in the voltage required to maintain a constant current. This drives the energy expenditure up as well.

Results from tests with higher pH show higher flow rate than those at lower pH as shown in Fig. 3. The authors hypothesize that sections close to the cathode have higher flow rate because of higher pH as compared to sections further away from the cathode. This resulted in depletion of water in these sections. The depletion of water resulted in a higher resistance to the current flow. Fig. 12 shows that the section closest to the cathode has the highest resistance to current flow. However in Fig. 13, where the influent was at pH of 12, the acid generated at the anode is neutralized by the influent. Since most of the specimen remained at a high pH, there was no depletion of water close to the cathode. The resistance of different sections in the cell was almost constant except very close to the anode. Water depletion was not a factor since the flow rate was high.

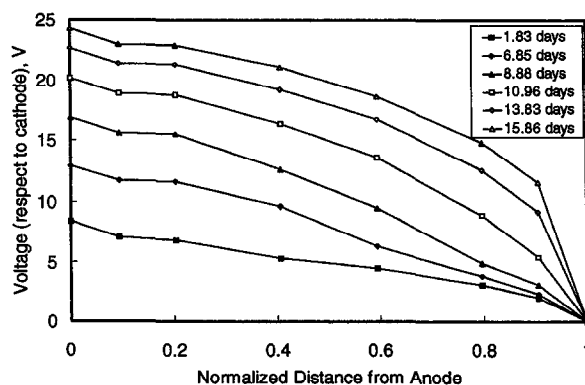


Fig. 12. Electric potential at different locations along the cell at current density of  $0.123 \text{ mA/cm}^2$  and distilled water as influent.

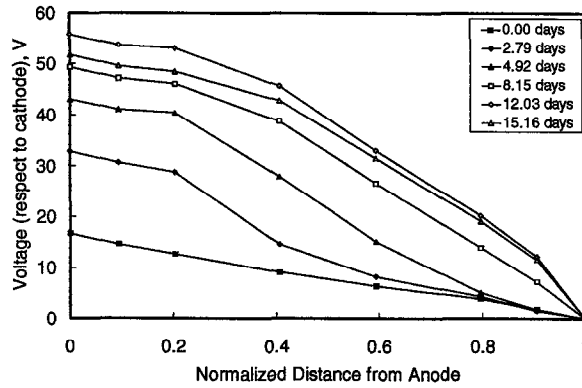


Fig. 13. Electric potential at different locations along the cell at influent pH of 12 and constant current density of  $0.123 \text{ mA/cm}^2$ .

### 3.6. Energy expenditure

Energy expenditure per unit volume of soil processed is given by the following equation for tests with constant current conditions. It is directly related to the time integral of the electric field across the cell.

$$E_U = \frac{E}{V_s} = \frac{1}{V_s} \int V I dt = \frac{1}{V_s} \int I^2 R dt$$

Fig. 14 presents the plots of the energy expended per unit volume of soil for tests with different current versus pore volumes of flow. This figure shows that beyond a current of  $15 \text{ mA}$  (i.e.  $0.185 \text{ mA/cm}^2$ ), increasing the current density does not result in increasing the energy expenditure per unit volume for the same numbers of pore volume. However, processing time has been reduced considerably. For example the energy expenditure at 2 pore volumes of flow for test at  $30 \text{ mA}$  is equal to the energy for test at  $20 \text{ mA}$  ( $160 \text{ kWh/m}^3$ ). At the same time, the processing time has decreased by almost 50%.

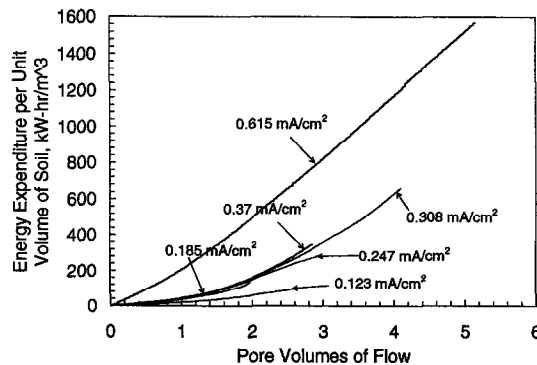


Fig. 14. Energy expenditure per unit volume of soil vs. pore volumes of flow for tests with different constant current densities and distilled water as influent.

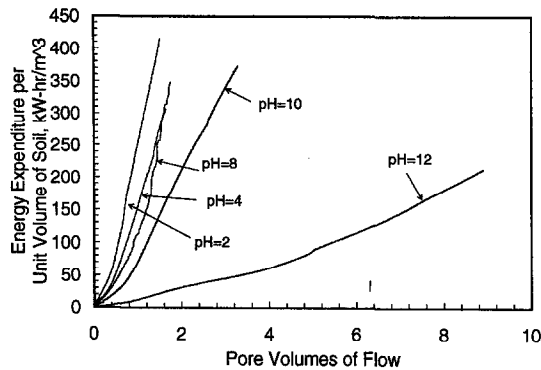


Fig. 15. Energy expenditure per unit volume of soil vs. pore volumes of flow for test with different influent pH at a constant current density of  $0.123 \text{ mA/cm}^2$ .

Fig. 15 presents the plots of the energy expended per unit volume of soil for tests with different influent pH versus pore volume of flow. The energy expenditure in tests with high influent pH was lower as compared to tests with lower influent pH by more than one order of magnitude (i.e. the energy expended for tests with influent pH of 12 corresponding to one pore volume was  $10 \text{ kWh/m}^3$  while the energy expended for tests with influent pH of 4 was higher than  $300 \text{ kWh/m}^3$  for one pore volume).

#### 4. Summary and conclusions

Two sets of electrokinetic experiments were conducted on compacted, saturated Georgia kaolinite to study the effect of current density and influent pH on electro-osmotic flow, energy, pH and conductivity of the effluent, and electric potential. A zeta-meter is used to measure the zeta potential at the surface of kaolinite at different pH. Based on the experimental results, the following can be concluded:

- Increasing the current density increased the electro-osmotic flow rate, resulting in higher number of pore volumes in a shorter period of time.
- Increasing the current density decreased the processing time considerably.
- Increasing the current density did not result in a considerable increase of energy expenditure per unit volume of soil processed.
- Increasing the influent pH from 2 to 10 resulted in a gradual increase in the flow rate. However, increasing the influent pH from 10 to 12 resulted in a sharp increase in the flow rate.
- The cathode pH for tests with influent pH of 8 and 10 dropped down faster than tests with influent pH of 2 and 4. This is due to the higher charge in the clay surface for higher pH resulting in higher flow rate.
- Increasing the influent pH did not result in any increase of the electric potential across the cell.
- Test with influent pH of 12 produced a high flow rate. At the same time the pH at the cathode did not drop down, resulting in continuous flow for the period of testing.

- Higher flow rate near the cathode (due to higher pH) will cause depletion of water in this region. The resistance will increase resulting in higher energy expenditure.
- Higher influent pH will neutralize the acid front generated at the anode, resulting in a constant flow rate. Therefore it is unlikely that there is no depletion of water.

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