

# Electroosmotic dewatering of dredged sediments: Bench-scale investigation<sup>☆</sup>

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## Abstract

The Indiana Harbor (Indiana, USA) has not been dredged since 1972 due to lack of a suitable disposal site for dredged sediment. As a result of this, over a million cubic yards of highly contaminated sediment has accumulated in the harbor. Recently, the United States Army Corps of Engineers (USACE) has selected a site for the confined disposal facility (CDF) and is in the process of designing it. Although dredging can be accomplished rapidly, the disposal in the CDF has to be done slowly to allow adequate time for consolidation to occur. The sediment possesses very high moisture content and very low hydraulic conductivity, which cause consolidation to occur slowly. Consolidation of the sediment is essential in order to achieve adequate shear strength of sediments and also to provide enough air space to accommodate the large amount of sediment that requires disposal. Currently, it has been estimated that if a one 3-foot (0.9-m) thick layer of sediment was disposed of at the CDF annually, it would take approximately 10 years to dispose of all the sediment that is to be dredged from the Indiana Harbor. This study investigated the feasibility of using an electroosmotic dewatering technology to accelerate dewatering and consolidation of sediment, thereby allowing more rapid disposal of sediment into the CDF. Electroosmotic dewatering essentially involves applying a small electric potential across the sediment layer, thereby inducing rapid flow as a result of physico-chemical and electrochemical processes. A series of bench-scale electrokinetic experiments were conducted on actual dredged sediment samples from the Indiana Harbor to investigate dewatering rates caused by gravity alone, dewatering rates caused by gravity and electric potential, and the effects of the addition of polymer flocculants on dewatering of the sediments. The results showed that electroosmotic dewatering under an applied electric potential of 1.0 VDC/cm could increase the rate of dewatering and consolidation by an order of magnitude as compared to gravity drainage alone. Amending the sediment with polymers at low concentrations (0.5–1% by dry weight) will enhance this dewatering process; however, the optimal polymer concentration and the cost-effectiveness of using polymers should be investigated further.

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## 1. Introduction

Dredging at the Indiana Harbor (Indiana, USA) has been precluded for over 20 years due to lack of an acceptable disposal site, resulting in the accumulation of over one million cubic yards of highly contaminated sediments mainly due to industrial discharges. Recently, the United States Army Corps of Engineers (USACE) selected a site

where a confined disposal facility (CDF) will be located and is currently designing and constructing this CDF. The main problems with the disposal of sediment into the CDF are: (1) slow consolidation of the sediment due to its very high water content (about 50–80%) and low hydraulic conductivity, and (2) low shear strength. Therefore, the dredging and sediment disposal at the CDF have to be performed in stages. Current plans call for the disposal of an approximately 3-foot (0.9-m) thick layer of sediment per disposal event. Subsequent layers can then be disposed of, allowing adequate lag time between the placements of the layers to allow consolidation to occur. The consolidation process is essential in order to achieve adequate shear strength as well as provide adequate storage capacity in the CDF, but it is a slow process because of the low hydraulic conductivity of the sediment ( $3.3 \times 10^{-7}$  cm/s). It has been estimated that it

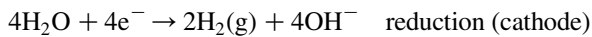
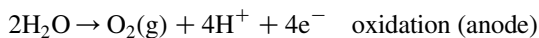
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would require approximately 10 years to dispose of the sediment that is currently present in the Indiana Harbor.

There is an obvious need for innovative methods to accelerate dewatering, so that dredging and disposal of excess and impacted sediment can be accomplished in a fast, safe, and cost-effective manner. There are different approaches to accelerated consolidation, such as the use of pumps, drains, or chemical admixtures. However, these methods are not effective or economical for low permeability sediment. Electroosmotic dewatering has a great potential to be a simple and efficient way to accelerate consolidation of the sediment. Basically, electroosmotic technology involves an application of a low electric potential across the sediment layers that need to be dewatered.

Due to the applied electric potential, the electrolysis of water occurs at the electrodes, generating oxygen gas and hydrogen ( $H^+$ ) ions (low pH solution) at the anode and hydrogen gas and hydroxide ( $OH^-$ ) ions (high pH solution) at the cathode.



The electric potential induces several contaminant transport mechanisms, such as *electromigration*, *electroosmosis*, *electrophoresis*, and *diffusion*. *Electromigration* refers to the transport of ionic species in the pore fluid, and this is the main mechanism by which the electrical current flows through the sediment. Electromigration also includes the movement of  $H^+$  and  $OH^-$  ions produced by electrolysis toward the oppositely charged electrode. *Electroosmosis* describes the bulk movement of the pore fluid, and electroosmotic flow is produced because excess ions migrating toward the oppositely charged electrode transfer momentum to the surrounding pore fluid molecules (Eykholt, 1992). *Electrophoresis* describes the transport of colloidal size particles through the pore fluid, and *diffusion* refers to the transport of species due to concentration gradients.

Electroosmosis is the most critical process for the successful dewatering of the sediments. The Helmholtz–Smoluchowski (H–S) equation is often used to estimate the average electroosmotic flow velocity ( $v_{eo}$ ) (Mitchell, 1993; Eykholt and Daniel, 1994):

$$v_{eo} = -\frac{D\epsilon_0\zeta}{\eta}E_x$$

According to this equation, the flow velocity is proportional to the electrical gradient ( $E_x$ ), zeta potential ( $\zeta$ ), and dielectric constant ( $D$ ), and it is inversely proportional to the viscosity ( $\eta$ ). The ( $\epsilon_0$ ) term represents the permittivity of vacuum ( $8.854 \times 10^{-12}$  C/V m), and the dielectric constant and viscosity are properties of the pore fluid. The zeta potential depends on the zero point of charge (ZPC), which refers to the pH at which the net charge on the

sediment particle surface is zero. When the pH is above the ZPC, the sediment particles usually have a negative zeta potential and the electroosmotic flow occurs toward the cathode. Conversely, when the pH is below the ZPC, the sediment particle surfaces generally have a positive zeta potential and the electroosmotic flow occurs toward the anode (reverse electroosmotic flow) (Shapiro and Probst, 1993). The H–S equation suggests that in addition to the pH, many other factors might affect the electroosmotic flow. For instance, the surface charge of the sediment particles and the zeta potential are affected by changes in the ionic strength, dielectric constant, and viscosity. Furthermore, the electrical gradient may not be uniform throughout the sediment; hence, the electroosmotic flow is generally not uniform spatially or temporally (Eykholt and Daniel, 1994).

This paper presents the results of laboratory experiments conducted using actual dredged sediment obtained from the Indiana Harbor to determine the extent of electroosmosis and consolidation. A total of eight experiments was conducted to investigate dewatering rates caused by gravity alone, dewatering rates caused by gravity and electric potential, and the effects of the addition of polymer flocculants on dewatering of the sediments. The test results were assessed to determine the most effective dewatering and consolidation operations.

## 2. Materials and methods

### 2.1. Sediment

Bulk samples of sediments were obtained by dredging from the Indiana Harbor. The sediment was tested for water content, specific gravity, particle size distribution, Atterberg limits, USCS classification, maximum dry density, optimum moisture content, pH, and organic content in accordance with the ASTM standard methods (American Society of Testing and Materials, 2003). These properties of the sediment are summarized in Table 1. The sediment was contaminated with heavy metals and polycyclic aromatic

Table 1  
Properties of dredged sediment

Property	Test method	Value
Water content	ASTM D 2216	78.60%
Specific gravity	ASTM D 854	1.25
Grain size distribution	ASTM D 422	% gravel=0.1, % sand=8.4, % fines=91.5
Atterberg limits	ASTM D 4318	LL=45%, PL=32%, PI=13%
Max. dry density	ASTM D 698	1.35 g/cm <sup>3</sup>
Optimum moisture content	ASTM D 698	24.0%
Hydraulic conductivity	ASTM D 5084	$3.3 \times 10^{-7}$ cm/s
pH	ASTM D 4972	7.0
Organic content	ASTM D 2974	19.20%
USCS classification	ASTM D 2487	OL

Table 2  
Contaminants found in dredged sediment

(a) Total metals (USEPA method SW6020/SW7471A)		(b) Polycyclic aromatic hydrocarbons (USEPA method SW8270/SW8270C)	
Chemical	Concentration (mg/kg)	Chemical	Concentration (mg/kg)
Aluminum	5400	2-Methylnaphthalene	9.8
Arsenic	42	Acenaphthene	23–34
Barium	92	Acenaphthylene	6.7–9.6
Beryllium	0.94	Anthracene	27–42
Cadmium	9.5	Benzo(a)anthracene	12–52
Calcium	26,000	Benzo(a)pyrene	31–36
Chromium	530	Benzo(b)fluoranthene	23–29
Cobalt	9	Benzo(g,h,i)perylene	23
Copper	200	Benzo(k)fluoranthene	25–30
Iron	110,000	Carbazole	58
Lead	570	Chrysene	6.3–34
Magnesium	8900	Dibenzo(a,h)anthracene	2.2–11
Manganese	1800	Dibenzofuran	14
Mercury	1.1	Fluoranthene	94–110
Nickel	67	Fluorene	31–37
Potassium	680	Indeno(1,2,3-cd)pyrene	5.2–24
Silver	2.4	Naphthalene	66
Sodium	150	Phenanthrene	100–120
Thallium	3.5	Pyrene	66–85
Vanadium	17		
Zinc	3700		

hydrocarbons (PAHs) as summarized in Table 2. The sediment was used as received from the field for all tests in this study.

## 2.2. Experimental test set-up and procedure

The experimental test set-up used was a modified electrokinetic test set-up developed previously at the University of Illinois at Chicago (Reddy and Shirani, 1997; Reddy and Saichek, 2003). The test set-up consisted of acrylic cylindrical cells, weights, deflection dials, graphite electrodes

and a power supply (Fig. 1). The cells were positioned vertically using laboratory stands and clamps. The cathode was placed at the bottom of the cell, whereas the anode was placed on top of the sediment sample and allowed to move as the sediment consolidated. Filter papers and porous stones were used to filter the solution coming out from the sediment. On the anode (top) electrode, a metal weight was placed to ensure uniform consolidation and constant contact between the electrodes and the sediment. A deflection dial used to measure the sediment consolidation was in contact with the top surface of the metal weight. During testing, effluent

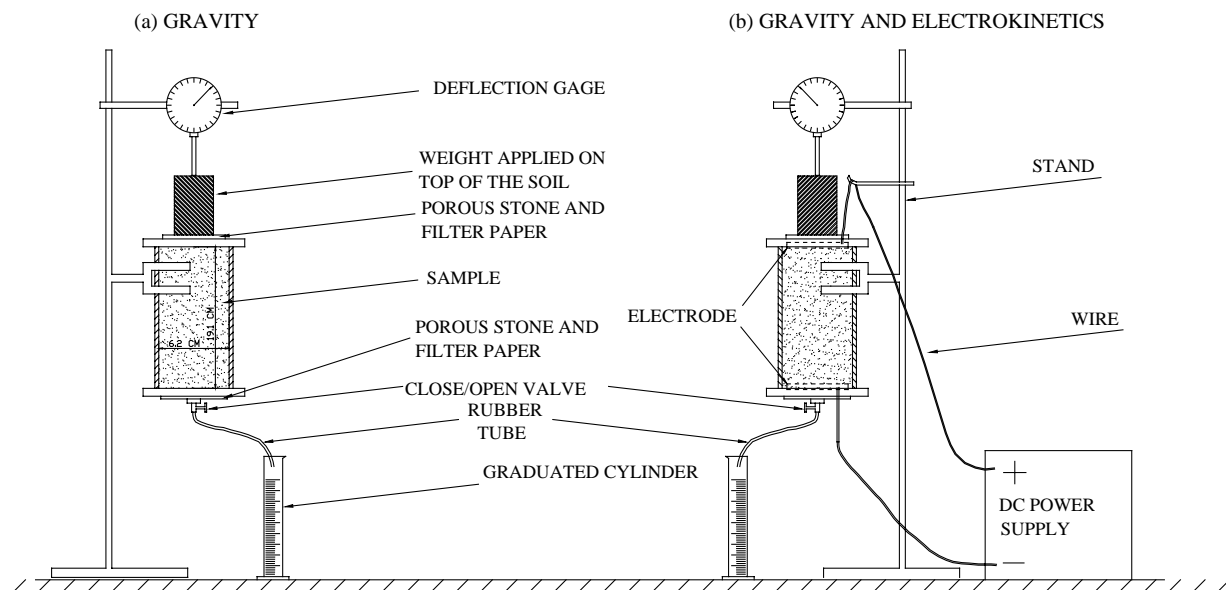


Fig. 1. Bench-scale test set-up to study dewatering of dredged sediments.

Table 3  
Experiment testing program

Test number	Test designation	Initial length of sediment sample (cm)	Voltage gradient (VDC/cm)	Polymer used	Test duration (h)
1	DW-1	19.1	0.0	None	145
2	EK-DW-2	19.1	1.0	None	145
3	EK-DW-5	18.0	1.0	0.5% Polyacrylic acid	211
4	EK-DW-3	18.0	1.0	1% Polyacrylic acid	290
5	EK-DW-7	18.0	1.0	2% Polyacrylic acid	210
6	EK-DW-6	18.0	1.0	0.5% Polyacrylamide	212
7	EK-DW-4	18.0	1.0	1% Polyacrylamide	290
8	EK-DW-8	18.0	1.0	2% Polyacrylamide	212

solution volume, consolidation settlement, current, and effluent pH were measured.

Table 3 shows the test designations and experiment conditions and durations. Test 1 was conducted under gravity only, while Test 2 was conducted to investigate the combined effects of gravity and electroosmosis. Tests 3–8 were conducted to investigate the effects of adding a polymer flocculant on dewatering of sediments. The first polymer was polyacrylic acid, an anionic flocculant, used for Tests 3, 4, and 5 with concentrations of 0.5, 1.0, and 2% per dry weight of the sediment, respectively. The second polymer was polyacrylamide, a nonionic flocculant, used for Tests 6, 7, and 8 with concentrations of 0.5, 1.0, and 2% per dry weight of the sediment, respectively. These specific polymers and their concentrations were selected based on their previous use in dewatering studies (Yu and Somasundaran, 1996; Watanabe et al., 1999; Bohm and Kulicke, 1997; Chitikela and Dentel, 1998; Lee and Liu, 2001). The sediment was mixed with the selected polymer in a glass beaker and then packed into the electrokinetic cell. At the end of each test, the sediment sample was extruded and sectioned, and moisture content, pH, oxidation–reduction potential (redox potential), and electrical conductivity were determined for each section as well as the effluent solution.

### 3. Results and discussion

#### 3.1. Dewatering efficiency

Tests 1 and 2 were the baseline for the rest of the experiments. Sediment in Test 1 was dewatered by means of gravity only. Sediment in Test 2 was dewatered by means of gravity and an initial potential difference of 1 VDC/cm length (1 VDC/cm) of the sample. Tests 3, 4 and 5 were conducted using sediments augmented with polyacrylic acid and Tests 6, 7 and 8 were conducted using sediments augmented with polyacrylamide. The duration of the test ranged from 145 to 290 h. The tests were stopped when outflow from the sediment was negligible.

Fig. 2(a) and (b) show the decrease in the water content of the sediments with time during the testing period.

Initially, the water content decreased rapidly and then the decrease in water content became negligible. The test conducted under gravity alone (Test 1) shows the lowest reduction in water content, approximately 3%. Conversely, the test conducted with the application of electric potential of 1.0 VDC/cm (Test 2) resulted in rapid reduction in water content initially and a continued gradual decrease. A maximum water content reduction of 25% was observed in this test. The effects of polyacrylic acid on dewatering of the sediment are shown in Fig. 2(a). The low concentration

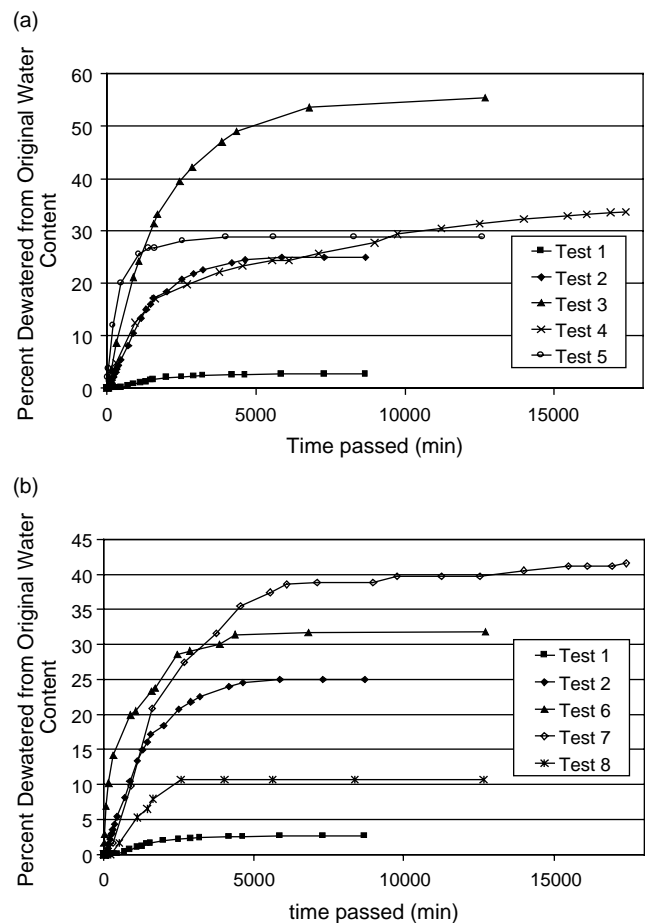


Fig. 2. (a) Dewatering efficiency vs. time: baseline and polyacrylic acid added tests. (b) Dewatering efficiency vs. time: baseline and polyacrylamide added tests.

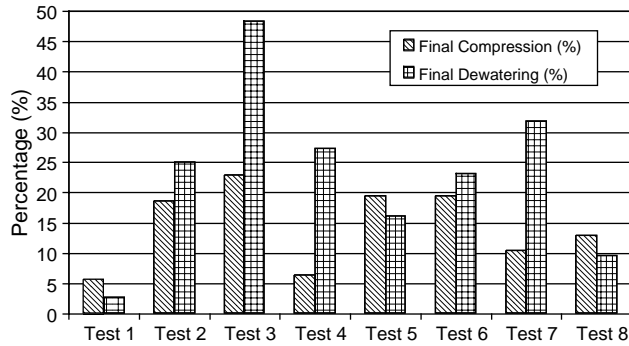


Fig. 3. Comparison of final dewatering and compressibility efficiency of the sediment under different tested conditions.

(0.5%) of this polymer resulted in a maximum moisture content reduction. Interestingly, an increase in the polymer concentration (1 and 2%) decreased the dewatering of the sediment. The effects of using a different polymer, polyacrylamide, on dewatering of sediment are shown in Fig. 2(b). It can be seen that augmentation with this polymer affected dewatering. Dewatering increased with the increase in concentration of the polymer from 0.5 to 1%, but it decreased when the polymer concentration was increased from 1 to 2%.

The overall dewatering efficiency was determined as reduction in the water content of the sample. This was accomplished by subtracting the final effluent volume, expressed in terms of moisture content of the sediment, from the initial moisture content. The measured dewatering efficiencies under different operating conditions considered in this study are compared in Fig. 3. Comparing baseline tests (Tests 1 and 2) with the tests where polyacrylic acid was used (Tests 3–5), it can be observed that higher concentrations of the polymer, 1 and 2% by dry weight of sediment, respectively, achieved similar or lower dewatering efficiency compared to when only EK was used. The optimum concentration for polyacrylic acid was 0.5% per dry weight of sediment, which achieved reduction in the water content of the sediment. Comparing baseline tests (Tests 1 and 2) with the tests where polyacrylamide was used (Tests 6–8), it can be observed that 1% per dry weight of sediment concentration of the polymer achieved the highest dewatering efficiency. Polyacrylamide concentration of 0.5% achieved a slightly lower dewatering efficiency compared to when only EK was used, and 2% polyacrylamide concentration experienced a significantly lower dewatering efficiency compared to when only EK was used. Additional testing will be required to determine the effects of using polymer concentrations lower than 0.5%.

### 3.2. Compressibility

Compressibility was determined as the percent reduction in sample height based on the readings from the deflection gage. Fig. 4(a) and (b) show the sediment compressibility efficiency

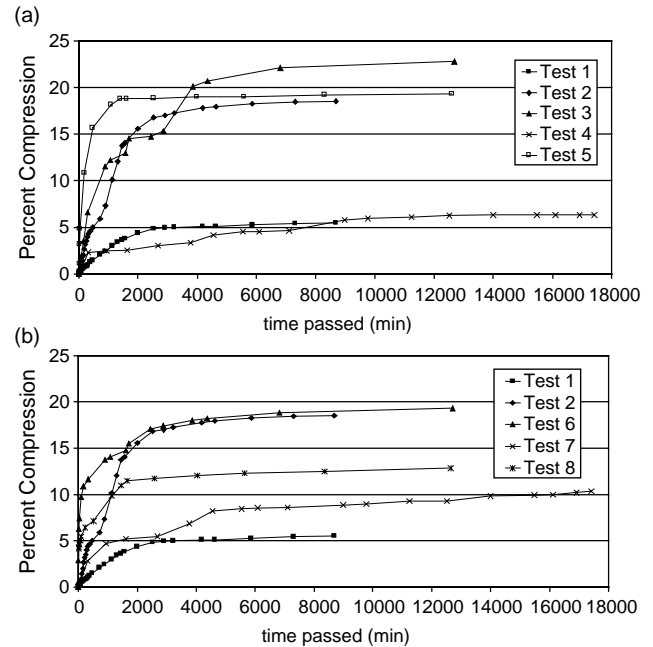


Fig. 4. (a) Compressibility efficiency vs. time: baseline and polyacrylic acid added tests. (b) Compressibility efficiency vs. time: baseline and polyacrylamide added tests.

vs. time. These results follow the dewatering trends observed. As sediment dewatering occurred, settlement also occurred. Settlements initially occurred rapidly and the rate of increase in settlement was lower at later stages of testing. Such a trend was observed in all of the tests conducted in this study.

The maximum compressibility of sediment observed in different tests is compared in Fig. 3. Based on these results, the compressibility efficiency was only 6% when no EK (gravity only) was used compared to about 18% when only EK was used. Comparing baseline tests (Tests 1 and 2) with the tests where polyacrylic acid was used (Tests 3–5), it can be observed that highest dewatering efficiency corresponds to the highest compressibility. Test 3, EK with 0.5% polyacrylic acid, achieved a compressibility of 23%. Tests 4 and 5 with polyacrylic acid concentrations 1 and 2% by dry weight of sediment, respectively, achieved compressibilities of 6 and 19%, respectively. Comparing baseline tests (Tests 1 and 2) with the tests where polyacrylamide was used (Tests 6–8), it can be observed that 1% per dry weight of sediment concentration of the polymer (Test 6) achieved the highest compressibility efficiency, 19%. In the case of polyacrylamide, it was not the test with the highest dewatering efficiency that experienced the greatest compression. It is noteworthy that compression of the sediment sample did not occur uniformly throughout the section. The inner portion of the sample compressed more than the outer ring of the sample.

### 3.3. Current and power consumption

Fig. 5(a) and (b) show the electric current with time. The current was high initially and gradually decreased.

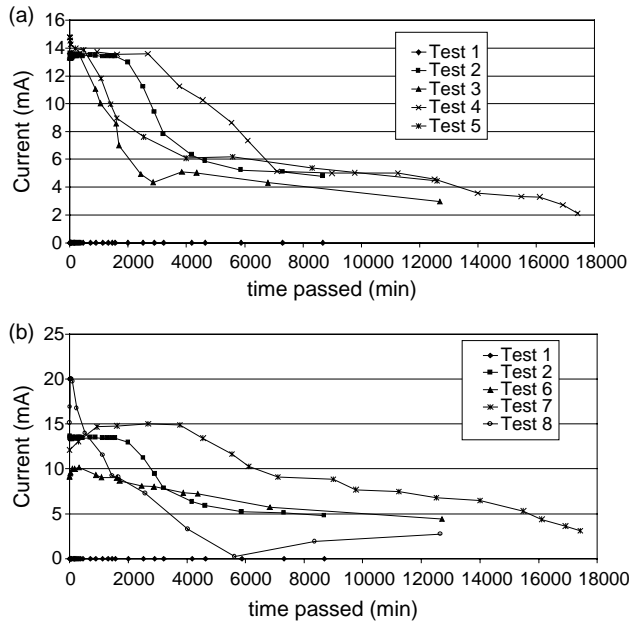


Fig. 5. (a) Current vs. time: baseline and polyacrylic acid added tests. (b) Current vs. time: baseline and polyacrylamide added tests.

The current finally stabilized at 2–5 mA. Generally, the current was proportional to the amount of ionic species present in the pore water. Initially, the ionic concentration was high, which resulted in high current. The ionic concentration decreased at later stages as a result of physicochemical changes, electromigration and electroosmotic flow. The energy consumption for each test can be calculated by the following equation:

$$E = \frac{P}{V_S} = \frac{1}{V_S} \int VI dt$$

where  $E$ , energy consumption per unit volume of sediment ( $\text{W h/m}^3$ );  $P$ , energy expenditure ( $\text{W h}$ );  $V_S$ , volume of sediment ( $\text{m}^3$ );  $V$ , the voltage ( $\text{V}$ );  $I$ , current ( $\text{A}$ );  $t$ , processing time ( $\text{h}$ ). The potential difference was kept constant at 1 VDC/cm of the sediment sample. Energy consumption for the baseline EK test was  $489 \text{ W h/m}^3$ . The energy expenditure ranged from 280 to  $894 \text{ W h/m}^3$  for tests using polyacrylic acid and from 365 to  $1022 \text{ W h/m}^3$  for tests using polyacrylamide.

#### 3.4. Sediment moisture content, pH, redox potential and electrical conductivity

Fig. 6(a) and (b) show the reduction in moisture content of the sediment after the testing. Test 1 conducted without applying electric potential shows less than 5% moisture content reduction. Test 2 conducted with the application of electric potential resulted in a moisture content reduction of 35% near the bottom of the sediment sample and 51% at the top of the sediment sample. However, tests conducted with the polymer amendment show significant variation in

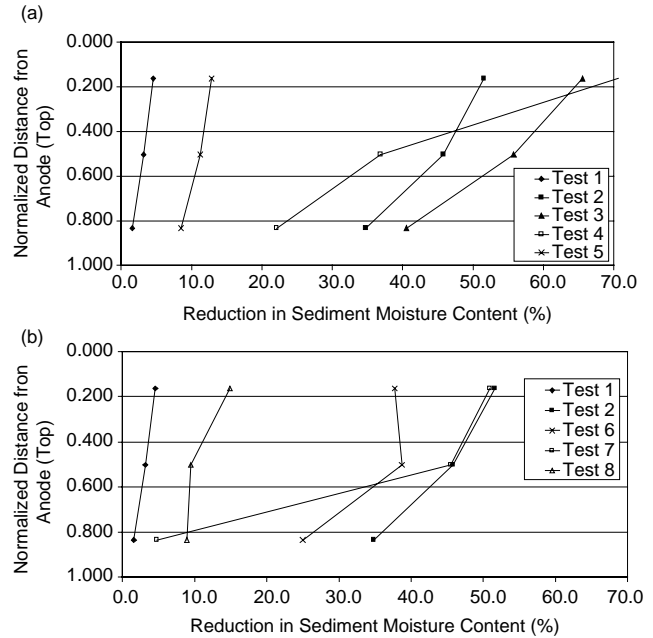


Fig. 6. (a) Reduction of water content vs. normalized distance from anode: baseline and polyacrylic acid added tests. (b) Reduction of water content vs. normalized distance from anode: baseline and polyacrylamide added tests

the reduction of moisture content. Higher percentages of polymer addition resulted in low reduction of moisture content; however, lower percentages of polyacrylic acid addition resulted in reductions in moisture content higher than the situation where electric potential was applied without polymer addition. The reduction in moisture content was high at the top of the sediment column and it ranged from 12 to 68% in the case of polyacrylic acid amended sediment, while the reduction in moisture content ranged from 15 to 51% in case of polyacrylamide amended sediment.

Fig. 7(a) and 7(b) show the sediment pH variation after the tests were completed. Comparing with the Test 1 results, sediment pH decreased near the top of the sediment columns and increased near the bottom. In other words, the value of pH increased when moving away from the anode and approaching the cathode. The value of pH at the anode was generally lower than pH of the sediment and polymer mix before a potential difference was applied. The pH value at the cathode was generally higher than pH of the sediment and polymer mix before a potential difference was applied. The sediment in the area surrounding the anode was acidified and sediment close to the cathode became more basic after EK was applied. When no EK was applied, the pH at the anode was approximately the same as the pH at the cathode. The observed pH changes in EK and polymer tests are attributed to the electrolysis reactions that generate  $\text{H}^+$  ions at the anode and  $\text{OH}^-$  ions at the cathode (e.g., Reddy and Saichek, 2003).

The redox potential and electrical conductivity of sediment measured after the tests were completed are shown

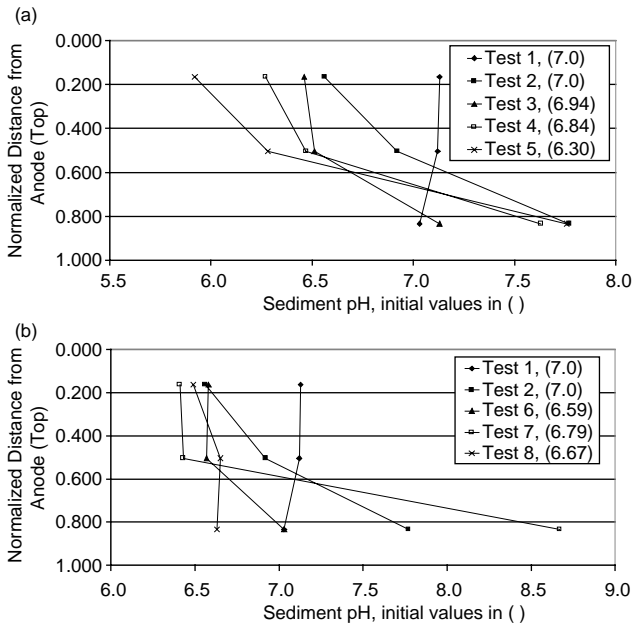


Fig. 7. (a) pH vs. normalized distance from anode: baseline and polyacrylic acid added tests (initial pH values shown for each test). (b) pH vs. normalized distance from anode: baseline and polyacrylamide added tests (initial pH values shown for each test).

in Figs. 8 and 9, respectively. The redox potential decreased when moving away from the anode and approaching the cathode. The value of redox at the anode was generally higher than redox of the sediment and polymer mix before a potential difference was applied. The electrical conductivity of the

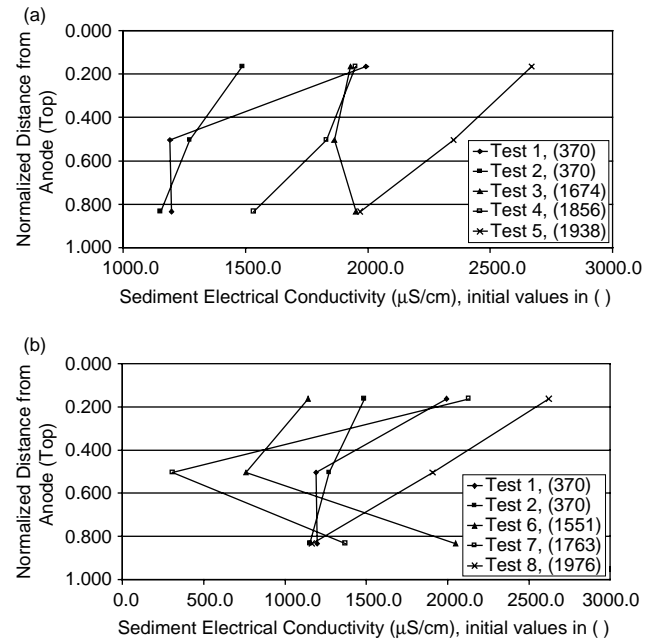


Fig. 9. (a) Electric conductivity vs. normalized distance from anode: baseline and polyacrylic acid added tests (initial values shown for each test). (b) Electric conductivity vs. normalized distance from anode: baseline and polyacrylamide added tests (initial values shown for each test).

sediment was usually higher at the anode. Also, there was generally an increase in electrical conductivity near the anode region after the tests were completed compared to the initial sediment and polymer mixes.

### 3.5. Effluent quality

Effluent samples were analyzed for PAHs using liquid–liquid extraction procedure followed by GC analysis (Reddy and Saichek, 2003). In addition, pH, redox potential, and electrical conductivity of the accumulated effluent samples was also measured. Although PAHs were initially present in the sediment, neither the PAHs nor their transformation products were detected in the effluent samples. This indicates that the PAHs are strongly bound to the organic matter that is present in the sediment. The measured pH, redox potential and electrical conductivity of effluent samples are summarized in Table 4. For all tests, the effluent pH was greater than the pH at any section of the sediment or the pH of the initial sediment mix of each test. Application of EK made the effluent solution basic. Redox of the effluent volume was higher than the redox of the initial sediment mix when no EK was applied to the sediment sample. After EK and polymers were applied, redox of the effluent volume was always lower than the initial redox of the sediment sample for each test. For electrical conductivity, there was an increase in the values of the effluent compared to initial sediment values for Test 1 and 2 by factors 1.8 and 7.8, respectively. However, when polymers were added, as in Tests 3 to 8, electrical

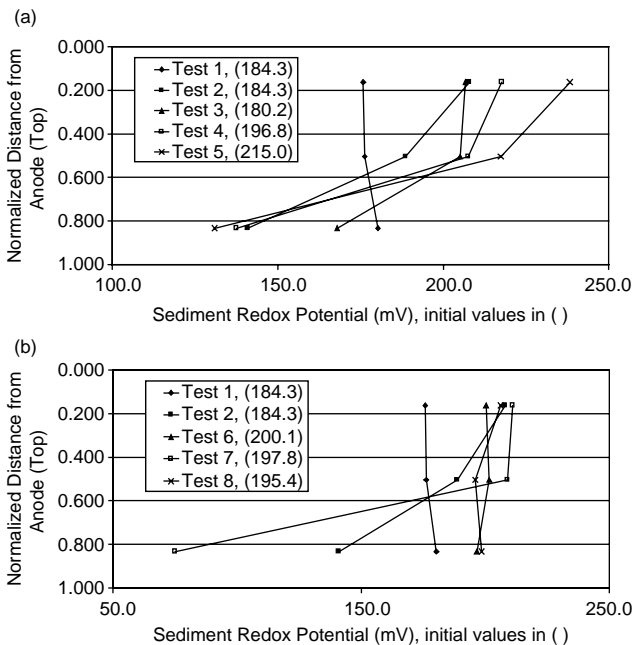


Fig. 8. (a) Redox vs. normalized distance from anode: baseline and polyacrylic acid added tests (initial values shown for each test). (b) Redox vs. normalized distance from anode: baseline and polyacrylamide added tests (initial values shown for each test).

Table 4  
Results of effluent analysis

Test number	Test designation	pH	Redox (mV)	Conductivity ( $\mu\text{S}/\text{cm}$ )
1	DW-1	8.15	291.0	669
2	EK-DW-2	11.83	−111.6	2910
3	EK-DW-5	11.37	−81.0	1407
4	EK-DW-3	11.31	−78.5	2130
5	EK-DW-7	11.12	−71.6	1609
6	EK-DW-6	10.4	−28.0	1389
7	EK-DW-4	8.88	−62.8	1938
8	EK-DW-8	9.44	−29.8	1257

conductivity of the effluent was generally lower than its initial value of the sediment.

### 3.6. Effect of flocculant on final dewatering and compression

The data from Table 4 show pH, redox, and conductivity values of the effluent. The conductivity values were higher for Tests 3–5 conducted with polyacrylic acid (an anionic polymer flocculant) than for Tests 6–8 conducted with polyacrylamide (a nonionic flocculant). The anionic flocculant under the EK test conditions may be responsible for a higher proportion of ionic species in the sediment. The anionic species attempt to electromigrate towards the anode under the applied electric potential. However, the electro-osmotic flow may have caused the elution of these species in effluent, leading to higher values of conductivity in the effluent in the test using anionic flocculant. The effluent pH values were higher for the tests using the anionic flocculant than for the tests using the nonionic flocculant. The pH values in the effluent were highly alkaline (11–12) using the anionic flocculant. The effluent pH values for the nonionic flocculant were closer to neutral, suggesting that the nonionic flocculant had a buffering effect on the pH of the EK solution across the sediment column. A reverse trend was observed for redox values, where redox values in the effluent were lower for Tests 3–5 than for Tests 6–8.

#### 3.6.1. Dewatering efficiency

For the anionic flocculant, the lowest concentration of flocculant (0.5%) resulted in the greatest dewatering (Test 3) with less dewatering at higher flocculant concentrations (1 and 2%). The sediment pH data from Fig. 7(a) show that the smallest and the greatest pH polarization across the sediment column occurred for the EK tests using the highest and lowest flocculant concentrations, respectively. The data from Figs. 7(a) and 3 suggest that for the EK tests with the anionic flocculant, the final dewatering efficiency varied inversely with pH polarization across the sediment column. High effluent pH values and thus higher dewatering resulted throughout the sediment column and persisted with time (Fig. 2(a)). The data from Fig. 3 and Table 3 show that the effluent pH value was

highest for the greatest final dewatering efficiency (at the lowest flocculant dosage).

For the nonionic flocculant, the intermediate concentration of flocculant (1%) resulted in the greatest dewatering (Test 7) with decreasing dewatering at both higher and lower flocculant concentrations (0.5 and 2%). The sediment pH data from Fig. 7(b) show that the greatest pH polarization across the sediment column occurred for the EK test using the intermediate flocculant concentration (Test 7). The data from Figs. 7(b) and 3, suggest that for the EK tests with the nonionic flocculant, the final dewatering efficiency increased with increasing pH polarization across the sediment column. The data from Fig. 3 and Table 4 show that the effluent pH value was lowest for the greatest final dewatering efficiency (at intermediate flocculant dosage).

#### 3.6.2. Compression efficiency

For the anionic flocculant, the intermediate concentration of flocculant (1%) resulted in the lowest final compression (Test 4) with higher compression efficiencies at lower and higher flocculant concentrations (0.5 and 2%). The data from Fig. 3 and Table 4 show that the effluent electrical conductivity value was highest for the lowest final compression efficiency (at intermediate anionic flocculant dosage). The sediment electrical conductivity data from Fig. 9(a) show that for Test 4, the sediment electrical conductivity values of the middle and bottom sections of the sediment column were lower than the values for the sediment middle and bottom sections in Tests 3 and 5. The data from Figs. 9(a) and 3 suggest that for the EK tests with the anionic flocculant, the final compression efficiency decreased with decreasing sediment electrical conductivity in the bottom section of the sediment column (towards the cathode).

For the nonionic flocculant, the intermediate concentration of flocculant (1%) resulted in the lowest final compression (Test 7) with higher compression efficiencies at lower and higher flocculant concentrations (0.5 and 2%). The data from Fig. 3 and Table 4 show that the effluent electrical conductivity value was highest for the lowest final compression efficiency (at intermediate nonionic flocculant dosage), while decreasing for higher compression efficiencies.

#### 3.6.3. Comparison of flocculants

Fig. 3 shows the final dewatering and compressibility efficiencies of the sediment for all tests. The data from Fig. 3 show that, overall, higher final dewatering was obtained in EK tests using the anionic flocculant (Tests 3–5) than in EK tests using the nonionic flocculant (Tests 6–8). The data from Fig. 3 show that, overall, comparable final compressibilities were obtained in EK tests using either the anionic flocculant (Tests 3–5) or the nonionic flocculant (Tests 6–8). The compression efficiency of the sediment after the application of the flocculant depends on the quality and consistency (density and size, pore water) of the flocculated

sediment particles. Better compressibility would more likely result from a lighter sediment cake. The final dewatering and compression results from Fig. 3 indicate that, for this sediment, the application of an anionic flocculant during EK led to a significant enhancement in the dewatering and compression of sediment.

#### 4. Conclusions

Based on the results of experiments, the following conclusions can be drawn:

- Dewatering of sediment can be enhanced by the electroosmosis induced by the application of an electric potential. Amending sediment with polymers will enhance this dewatering process even more. However, the optimal polymer concentration and the cost-effectiveness of using polymers should be investigated further.
- Concentration of the polymers affects the dewatering efficiency. Lower concentrations proved to be more effective in water removal.
- Application of electric potential and polymers enhanced consolidation of sediment more effectively than the use of gravity alone.
- Application of electric potential will result in energy consumption. The energy consumption is proportional to dewatering efficiency; greater potential difference yields greater dewatering.
- Chemical properties of the sediment as well as the effluent are changed when electrokinetics and polymers are applied. Because of high organic content of the sediment, PAHs are held strongly within the sediment mass. As a result, the management of effluent may be easier.

Overall, the results showed that the electroosmotic flow and the consolidation of the sediment were increased by an order of magnitude under an applied voltage gradient of

1.0 VDC/cm for less than 10 days. Although these tests proved that electroosmosis is very effective for increasing sediment dewatering rates, several system parameters relevant to the Indiana Harbor sediment have not been determined. These parameters include the optimal electric potential, mobility/immobility of contaminants, and management of outflow as well as capital costs and operational and maintenance costs.

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