1 of 1

**Removal of Contaminants from Fine-Grained Soils
Using Electrokinetic Flushing**

**Semiannual Report
July 1 through December 31, 1992**

**B.E. Reed
M.T. Berg**

January 1993

Work Performed Under Contract No.: DE-FC21-87MC24207

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
West Virginia University
National Research Center for Coal and Energy
Morgantown, West Virginia

MASTER

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January 1993

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EXECUTIVE SUMMARY

This report details the current status of the work conducted on the use of electrokinetics (EK) to remediate a fine grained soil contaminated with lead. The first portion of the experimental work entails soil collection and characterization, soil adsorption and desorption of lead, and experimental setup construction and testing.

Test soil was collected from a site in Northern Erie County, New York and underwent standard preparation and physical/chemical characterization. Based on the Soil Conservation Service classification, the soil is a silt loam. The soil has a low hydraulic permeability ($\approx 10^{-7}$ cm/s), has a large amount of fine materials, moderate organic carbon content, and a moderately high cation exchange capacity (CEC). The soil has a low indigenous lead content and is slightly acidic.

The study soil was artificially contaminated with lead to concentrations of 95, 800, and 7600 mg Pb/kg soil. Laboratory determined soil lead concentrations agreed well (within 10 percent) with those calculated from mass balance calculations.

Lead desorption experiments were conducted using several concentrations of HCl, HNO₃, EDTA, CaCl₂, acetic acid, and tap water. HCl, HNO₃, and EDTA desorbed the majority of the soil-bound lead. Acetic acid and CaCl₂ were less effective while, tap water was ineffective. Based on these results, the addition of these reagents to the electrokinetic flushing process may improve remediation efficiency. In future work the effectiveness of the additives will be tested in the actual EK flushing apparatus.

An experimental apparatus to mimic EK flushing in the field was designed and one unit was constructed. The experimental apparatus consisted of a consolidation unit and electrokinetic (EK) soil reactor. A schematic of the experimental setup and detailed drawings of the consolidator and EK reactor are provided in the body of this report. The single experimental unit underwent testing to determine if water could be moved through the soil under an applied electric current. Significant quantities of water were moved through soil. Water movement experiments were conducted at several make-up and reservoir water conductivities. Based on limited results, water movement increased with increased conductivity. The pH and conductivity of the reservoir waters were monitored during the reactor testing. With time, the pH at the cathode dropped to less than 4 and at the anode was raised to about 10. Conductivities of the two reservoirs increased from their initial values because of ion migration from the soil into the reservoirs and the increase in either H⁺ and OH⁻. The change in pH and conductivity with time was expected based on literature results and indicates that the EK reactor was working properly.

Based on these initial tests, five consolidation units and EK reactors are being constructed. Following testing of the new units, the soil remediation portion of the project (Task 3) will begin. In Task 3, the ability of the electrokinetic process to remediate lead contaminated soils will be investigated. Lead contaminated soils will be placed in the electrokinetic reactors and the reactors will be operated under the optimum conditions determined from earlier work. Water samples from the cathode and anode will be periodically measured for lead concentration. Soil pH and other parameters will be monitored. At the end of the experiments, soil samples will be taken from the reactors and the lead content will be determined. The efficiency of the electrokinetic process will be determined based on the amount of lead removed from the soil. Reactor experiments will be repeated using chemical agents that were effective in desorbing lead in batch desorption experiments. Task 3 will take 6 months to complete.

INTRODUCTION

Recently, attention has focused on developing cost effective techniques to remove contaminants from soils *in-situ*. Examples of these technologies are *in-situ* extraction (e.g., soil flushing) and *in-situ* biological treatment. *In-situ* technologies have had success predominately at sites containing sandy soils and have not shown much promise for soils with large amounts of clay and silt (i.e. fine grained, low permeability soils) primarily because of the difficulty in transporting groundwater, contaminants, and chemical additives through the subsurface. Unfortunately, soils high in clay and silt sequester large quantities of inorganic and organic contaminants. Thus, soils having low permeabilities are generally efficient in sequestering pollutants but are resistant to *in-situ* remediation techniques because of the difficulty encountered in promoting groundwater movement and chemical transport.

What is needed are cost effective and more efficient technologies that can be used to remediate low permeability soils *in-situ*. A candidate technology for the remediation of low permeability soils is electrokinetics flushing.

PURPOSE

The purpose of the proposed research is to study electrokinetics as a method of remediating contaminated soils *in-situ*. For this study lead has been chosen as the study contaminant because of its wide spread existence at hazardous waste sites. The research has as

its objective the lab-scale testing of electrokinetic process to determine the parameters governing the transport of water and contaminants in a soil-groundwater system under an applied electric field. Specific tasks to be completed during year one of the project are listed below.

Task 1: Selection and characterization of soil, contamination of soil with lead, and batch desorption isotherms.

Task 2: Electrokinetic (EK) reactor construction and testing.

Task 3: Remediation of a lead contaminated soil using electrokinetics flushing. Specifically, methods of electrode reservoir water conditioning that promote metal transport into the cathode reservoir water will be developed.

Tasks 1 and 2 have been partially completed during the first six months of the research project. Task 3 will be performed after the completion of Tasks 1 and 2. Possible condition schemes include the altering of reservoir pH and conductivity, and the addition of a pH buffers and strong metal chelating agents. It should be noted that work on the research project did not start until September 1992. Funding for the project did not reach the PIs until July 1992 thus, the hiring of graduate research assistants was delayed until the start of the Fall 1992 semester.

BACKGROUND

Electroosmosis (EO) is defined as the movement of a liquid phase under the influence of an electric potential, while the solid phase remains stationary. EO technology has been used for decades for removing water from fine soils and sludges, stabilization of earthen embankments, and dewatering construction sites (Casagrande 1952, 1983). A primary driving force for developing EO technology was the inefficiency of using hydraulic pressure (*i.e.*, pumping) to induce fluid flow in low permeable soils. A schematic of the process is presented in Figure 1. In the presence of an electric field, water molecules will move towards the cathode. Several mechanisms responsible for electroosmotic flow have been proposed:

1. The diffuse portion of the electric double layer (net positive charge for most soils), surrounding the charged soil particle, is attracted to the cathode resulting in water movement toward the cathode.

Figure 1. Schematic of the Electroosmosis/Electrokinetic Process

2. Under an electric potential, hydrated cations will move towards the cathode. The associated water molecules will migrate with the cations. (Note: anions are not usually hydrated thus, no water movement occurs).

Regardless of the exact mechanism responsible for water movement, the quantity of water moved is a function of several factors such as the magnitude of the applied current, conductivity (resistivity) of the groundwater, dielectric constant of the liquid, soil pore radius, viscosity of the fluid (temperature), and the length between electrodes. In addition, as the soil is dewatered, consolidation can occur, altering soil properties and reducing fluid movement. Consolidation is less of a problem in larger grained soils because the granular skeleton is more rigid. Soil temperature may also rise considerably during the application of the electric field, decreasing the soil water content and water flow. Consolidation and soil drying can be minimized if fluid is added at the anode (Khan *et al.* 1989).

The transport of chemical compounds during electroosmosis is often referred to as electrokinetics. A schematic of the electrokinetic phenomenon is also presented in Figure 1. Net contaminant transport is the sum of the transport via convection, ion migration and diffusion. Convection describes the movement of contaminants with the flowing fluid. Ion migration is defined as the movement of cations and anions to the electrodes as a result of the applied electric field. Cations will move towards the cathode, anions towards the anode. In diffusion, contaminants move from areas of high concentration (at the electrodes) to areas of low concentration. Ionic diffusion opposes contaminant migration to the electrodes but it can be reduced if contaminants are extracted at the cathode and an electrolyte is added at the anode (Cabrera-Guzman *et al.* 1990).

In addition to transport, chemical contaminants can undergo several types of reactions. For simplicity, these reactions are divided into two classes; those that would occur in the absence of the applied electric field and those that occur because of the electric field. Examples of the former include, adsorption-desorption of the contaminant from soil surfaces, precipitation-dissolution reactions, and interactions between soluble chemical constituents in the pore water. For the latter, Banerjee *et al.* (1988) has identified two types of reactions; electrochemical and electrodic. Electrochemical reactions refer to the reactions that result from the electron transfer and from the separation of ions in the electrolyte under an applied electric field.

Electroodic reactions are defined as the reactions between the contaminant and the electrode. Examples of electroodic reactions are the "plating" of a heavy metal on the cathode or the electrolysis of water at both electrodes. The electrolysis reactions are at the electrodes are:

Water electrolysis results in a high pH at the cathode and a low pH at the anode. The difference in pH between the two electrodes produces a "pH-front" that migrates with time towards the cathode. A hypothetical representation of this phenomenon is presented in Figure 2. Soil pH is very important for soils contaminated with heavy metals. Generally, as the soil pH decreases desorption of metals from soils increases. As the pH-front moves from the anode to the cathode, the pH of the soil is lowered and metals are desorbed and transported towards the cathode. Thus, for heavy metal contaminated soils, the acidification of the soil is critical for successful treatment. However, the high concentration of OH^- near the cathode will cause precipitation of metals (as $\text{Me}(\text{OH})_2 (\text{s})$) *in the soil*. For remediation to be completely successful, methods need to be developed that allow metal ions to be transported to the cathode reservoir water. The reservoir water can then be removed and treated. Development of ways to chemically condition reservoir water to allow this process to occur is the primary goal of this research. Possible conditioning schemes include the altering of reservoir pH, conductivity, and the addition of a pH buffers and strong metal chelating agents.

In summary, the electrokinetic process is a complex set of physical, chemical, and electrical phenomena. While the electroosmosis process (*i.e.*, water movement) has been studied for decades, the fate and transport of contaminants in a soil-groundwater system under an applied electric field is poorly understood. However, based on a limited amount of research, using electrokinetics to remediate hazardous waste sites shows great promise.

METHODOLOGY

In this section the methodologies used in soil selection and characterization, contamination of the study soil with lead, lead desorption experiments, and the construction and testing of the electrokinetic reactors are described. For the reader's convenience, the methodology used for each task is described separately.

SOIL SECTION AND CHARACTERIZATION

Soil was collected at a depth of three feet from an exposed bank of Tonawanda Creek, located in northern Erie County, New York. Soil was then air-dried at the West Virginia University Department of Civil Engineering's Environmental Laboratories and stored in air

Figure 2. Hypothetical pH-Front Behavior With Time

tight containers for future use. The soil underwent the physical and chemical characterization procedures listed in Table 1. Standardized test methods were employed.

SOIL CONTAMINATION AND DESORPTION EXPERIMENTS

Soil Contamination

The study soil was artificially contaminated with lead using aqueous lead concentrations of 10, 100, and 1000 mg/L. If 100 percent of the lead was adsorbed by the soil, soil lead concentrations would be 100, 1000, and 10000 mg/kg Pb for 10, 100, and 1000 mg/L Pb, respectively. A 10:1 solution:soil mass ratio was employed in the contamination step. Lead nitrate was the source of lead. Sodium nitrate was also added such that the final NaNO_3 concentration was 3200 mg/L. This value corresponds to a Total Dissolved Solids (TDS) concentration of 2300 mg/L, which is typical for groundwaters.

One hundred fifty grams of air-dried soil was sieved using a No. 10 sieve and placed in a 2 liter Nalgene container with 1.5 liters of the appropriate Pb- NaNO_3 solution. An aliquot of the Pb- NaNO_3 solution was acidified and kept for Pb analysis. Initial slurry pH's were taken, and the samples were placed on mechanical shakers for 21 days. To reduce the possibility of lead precipitation as $\text{Pb}(\text{OH})_2$ (s), the 1000 mg/L Pb contamination solution was pH adjusted to 4.8 with concentrated HNO_3 before being mixed with the soil. After 21 days, the samples were allowed to settle overnight to provide adequate time for the colloidal clay particles to settle. The supernatant was decanted and the volume removed is recorded for subsequent mass balance calculations. A small aliquot of the supernatant was filtered through a $0.45 \mu\text{m}$ filter, acidified, and analyzed for Pb content. The soil was allowed to air-dry. The difference between the Pb concentrations of the initial Pb- NaNO_3 solution and supernatant was used to determine the amount of soil-bound lead (*i.e.*, mass balance approach). To verify the mass balance calculations, triplicate samples of the contaminated soil underwent EPA Method 3050 Total Metal Digestions. Since indigenous Pb values were small relative to the levels of contamination used, the total Pb concentration obtained by the digestion method should be very similar to the value obtained using the mass balance approach.

Desorption Experiments

Following the contamination step, the soil was air-dried, crushed, and passed through an ASTM number 10 sieve. In order to assess the behavior of soil-bound lead under electrokinetic conditions, the contaminated soil was extracted with the solutions listed in Table 2. As envisioned, the reagents listed in Table 2 will be added to the electrode reservoir waters as conditioning agents.

Table 1
Physical and Chemical Characterizations and Methods Used

Particle Size Analysis (ASTM Method D422)
Hydraulic Conductivity (ASTM Method D5084)
Field Moisture Content (ASTM Method D2216)
Cation Exchange Capacity (USEPA Method 9081)
Organic Matter Content (ASTM D2974)
Soil Digestion for Lead (USEPA Method 3050)
Aqueous Lead Determination (USEPA Method 7420)
Soil pH (USEPA Method 9045)

Table 2
Candidate Conditioning/Extraction Solutions

Tap Water
1 and 0.1 N HCl
1 and 0.1 N HNO ₃
1 and 0.1 N Acetic Acid
1 and 0.1 M CaCl ₂
0.1 and 0.01 M EDTA

Acids were employed to simulate the conditions that occur as the pH-front moves from the anode to the cathode. CaCl_2 was used to replicate the behavior of soil-bound lead as the conductivity of the pore water solution is increased. EDTA, a strong complexing agent, was used to assess its possible use as a desorptive additive to the EK process. Tap water was used to provide a benchmark.

In the batch desorption experiments, 25 mL of extraction solution was delivered (via a wide-mouth volumetric pipette) into 60 mL Nalgene bottle containing 1.00 ± 0.02 grams of contaminated soil. To induce rapid equilibration, the samples were placed on mechanical shakers for a 24 hour period. At the end of the 24 hour period, the pH of the sample slurries were measured and recorded. Samples were filtered through a $0.45 \mu\text{m}$ filter, acidified with concentrated HNO_3 to $\text{pH} < 2$ if required, and stored for lead determination. Aqueous lead content was determined using USEPA Method 7420. Desorption experiments were performed in triplicate. The filter assembly was rinsed between triplicates in order to reduce the possibility of sample contamination.

EXPERIMENTAL APPARATUS CONSTRUCTION AND TESTING

Apparatus Construction

The experimental apparatus consisted of a consolidation unit and electrokinetic (EK) soil reactor. Schematic of the experimental setup is presented in Figure 3. Detailed drawings of the consolidator and EK reactor are provided in Figures 4 and 5, respectively. At the time of writing this report one consolidator and one EK reactor have been constructed by technicians from the Department of Civil Engineering. Materials used to construct the units are indicated on the drawings. Five additional units will be built after the initial testing of the two units is completed.

Apparatus Testing

Consolidation Apparatus

Soils must be consolidated prior to placement in the EK reactor. To ensure experimental reproducibility, a consistent and reliable method of consolidation must be identified. Uncontaminated soil was used in consolidation experiments. Approximately 48 hours was required to complete the consolidation of one soil sample. The consolidation procedure used is described in the following paragraphs.

1. Soil was crushed and passed through a number 10 sieve to remove gravel or large organic material.

Figure 3. Schematic of Experimental Setup

Figure 4. Detailed Drawings of Consolidation Unit

SCALE: DRAWN TO 1/2" SCALE
 NOTE: BOTH SIDES SYMMETRIC FROM VERTICAL CENTER LINE

Figure 5. Detailed Drawings of Electrokinetic (EK) Unit

2. Tap water was added to approximately 200 g of soil to form a slurry having a water content of about 60 percent. The actual water content of the slurry was measured and recorded prior to consolidation. For several experiments, electrolyte (NaNO_3) was added to the tap water to change the conductivity of the pore water.

3. The soil slurry was mixed for 5 minutes with a soil mixer to break up any clumps, reduce the amount air voids, and provide a homogeneous mixture.

4. The soil slurry was poured into the reactor cell and consolidation guide, leaving about 2 inches of clear space near the top of the guide. The pneumatic piston is then placed in the consolidation sleeve and secured.

5. Pressure regulators were used to adjust the air pressure to the consolidation devices which applies the consolidation pressure to the soil specimen. The consolidation devices were calibrated to determine the amount of air gauge pressure needed to produce the desired consolidation pressures at the piston and soil interface. The amount of consolidation was measured as the amount of piston movement. The soil sample was consolidated using the pressure schedule listed below.

Pressure (psi)	Duration (hr.)
5.0	2.0
10.0	2.0
15.0	10.0
20.0	10.0
25.0	2.0
30.0	2.0

6. After consolidation, the reactor cell containing the consolidated soil was removed from the consolidator and trimmed so that porous stones and filter paper could be placed at each end. The reactor cell, intact with consolidated soil specimen, filter paper, and porous stones was then placed into the EK reactor. The water content of the consolidated soil was determined using the trimmed soil.

Electrokinetic (EK) Reactor

The EK reactor utilizes a Triple Output DC Power Supply. Each power supply has the capability of powering two separate electrokinetic reactors with constant current or voltage. The power supply is capable of providing 30 volts of electricity to two separate reactors, or it may also be hooked up in series operation to obtain a maximum output of 60 volts to a single reactor.

The test soil is contained in the same acrylic cylinder used for the consolidation. The reactor cell is placed between the two reservoirs. A pair of inert graphite plate electrodes are used to apply the electric current to the soil cell. The electrodes are directly submerged in water contained by reservoirs adjacent to each end of the soil cell. Flow measurement is accomplished by graduated burettes connected to the top of each reservoir. The burettes are opened to the atmosphere to allow for the passage and release of gas generated from electrolysis reactions. Sampling ports are located at the bottom of each reservoir to allow for removal of reservoir water for analysis. Each reservoir was designed to allow for the insertion of a pH probe and reservoir conditioning. The reservoirs are also elevated to allow for a mini-magnetic stirrer to be placed below them, to be used in conjunction with conditioning. A multimeter was used to attain accurate measurements of the magnitude of the current, voltage drop, and resistance between the electrodes.

The initial testing of the EK reactor consisted of determining the water movement with respect to time (measured as the amount of water discharged at the cathode) as a function of ionic strength of the soil slurry make-up and reservoir water. Constant voltage (30 volts) conditions were employed. The pH and the conductivity of the electrode reservoir water were also monitored.

RESULTS AND DISCUSSION

In this section the results from soil selection and characterization, soil contamination and desorption experiments, and experimental apparatus construction and testing are described. For the reader's convenience, results from each task are described separately.

SOIL SELECTION AND CHARACTERIZATION

The soil was collected from a site in Northern Erie County, New York. Results from the particle size analysis are listed in Table 3. Additional physical and chemical characteristics of the soil are listed in Table 4.

Table 3
Particle Size Analysis of Study Soil

Sieve Number	Percent Passing
10	96.5
20	75.8
40	57.5
60	47.1
100	40.6
200	30.5

Table 4
Physical and Chemical Characteristics of the Study Soil

Characteristic	Value
Hydraulic Conductivity	5.1×10^{-8} cm/sec
Field Moisture Content	17.5 percent
Cation Exchange Capacity	25.6 meq/100 g
Loss on Ignition	5.53 percent
Total Lead Content	2.75 mg/kg
Soil pH	5.64

The Soil Conservation Service classifies this soil a silt loam. The low hydraulic permeability is attributed to the large amount of fine materials (amount passing through a number 200 sieve). The soil has a moderate organic carbon content (as measured by the loss of mass on ignition) and moderately high cation exchange capacity (CEC). The soil has a low indigenous lead content and is slightly acidic.

SOIL CONTAMINATION AND DESORPTION EXPERIMENTS

Soil Contamination

The extent of lead adsorption by the study soil is presented in Table 5. Soil bound lead concentrations, as measured by USEPA Methods 3050 and 7420, were 94.5 mg/kg for 10, 798 mg/kg for 100 mg/L Pb and, 7622 mg/kg for 1000 mg/L Pb. The vast majority of the aqueous lead was adsorbed by the soil. This was not surprising given the large fine particle content and high CEC. Method 3050/7420 values agreed well with those determined using the mass balance approach. The largest percent difference between the two methods was about 10 percent. Based on these results there should not be any problem controlling the lead content of the study soil.

Desorption Experiments

The amount of lead removed for each of the extracting agents tested are presented in Figure 6. Tap water removed very little lead thus, the majority of the lead is in the sorbed form and not associated with soil pore water. The most effective reagents are HCl, HNO₃, and EDTA. For the conditions tested in this study, lead desorption does not appear to be related to the concentration of these three reagents. The addition of HCl and HNO₃, both strong acids, lowered the pH to less than 3. For most solid-heavy metal systems desorption of the metal occurs as the pH is lowered. In the EK process, soil pH behind the pH-front can be less than that observed in the desorption experiments. Thus, it appears that the majority of the soil-bound lead should be desorbed in the low pH regions of the EK soil reactor. EDTA, a strong heavy metal complexer, was an excellent extracting agent. However, the EDTA-Pb complexes are negatively charged and thus are attracted to anode under electrostatic forces and towards the cathode under convective forces. Thus, despite the beneficial complexing traits of EDTA, the possible inability to achieve effective mass transport may render EDTA unsuitable for use in EK remediation. The effectiveness of EDTA in improving the efficiency of the EK flushing process will be tested in Task 3 of the project.

CaCl₂ was an effective extracting agent at a concentration of 1.0 M but was inadequate at 0.1 M. It is hypothesized that the desorption of lead in the presence of CaCl₂ is caused by ion exchange (exchange of Pb with Ca on the soil surface). The increase in lead desorption with

Table 5
Soil Lead Concentrations

Aqueous Pb, mg/L	Soil-Bound Pb, mg/kg	
	Mass Balance	Method 3050
10	96.8	94.5
100	878	798
1000	8356	7622

Figure 6. Lead Desorbed For Study Extraction Agents

increase CaCl_2 concentration reinforces this hypothesis. Since both pore water conductivity and pH is expected to increase with EK treatment significant remediation can be expected. Acetic acid was moderately effective in desorbing soil-bound lead. Acetic acid is a weak acid-base complex with a $\text{pK}_a = 4.7$ (*i.e.*, maximum pH buffering capacity near $\text{pH} = 4.7$) thus, desorption efficiencies should be less than those observed for HCl and HNO_3 . Soils with high buffering capacities will behave in a similar fashion. Acetic acid (or a similar weak acid-base system) may be used to pH buffer cathode reservoir water and soil near the cathode. Under these conditions it is hypothesized that lead, desorbed from other sections of the soil reactor, will not precipitate near the cathode but will be transported into the cathode reservoir. This hypothesis will be tested in Task 3 of the project.

EXPERIMENTAL APPARATUS CONSTRUCTION AND TESTING

Apparatus Construction

Details of the construction of the consolidation unit and EK reactor have been presented in the Methodology section. In the remainder of this section, preliminary results from apparatus testing will be presented and discussed.

Apparatus Testing

The principal objective of this study is to improve the remediation aspect of EK. In conventional EK systems the reservoir waters are not conditioned with chemical reagents. As mentioned previously, one possible conditioning process is the adjustment of reservoir water pH. Without pH adjustment, a region of high pH ($\text{pH} \approx 10$) exists near the cathode and low pH ($\text{pH} \approx 3$) exists near the anode. With time, the pH front will move towards the cathode (*i.e.*, the soil pH throughout the soil specimen will drop). Soil-bound metals that desorb and migrate to the cathode, can precipitate as $\text{Me}(\text{OH})_2$ (s) in the soil surrounding the cathode. Thus, the soil is not truly remediated. The PIs hypothesize that by altering the pH of the cathode and/or anode reservoir water more lead can be transferred from the soil to the reservoir water. A possible drawback to this scheme is that water movement via EK is dependent on the conductivity of the soil and reservoir waters. Several studies indicate that as the conductivity increases water movement decreases (reducing the effectiveness of EK flushing). Other researchers have reported the opposite. Since adjusting the pH of the reservoirs will increase the conductivity, it is imperative that the effect of conductivity on water movement be determined for the soil under investigation. The addition of the other extracting agents tested in this project will also alter the conductivity of the system.

With this in mind, the first task in EK reactor testing was to determine the effects pore and reservoir water conductivity have on water movement in the EK soil specimen. As of the

writing of this report, the single operational EK unit was operated under conditions reported in Table 6. Conductivity was altered using NaNO_3 . Volume water discharge as a function of time are presented in Figures 7, 8, and 9, for conductivities of ≈ 1 , 123, and 1174 micromho, respectively. Volume of water moved in 24 hours versus conductivity of make-up and reservoir waters is presented in Figure 10. As the conductivity was increased, water movement increased. This is expected at the range of conductivities tested as the resistivity is inversely proportional to the conductivity. Further tests will be conducted to determine if the relationship observed in Figure 10 is valid at higher conductivities (up to $\approx 10,000$ micromho). The results in Figure 10 are encouraging for the use of conditioning agents as the water movement was not adversely affected.

The pH and conductivity of the reservoir waters versus time are presented in Figures 11 and 12, respectively. The initial pH of the anode and cathode reservoir waters was approximately 8. With time, the pH at the cathode dropped to less than 4 and at the anode was raised to about 10. The pH values of 4 and 10 represent the extremes of the pH-front. Conductivities of the two reservoirs increased from their initial values because of ion migration from the soil into the reservoirs and the increase in either H^+ or OH^- . The change in pH and conductivity was expected based on literature results and indicates that the EK reactor is working properly.

FUTURE WORK

The remainder of the project will focus on completing Task 3. In Task 3, the ability of the electrokinetic process to remediate lead contaminated soils will be investigated. Lead contaminated soils from Task 1 will be placed in the electrokinetic reactors and the reactors will be operated under the optimum conditions determined in Task 2. Water samples from the cathode and anode will be periodically measured for lead concentration. Soil pH and other parameters mentioned in Task 2 will be monitored. At the end of the experiments, soil samples will be taken from the reactors and the lead content will be determined. The efficiency of the electrokinetic process will be determined based on amount of lead removed from the soil. Reactor experiments will be repeated using chemical agents that were effective in removing lead from Task 1 batch experiments. Task 3 will take 6 months to complete.

Table 6
Initial EK Reactor Operating Conditions

Constant Voltage = 30 V
Conductivities of Make-Up and Reservoir Waters:
≈ 1 micromho (Distilled Water)
123 micromho (10^{-5} M NaNO ₃)
1174 micromho (10^{-2} M NaNO ₃)

Test #3 Distilled Water; Conductivity=0.95micromho

Constant Voltage (30V)

Figure 7. Volume Water Discharge Versus Time for Conductivity = ≈ 1 micromho

Test #4: 10^{-5} M Na NO₃; Conductivity= 123.4 micromho

Constant Voltage (30V)

Figure 8. Volume Water Discharge Versus Time for Conductivity = 123 micromho

Test #5: 0.01M NaNO₃; Conductivity=1174 micromho

Constant Voltage (30V)

Figure 9. Volume Water Discharge Versus Time for Conductivity = 1174 micromho

Constant Voltage (30V)

Figure 10. Volume of Water Moved in 24 hours Versus Conductivity of Make-Up and Reservoir Waters

Figure 11. pH of Reservoir Waters Versus Time

Figure 12. Conductivity of Reservoir Waters Versus Time

SUMMARY

Test soil was collected from a site in Northern Erie County, New York and underwent standard preparation and physical/chemical characterization. Based on the Soil Conservation Service classification, the soil is a silt loam. The soil has a low hydraulic permeability ($\approx 10^{-7}$ cm/s), has a large amount of fine materials, moderate organic carbon content, and a moderately high cation exchange capacity (CEC). The soil has a low indigenous lead content and is slightly acidic.

The study soil was artificially contaminated with lead to concentrations of 95, 800, and 7600 mg Pb/kg soil. Laboratory determined soil lead concentrations agreed well (within 10 percent) with those calculated from mass balance calculations.

Lead desorption experiments were conducted using several concentrations of HCl, HNO₃, EDTA, CaCl₂, acetic acid, and tap water. HCl, HNO₃, and EDTA desorbed the majority of the soil-bound lead. Acetic acid and CaCl₂ were less effective while, tap water was ineffective. Based on these results, the addition of these reagents to the electrokinetic flushing process may improve remediation efficiency. In future work the effectiveness of the additives will be tested in the actual EK flushing apparatus.

An experimental apparatus to mimic EK flushing in the field was designed and one unit was constructed. The experimental apparatus consisted of a consolidation unit and electrokinetic (EK) soil reactor. Schematic of the experimental setup and detailed drawings of the consolidator and EK reactor are provided in the body of this report. The single experimental unit underwent testing to determine if water could be moved through the soil under an applied electric current. Significant quantities of water were moved through soil. Water movement experiments were conducted at several make-up and reservoir water conductivities. Based on limited results, water movement increased with increased conductivity. The pH and conductivity of the reservoir waters were monitored during the reactor testing. With time, the pH at the cathode dropped to less than 4 and at the anode was raised to about 10. Conductivities of the two reservoirs increased from their initial values because of ion migration from the soil into the reservoirs and the increase in either H⁺ and OH⁻. The change in pH and conductivity with time was expected based on literature results and indicates that the EK reactor was working properly.

Based on these initial tests, five consolidation units and EK reactors are being constructed. Following testing of the new units the soil remediation portion of the project (Task 3) will begin.

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