

A laboratory feasibility study on electrokinetic injection of nutrients on an organic, tropical, clayey soil

Celina A.B. Schmidt^{a,*}, Maria Claudia Barbosa^b, Márcio de S.S. de Almeida^b

^a Department of Structures and Foundations,
University of State of Rio de Janeiro, UERJ, Brazil

^b COPPE, Graduate School of Engineering Federal University of Rio de Janeiro, Brazil

Available online 9 January 2007

Abstract

Based on the results of an environmental investigation program, carried out on an oil production field at Brazilian Northeast, a contamination diagnosis was made. The field was contaminated by crude oil and saline production water and the use of *in situ* electrokinetic bioremediation techniques *in situ* were suggested for the remediation of the contaminated site. The analyzed soil is a very humid clayey silt, with high plasticity, high electrical conductivity, low hydraulic conductivity, low density, large buffering capacity and high cation exchange capacity. The soil is rich in organic matter and poor in nitrogen. The removal of the contaminated soil for *ex situ* treatment is not advisable in contaminated studied area due to the restrictions imposed by local environmental authority, as well as operational impediments caused by the presence of vegetation and flooded conditions. After the diagnosis a program of laboratory tests was carried out on soil from the location in an electrical cell which was developed for this purpose. The study showed the feasibility of injecting nitrate and ammonium to this kind of soil, though the injection of phosphorous did not prove to be successful. It is recommended to control variations changes in pH, caused by the application of electrokinesis, in order not to harm the biodegradation process.

© 2007 Published by Elsevier B.V.

Keywords: Electrokinetic transport; Bioremediation; Soil remediation

1. Introduction

Electrokinetic remediation (EK) is an innovative technology for cleaning up contaminated fine soils. It has the ability to promote fluid and mass migration through low permeability soils. The other *in situ* remediation technologies, based on hydraulic or gas flow, have limited application in low permeability soils.

Electrokinetic techniques are only effective for transporting species presents on liquid phase and are not able to efficiently promote the transport of non-polar organic contaminants. In this case, the technique is used to improve biodegradability conditions on *in situ* bioremediation processes, by promoting the transport of nutrients, such as nitrogen and phosphorous, and electron acceptors. This technology is called electrokinetic bioremediation and has been studied since the 1990 years. In

1996 the eletrobioreclamation was incorporated to the remediation politics adopted in The Netherlands [1].

Some experimental programs demonstrated the feasibility of the process for injecting nutrients into fine soils like kaolinite and fine sand. Acar et al. [2] studied the injection of sulfate and ammonium ions into sand and kaolinite. Borresen [3] executed a bench scale study on nitrate and phosphate injection into fine sand.

This paper presents results of a laboratory study investigating the feasibility of electrokinetic injection of nutrients in a natural organic tropical fine soil, from an oil contaminated area, after diagnosis based on a site investigation program. The transport of nitrogen and phosphorous compounds were analyzed by the injection of prepared solutions into the soil in a electrokinetic cell. The variation of electrokinetic parameters monitored during tests and the effects of the application of the technology on soil pH and temperature were also analyzed.

The relevance of this work is the presentation of results and analyses of an electrokinetic bioremediation study carried out on a real, natural, organic soil with high electrical conductivity, representing an instrument for the application of this technology

* Corresponding author at: Department of Structures and Foundations-FEN-UERJ, PEAMB-UERJ, Rua São Francisco Xavier 524, 5001-A Rio de Janeiro, Brazil.

E-mail address: aida@uerj.br (C.A.B. Schmidt).

in other locations were the soil has similar characteristics of the studied soil.

2. Bioremediation

There is a wide range of NAPL (non-aqueous phase liquids) organic compounds that can be biodegraded. Bioremediation is capable to degrade organic pollutants to lower concentrations than the maximum levels accepted by the human organism. Biodegradation processes can occur under existing conditions or can be stimulated by bioremediation techniques.

Biodegradability involves the characteristics of the subsoil in the contaminated area, the existing microbial population and the characteristics of the contaminants. There are six basic requirements for biodegradation to occur [4]: sources of energy, sources of carbon, nutrients, electron acceptors, the presence of appropriate micro-organisms and suitable environmental conditions. Temperature and pH affect microbial population. Microbiota grows faster under temperatures between 20 and 45 °C [5]. Micro-organisms tolerate pH values between 5 and 9, preferentially between 6.5 and 7.5. Biodegradation occurs for the material dissolved in the liquid phase. The compounds in the NAPL phase, when in contact with water, dissolve as the dissolved phase is biodegraded [6].

3. Electrokinetics in soils

An *in situ* electrokinetic remediation technology application consists on the generation of a low intensity direct current or a low electric potential difference across the soil. Electrode pairs are inserted in boreholes in the ground on each side of the contaminated soil region and are connected to an electric source. The electric current developed across the electrodes causes the transport mechanisms of electroosmosis and electromigration. These two mechanisms permit the introduction and transportation of nutrients and electron acceptors to the soil mass with *in situ* electrokinetic bioremediation technology.

Electroosmosis is a fluid movement relative to a stationary charged surface, from the anode to the cathode, under the effect of applied electric potential gradients. It is an advective flow that can transport ionic and non ionic species present in pore water. Helmholtz–Smoluchowsky's model is widely used for the theoretical description of electroosmosis phenomena [7] and assumes that the electroosmosis flow is caused by the movement of the positive charge (cations) in the diffused double layer towards the cathode, dragging the soil pore fluid. The mass flux due to electroosmosis, J , is given by Eq. (1), where v_e is the velocity, k_e the electroosmotic conductivity; C the concentration of solute and i_e is the electric gradient between electrodes. The electroosmotic permeability, k_e , has a small variation, from 10^{-9} to 10^{-8} m²/Vs [7–9]

$$J = v_e \times C = k_e \times i_e \times C \quad (1)$$

Electromigration is the movement of ionic species in pore water towards the electrode with an opposite charge, when an electric gradient is applied to the soil. The rate of transport by

electromigration is 5–40 times the electroosmotic rate [8]. The mass flux due to electromigration is given by Eq. (2), where u^* is the effective ionic mobility in the porous medium.

$$J_x = u^* i_e C \quad (2)$$

Another important aspect of electrokinesis in soils is the generation of acidity near the anode and alkalinity near the cathode due to the oxi-reduction reactions that occur around the electrodes. These reactions also produce gases which composition depends on the species which are present in pore water. The variation in pH is very important for the application of electrokinesis in bioremediation processes, due to the effects on micro-organisms, especially acidity. The kind of gas generated is relevant in relation to the quality aspect of atmospheric emissions. During water electrolysis reactions it is produced oxygen by the anode and hydrogen by the cathode.

4. Site investigation and diagnosis

4.1. Investigated area

The investigation was carried out in 2001. The investigated area is located in an oil production field that has been in production for about 40 years. It is a wetland region that is flooded during almost all year, and is only dry for 3 months of the year. The local vegetation is predominantly shrubby. The subsoil profile obtained from the standard penetration test (SPT) consists of clayey silt layers, interposed with a limestone layer located at a depth of 10 m. The existence of artesianism was found in the region, with vertical hydraulic gradients varying between 0.026 and 0.070.

4.2. Contamination description

The local problem consists on the residual contamination of successive spillages of crude oil, since 1995, concentrated in the superior portion of the clayey silt strata, which is difficult to treat due to the presence of a large mass of shrubby vegetation that cannot be removed. The results of the investigation demonstrate that the volatilization and natural attenuation processes are practically exhausted.

The TPH analysis of the soil indicated a maximum level of 4642 mg/kg observed in samples collected at interval depth of 0.0–0.15 m [10]. Although this value does not characterize the need for intervention (according to Dutch Norms the intervention limit value is 5000 mg/kg), it shows to be necessary more detailed studies on the characterization of the risk.

4.3. Biodegradability parameters

The treatment using *in situ* bioremediation technology was considered to be the most suitable alternative. Biodegradability studies showed that the local soil contained micro-organisms which are capable to degrade aerobic and anaerobic organic compounds. A deficiency of nitrogen was identified in the soil.

Table 1
Original characteristics of soil used in the electrokinetic studies

Soil characteristics	Value
Liquid limit (%)	240.0
Plastic limit (%)	128.3
Specific gravity	2.034
Organic content (%)	29
Hydraulic conductivity (m/s)	7×10^{-9}
pH	6.0
Cation exchange capacity (cmol _c /kg)	
Ca ⁺⁺	54.7
Mg ⁺⁺	12.5
K ⁺	0.15
Na ⁺	0.69
H ⁺	6.9
Total	75.0

The levels of phosphorous (P) varied between 1.08 and 1.77% and the levels of nitrogen (N) varied between 0.15 and 0.20%. The levels of N were considered insufficient, while the levels of P were considered sufficient to meet the C:N:P ratio = 100:10:1 (molar), considered adequate for most biodegradation processes. In relation to the presence of micro-organisms, the quantity of total heterotrophic bacteria varied between 3.8×10^6 and 7.6×10^7 UFC/g of soil, while the quantity of hydrocarbon degrading bacteria varied between 1.7×10^3 and 7.6×10^4 NMP/g of soil [11].

4.4. Remediation diagnosis

Although being superficial, the contamination was evident in the investigations, and its effects and presence were visually observed through the presence of dry trees and oil in the location. A long period of surface contamination can make it reach greater depth as a dissolved phase.

Based on the type of vegetation, contamination and the soil, an *in situ* electrokinetic bioremediation was suggested for remediation of the contaminated area, considering legal and operational conditions that limit the utilization of “*ex situ*” technologies.

5. Soil type

Superficial soil samples were collected at the contaminated area for the laboratory research. The soil was characterized physically and chemically, with the results being given in Table 1. Mineralogical analysis of the soil fine fraction showed the presence of kaolinite, illite, smectite, and traces of chlorite.

The hydraulic conductivity was obtained from consolidation tests on undeformed samples collected at a depth of 0.15 m. The low value of *k* is a limiting factor for various types of “*in situ*” remediation technologies.

The original pore fluid was analyzed in terms of pH, electric conductivity (EC), the presence of Cl, SO₄, Na, K, Ca, Mg ions and redox potential (Eh). The results obtained are given in Table 2.

Table 2
Pore water chemical analysis

pH	6.9
SEC (mS/cm)	6.7
Cl ⁻ (mmol _c /l)	32.3
SO ₄ ²⁻ (mmol _c /l)	46.2
Na ⁺ (mmol _c /l)	27.7
K ⁺ (mmol _c /l)	0.2
Ca ²⁺ (mmol _c /l)	40.1
Mg ²⁺ (mmol _c /l)	24.5
Eh (mV)	147.5

6. Experimental setup

The electrokinetic apparatus (EK cell) used in laboratory studies is shown in Fig. 1. The tests were carried out without pH control. The EK cell consists on an acrylic tube, 146 mm long and with a 72.5 mm diameter, where the soil is molded, connected at both ends to acrylic cylindrical chambers of the same diameter, containing the electrodes. The electrodes have a central pin that goes out of the chambers and are connected to a power supply.

Electrodes made of stainless steel-360, resistant to chemical attack, were used because of their low cost and easy acquisition. However, the anodes suffered degradation and were substituted at every test. The analysis of anode degradation by oxidation is not in the scope of this work.

Two acrylic tubes of small diameter connected at each electrode chamber works as gas outlets. Two reservoirs were connected to the electrode chambers by plastic tubes provided with peristaltic pumps for fluid circulation.

7. Experimental program

In order to evaluate the injection and transport of nitrogen compounds (ammonium and nitrate) into the soil, the EKS3 and EKS5 tests were carried out and a single test, EKS6, was carried out for the analysis of phosphate transport.

The soil was molded simply by placing it into the sample tube of the cell, maintaining the natural water content. Perforated acrylic discs and filter paper were used at both ends of the tested soil samples. Physical properties of soil samples before the EKS3, EKS5 and EKS6 tests are given in Table 3.

The sample tube was then adapted to the electrode chambers and connected to micro-instrumentation sensors.

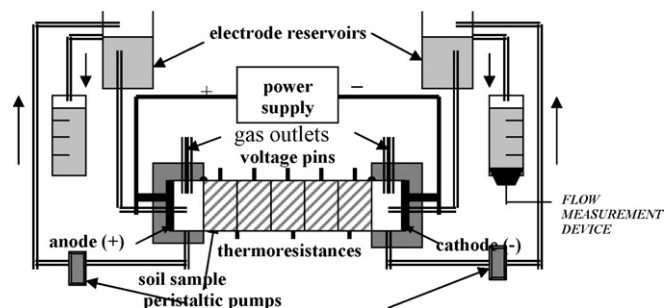


Fig. 1. Scheme of electrokinetic cell.

Table 3
Electrokinetic experimental program

Test	Water content (%)	Degree of saturation	Porosity	Duration (h)	Initial solution in distilled water		Applied electric potential (V)
					Anolyte	Catholyte	
EKS3	261.0	96.74	0.84	47.8	NH ₄ NO ₃ (2 g/l)		10
EKS5	265.5	96.89	0.85	71.3	NH ₄ NO ₃ (2 g/l)		10
EKS6	262.7	98.83	0.84	46.6	NH ₄ NO ₃ (2 g/l)	KH ₂ PO ₄ (5 g/l)	10

The chambers were filled with the solutions presented in Table 3 as initial solution of anode and cathode, respectively, anolyte and catholyte. All the utilized solutions had the same electric conductivity, near to 4 mS/cm. The same water level was maintained in the two reservoirs to avoid an additional advective flow. The anode reservoir was replenished as the fluid was transported across the soil by electroosmosis.

For EKS3 and EKS5 tests the NH₄NO₃ solution was used in the electrode chambers and reservoirs. For EKS6 test, the solution of dihydropotassium phosphate (KH₂PO₄) was used in the cathode chamber and reservoir. At the anode the NH₄NO₃ solution was used in the anode chamber, but the reservoir was filled with a 0.1 M ammonium hydroxide (NH₄OH) solution, which was injected during the test, with the aim of controlling the acid pH and releasing the ammonium ion in the solution.

During the experiments a constant electric potential of 10 V was applied between the electrodes and electric parameters, temperature and electroosmotic flow were continuously monitored and registered by a data acquisition system.

After each experiment the soil sample was extracted from the tube and divided into five slices for physical and chemical analysis as schematically shown in Fig. 2 [12].

8. Monitored parameters

8.1. Electric and electroosmotic parameters

The voltage in voltage pins in the soil, the current, and the electroosmotic flow monitored during the tests, resulted on the curves presented in Figs. 2 and 3, and calculated electrokinetic parameters presented in Table 4 for EKS3 and EKS5 tests.

The EKS6 test was accidentally turned off after 6 h and turned back on 17 h later. The electric current was drastically reduced just after the test was turned back on. No electroosmotic flow was observed during this test.

A good reproducibility was obtained in EKS3 and EKS5 relatively to the development of electroosmotic flow, given in Fig. 3, and current, electric gradient and electric conductivity given in Fig. 4. Electroosmotic flow and current was obtained directly and electric gradient and conductivity were calculated.

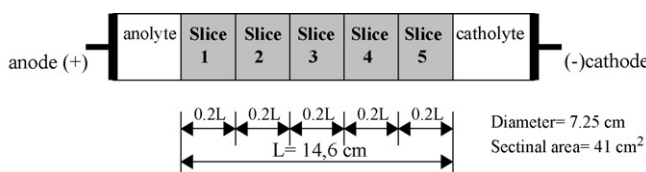


Fig. 2. Distribution of the soil sample slices.

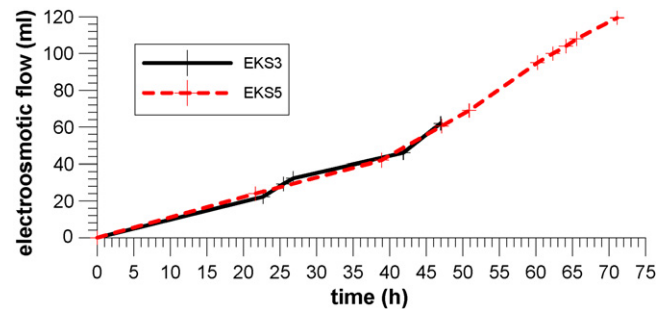


Fig. 3. Electroosmotic flow in time.

The constant applied voltage was distributed along the fluid in the electrodes chambers and the soil sample. The voltage and consequently the electric gradient in the soil changed along the experiment, as shown in Fig. 3, because the electrical conductivity

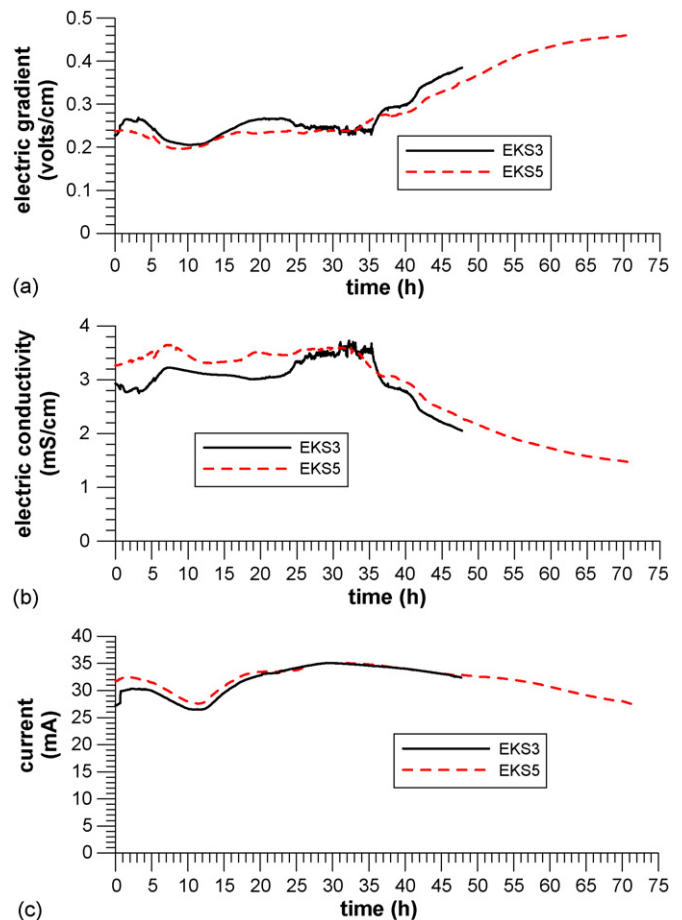


Fig. 4. Electric parameters in time: (a) current, (b) electric conductivity, and (c) electric gradient.

Table 4
Average calculated electrokinetic parameters

Test	Testing duration (h)	Total volume flow (cm ³)	Electroosmotic velocity (cm/s)	Electric gradient (V/cm)	k_e (cm ² /V s)	Current density (μA)
EKS3	47.8	62.0	8.95E-06	0.27	3.36E-05	776
EKS5	71.3	119.5	1.14E-05	0.31	3.70E-05	778

ities changed with the variation of the composition of the pore fluid and fluids of the chambers in the process.

From the results of monitoring, the average values of electroosmotic velocity, electroosmotic conductivity, k_e , electric gradient and current density were calculated for EKS3 and EKS5 tests [12]. These parameters are summarized in Table 4, as well as testing duration and total volume flow measured. A cross-section area of 41 cm² was adopted for calculating the electroosmotic velocity and the current density within the soil sample (equal to the current value divided by the cross-sectional area).

Values of k_e calculated for both tests, shown in Table 4, are in the range of usual electroosmotic conductivities reported for soils in the literature. The values of current density observed are greater than the values usually obtained for EK experiments. In the other hand a low electric gradient, around 0.3 V/cm, was developed in both tests (the electric gradient of 1.0 V/cm is used in several researches on EK remediation).

8.2. Temperature variation

The temperature was monitored in thermo resistances along the soil sample and it had not presented any significant variation in relation to the environmental temperature during the tests. The maximum difference observed between soil sample and laboratory temperature was about 2 °C for the three tests.

9. Chemical analysis

The pore fluid was extracted from a soil sample before tests and from the five slices (see Fig. 2) of the soil after tests, which chemical analysis gives respectively the initial and final results. The electrolyte chambers solutions (anolyte and catholyte) were also analyzed before and after tests. The results are presented in Figs. 5–10, where the graphs show the initial and final concentration of chemical species and pH in the slice fluids, anolyte and catholyte.

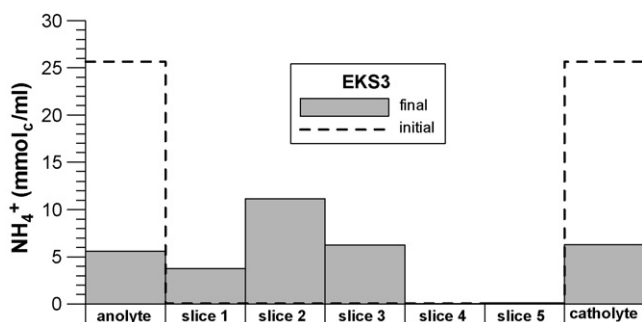


Fig. 5. Initial and final ammonium concentration; test EKS3.

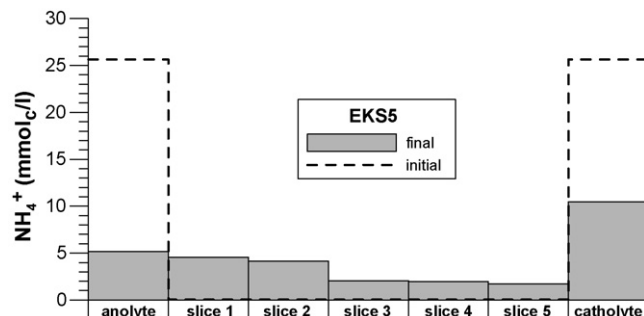


Fig. 6. Initial and final ammonium concentration after test EKS5.

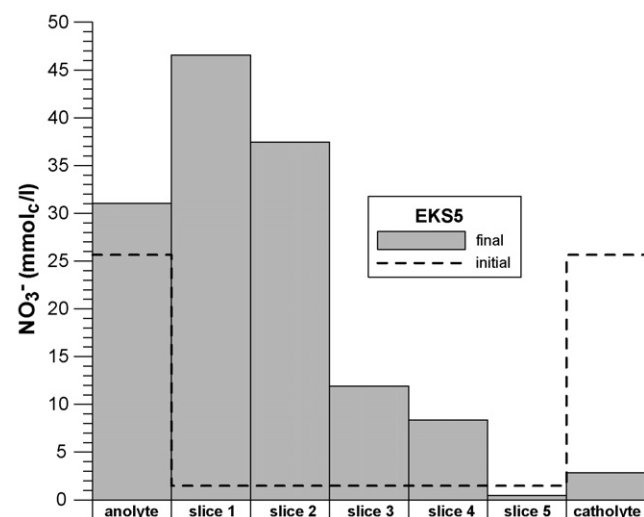


Fig. 7. Initial and final nitrate concentration after test EKS5.

9.1. Ammonium and nitrate analysis

Before and after the EKS3 test, the ammonium NH₄⁺ concentration was analyzed throughout the sample. In the EKS5 test, as well as the transport of ammonium from the anolyte to the catholyte, it was analyzed the transport of nitrate (NO₃⁻)

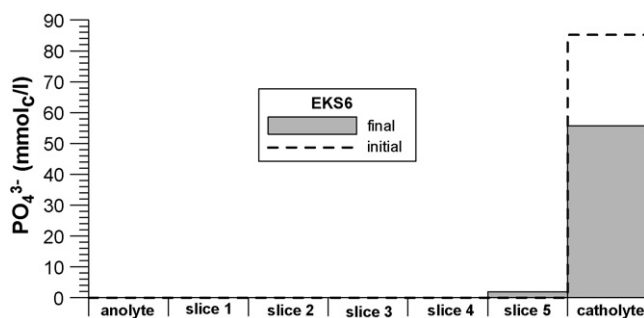


Fig. 8. Analysis of phosphate in the EKS6 test.

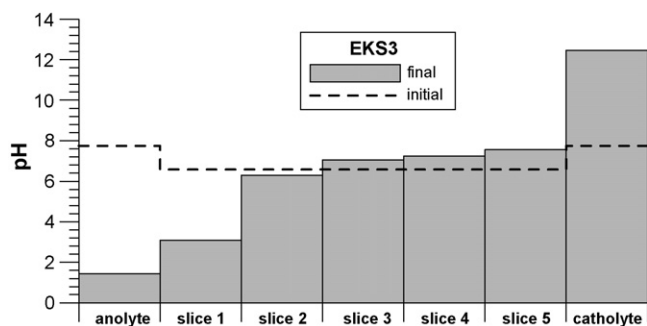


Fig. 9. pH soil pore fluid variation in the EKS3 test.

from catholyte to the anolyte. The ammonium functions as a nutrient and the nitrate as an electron acceptor in anaerobic bioremediation processes.

In relation to the EKS3 test, Fig. 5 shows that the level of ammonium decreased in the anolyte, and increased in the slices towards the catholyte, without reaching slices 4 and 5 during the 2-day test. In the catholyte, the level of ammonium decreased, possibly due to the reduction of ammonium (NH_4^+) to ammonia gas (NH_3). The ammonium in the reservoirs was replaced only in the anolyte whenever the level of liquid decreased, with there being no continual reposition in the two tests. In test EKS5 (Fig. 6), which lasted 1 day more than test EKS3, the ammonium reached slices 4 and 5. It was also observed a decreasing in ammonium concentration in the anolyte and catholyte.

Fig. 7 shows that in EKS5 test the nitrate was transported more effectively than the ammonium. The transport occurred from the catholyte to the anolyte, coherent with the technique applied, and without any significant loss of mass. Apparently, the reduction of concentration in the catholyte and in slice 5 is solely due to ionic migration and not to chemical reactions.

9.2. Analysis of phosphate transport

Fig. 8 shows that the phosphate concentration decreased in the catholyte at the end of the test, but it was not transported to the anolyte. As the soil is rich in calcium, this must have occurred because of precipitation of phosphate combined to the calcium carbonate in the reductive environment produced by electrokinesis (see Tables 1 and 2). The results are suitable to other studies as Borresen [3], who has studied the injection of

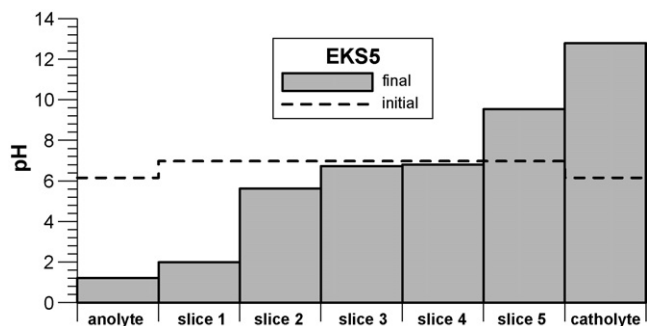


Fig. 10. pH soil pore fluid variation in the EKS5 test.

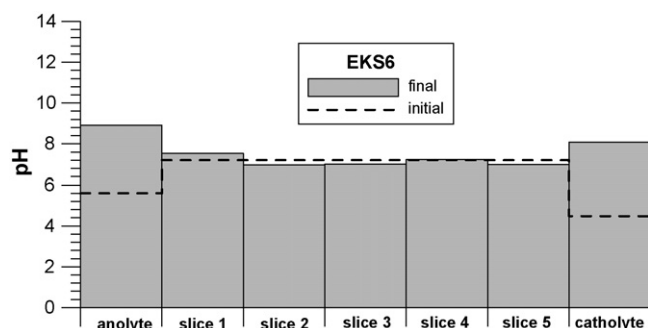


Fig. 11. pH soil pore fluid variation in the EKS6 test.

nitrate and phosphate in a fine sand, were the source of nutrients was an enriched sand. The work has concluded that the bioavailable content of nitrate and phosphate in the fine sand after tests was quantified as from 53% a 84% of the nitrate and only 1–2% of the phosphate initially added.

9.3. pH variation

The pH values for the EKS3 and EKS5 tests increased near the cathode and decreased near the anode, as shown in Figs. 9 and 10. In test EKS5, due to its longer duration, the pH was more acid in slice 1 and more basic in slice 5 in relation to the pH values obtained from EKS3 test. The soil pH after EKS6 test did not change drastically as shown in Fig. 11, due to continuous injection of ammonium hydroxide.

According to Reddy and Chinthamreddy [13], in low buffering soils, such as kaolin, the pH of the soils decreases to 2–3 near the anode and increases to 8–12 near the cathode. In the present study the pH has changed to values below 2 near the anode and above 13 near the cathode, although it is a high buffering capacity soil.

9.4. Microbiological analysis

A microbiological test using the MPN method executed on the slices just after the EKS5 test showed the negative impact of acid condition for microbiological population. In the slice 1, where the pH is equal to 1.99, the bacteria population apparently disappeared, and had not recovered after 41 days. In slice 5, where the pH is basic, equal to 9.53, there was a negative impact, but lower than in slice 1. The central region of the samples remained with a pH close to the initial value and apparently did not suffer a negative impact, which indicates that the other effects of the technique application did not harm the microbial population of interest.

Maillacheruvu and Alshawabkeh [5] showed that microbial activity, measured as a function of the ability of the anaerobic micro-organisms to consume readily degradable acetate, generally decreased as expected if the pH and dissolved oxygen were not controlled.

Maillacheruvu and Alshawabkeh [14] concluded that anaerobic microbial cultures seem to experience an environmental shock when exposed to electric field intensities above 1.5 V/cm. Aerobic cultures did not seem to be affected by exposure to field

intensities lower than 0.27 V/cm, value near the electric gradient obtained at the experiments described here.

10. Conclusions

1. The use of the natural soil from a contaminated site permitted the execution of a feasibility study on the application of the proposed technique in a form much closer to reality. No reports were found in the bibliography about EK experiments with very organic soils with a high cation exchange capacity and electric conductivity, such as used in this research. In the majority of experimental works in laboratories, less reactive soils have been used, as kaolin and fine sand.
2. In the studies presented here the electrokinetics technique was found capable to introducing nitrogen compounds in the organic soil used, with the nitrate showing greater mobility than the ammonium. The mass of ammonium, as well as moving, has decreased in the system during the tests, due to chemical reactions. The nitrate showed a behaviour less reactive, remaining in the system and only moving from anode to cathode. The same success was not obtained with phosphorous, probably because of the calcareum nature of the studied soil. The phosphate concentration declined in the catholyte where it was placed, possibly due to reactions with calcium carbonate and precipitation, but it did not travel through the soil.
3. The microbiological studies indicated that the acid pH conditions in the region nearest the anode had a high negative impact on the population of hydrocarbon degrading bacteria. For the catholyte the basic pH caused a negative impact but to a lower degree. It is therefore necessary to control the pH in the application of electrokinetic processes for bioremediation of the studied soil.

References

- [1] R. Lageman, W. Pool, Thirteen years eletro-reclamation in The Netherlands, in: proceedings of the Third Symposium and Status Report on Electrokinetic Remediation—EREM 2001, Karlsruhe, 1, 1–17, April 18–20, 2001.
- [2] Y.B. Acar, M.F. Rabbi, E.E. Ozsu, Electrokinetic injection of ammonium and sulfate ions into sand and kaolinite beds, *J. Geotechn. Geoenviron. Eng.* (1997) 239–249.
- [3] M. Borresen, Increased mobility for nutrients in fine grained soil using electrokinetics, in: Proceeding of the Third Symposium and Status Report on Electrokinetic Remediation—EREM-2001, Karlsruhe, 38, 1–13, April 18–20, 2001.
- [4] P.B. Bedient, H.S. Rifai, C.J. Newell, *Ground Water Contamination*, Prentice Hall, New Jersey, 1994.
- [5] K. Maillacheruvu, A.N. Alshawabkeh, *Anaerobic Microbial Activity under Electric Fields. Emerging Technologies in Hazardous Waste Management 8*, Kluwer Academic/ Plenum Publishers, NY, 2000, pp. 69–79.
- [6] D.G. Grubb, 1998, Review Technologies for Management of NAPL Contaminant Sites, *Simpósio Brasileiro de Geotecnia Ambiental—SIGA/98*.
- [7] J.K. Mitchell, *Fundamentals of Soil Behaviour*, 2nd ed., John Wiley & Sons Inc., New York, 1993.
- [8] Y.B. Acar, A.N. Alshawabkeh, Principles of electrokinetic remediation, *Environ. Sci. Technol.* 27 (1993) 2638–2647.
- [9] A.N. Alshawabkeh, A.T. Yeung, R.M. Bricka, Practical aspects of in-situ electrokinetic extraction, *J. Environ. Eng.* (1999) 29–35.
- [10] A.A.C. Souza, 2001. A geoenvironmental investigation on clayey soil contaminated with hydrocarbons, MSc Thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, in Portuguese.
- [11] R.M.H. Borges, 2001. Biodegradation on a clayey soil contaminated with petrol, M.Sc. Thesis, EQ/UFRJ, Rio de Janeiro, RJ, Brasil, in Portuguese.
- [12] C.A.B. Schmidt, 2004. Electrokinetic laboratory experiments on clayey soils, DSc Thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, in Portuguese.
- [13] K.H. Reddy, S. Chinthamreddy, Sequentially enhanced electrokinetic remediation of heavy metals in low buffering clayey soil, *J. Geotechn. Geoenviron. Eng.* (2003) 263–277.
- [14] K. Maillacheruvu, A.N. Alshawabkeh, Microbial activity under electric fields, in: *Emerging Technologies in Hazardous Waste Management*, American Chemical Society (ACS) Meeting, Industrial and Engineering Chemistry Division, Boston, MA, August 23–27, 1998.