Contribution to the Remediation of Saline Soils by Electrokinetic Process: Experimental Study

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Abstract Salinization affects ecosystem biodiversity, human health, agricultural productivity, as well as engineering and construction infrastructure. In Algeria, many arid, semi-arid, and near-coastal areas are suffering from soil salinization for more than two decades. In order to restore contaminated soils (saline), the electrokinetic process was tested in laboratory to study the mobility, migration, and elimination of ions (salts) in the soils of two regions of Mostaganem and Relizane (north-west of Algeria). The electrokinetic method is one of the most promising fine-grained soil decontamination processes. In this work, the variation of the electric current, the electro-osmotic flow, the pH, and the rate of elimination of the cations, such as sodium and calcium according to the treatment duration, were determined. According to the results obtained, the electrokinetic treatment proves to be a new technique used successfully, reliably, and inexpensively. It allows the remediation and restoration of fine-grained soils affected by salts. Our research demonstrates the economic and environmental value and the efficiency of electrokinetic technology, which is an innovative process. It deals very effectively with the depollution and remediation of saline soils and helps to inhibit the scourge of soil salinization and environmental pollution.

Keywords Saline soils · Electrokinetic · Remediation · Removal efficiency

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1 Introduction

Soil is a heterogeneous assemblage of particles with very different properties. It is a living resource for agricultural productivity and human activities.

Soil salinization continues to be a scourge of land degradation globally. The rate of soils affected by salinity in Algeria is of the order of 3.2 million hectares, particularly in arid and semi-arid zones. Soil salinization can be caused by several environmental factors, such as marine intrusion, deposition of marine salts carried by winds, or by inadequate human intervention (inadequate drainage, excessive irrigation with salt water). During recent two decades, contaminated (saline) land has become an area of increasing importance for the geotechnical and agricultural fields. Recently in Algeria, an extensive construction program has been planned in several parts of the country, while saline agricultural lands will be converted to receive infrastructure for future use.

Extreme concentration of ionic species, such as cations (sodium, potassium, and calcium), and anions, (chloride, sulfate, and nitrate), result in an increase of osmotic pressure, leading to a significant deterioration of the soil surface affecting as a result, on the civil engineering infrastructure and productivity of farmland [1, 2] Currently, geo-environment specialists are facing challenges related to the improvement of natural soils for the protection of the environment. In this context, it should be emphasized that the evaluation and control of the geo-environmental impact of saline soils in Algeria could guarantee better management and better elimination of pollutants, with a focus on development mechanisms adequate.

Several researches have been conducted on the remediation of contaminated soils, developing several processes, such as solidification, excavation, thermal desorption, and biological treatment, in order to remediate and restore such soils.

Nevertheless, many of these soil remediation methods have not been followed up in depth, since most of them remain inadequate, too expensive, and inefficient, especially for fine-grained soils because of their low permeability and mineralogical complexity.

Innovative and inexpensive EK technology has become an alternative method to conventional soil improvement methods, which involves electrochemical stabilization by electro-osmosis of fine-grained soils. This process was chosen in our research because it is easy to install, quick to use and can be used in the laboratory and in situ.

This new method of EK treatment has now begun to be used in several countries for stabilization and remediation of soils in general and fine sediments in particular [3–9].

Electrokinetic technology, inserted as part of the sustainable development strategy, combines social and economic progress with the protection and improvement of the environment.

The principles of electrokinetics involve the application of a low direct current (DC) or a low potential gradient to the electrodes inserted into fine and low permeability soils. These soils have specific mineralogical properties and are therefore electrically and chemically active. When a continuous electrical potential is applied to the sample, it activates the migration of electrical charges, pore fluid, ions, and fine particles through the soil-liquid medium to the opposite charged electrodes, thereby creating chemical combined effects, hydraulic and electric processes [10].

The electrochemical process depends on several parameters, such as the concentration and mobility of ions, the potential voltage, and the viscosity of pore water.

In recent years, many researchers have been interested in EK through the implementation of several successful applications [11–18]. For example, the technology of electro-osmosis has been used for several decades to remove water from clay and loam soils and to clean poorly permeable saline soils [19].

In this paper, the physicochemical characteristics of two local soils in the study areas of Ain Nouissy -Mostaganem and Hmadna - Relizane, Algeria, in particular pH variations, electro-osmotic flow, and ion mobility such as that sodium (Na^+) and calcium (Ca^{2+}) are studied and analyzed in the LCTPE research laboratory of the University of Mostaganem. The objective of this research is to study the efficiency and performance of the EK method to accelerate the treatment process and the effective remediation of fine saline soils.

2 Materials and Methods

2.1 Material Sampling

The first study area is located in northwestern Algeria, in the lower valleys of west Mostaganem, and more particularly in the region of Ain Nouissy, whose area is 680 Km^2. As for the second zone, it is also located in north-west of Algeria, precisely Hmadna in the region of Relizane. The salinity problems of these two soils have worsened over the last twenty years, due to low rainfall rates that have led to an accumulation of salts at the surface of the soil at an alarming rate. Samples from both soils were collected at a depth of approximately 0.5–1 m. The soil masses were contained in plastic bags and transported to the laboratory where they were air-dried and ground into a fine powder for analysis.

Table 1 shows the physicochemical properties of the two saline soils studied.

2.2 Experimental Cell

The electrokinetic experiments were conducted in a parallelepiped shaped cell with glass walls of 8 mm thick and whose dimensions are as follows: length 30 cm; width 10 cm, and height 10 cm, comprising three compartments: anode, sample cell floor, and cathode (Fig. 1). The tanks are made of glass because the latter is relatively, chemically, and electrically neutral, in order to minimize the ground reactions. The

Table 1 Physicochemical properties of used material

Soil properties	Ain Nouissy	Hmadna
pH	15	7.49
EC (dS/cm)	8.5	11.09
Particle size analysis (%)		
Clay (%)	30	6
Silt (%)	62	78
Sand (%)	8	16
Organic content (%)	1.7	16.66
Initial soluble concentration (mg/kg)		
Na^+	1917.2	905.2
Ca^{2+}	1165	1421.6

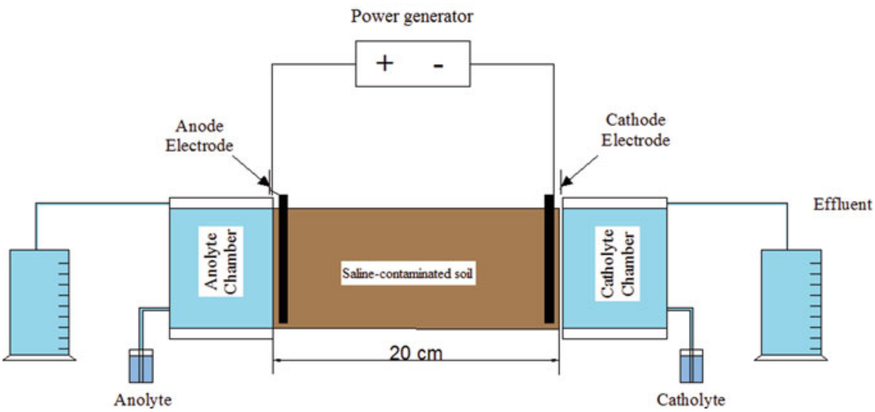

Fig. 1 Schematic draw of the electrokinetic test apparatus

two electrodes compartments of the anode and cathode contain an outlet, allowing the flow of electro-osmotic flow (amount of water collected in a graduated tank cylinder). The walls separating the compartments are perforated grids wrapped in geosynthetic material. Filter papers [Whatman No. 4] are placed against the grids separating the soil from the anode and cathode compartments, to prevent the movement of the fine particles from the soil toward these compartments (anode and cathode chambers). Soil samples were continuously fed with distilled water through the anode, using a pipe connected to an external tank to facilitate electro-osmotic flow.

2.3 Test Procedure

A mass of 2600 g each of the two soils was mixed with deionized water for each test, to obtain a water content of 5% above the liquid limit. The material is mixed for one hour, until a homogeneous and smooth paste is obtained, then placed in the central reservoir of the experimental cell in three successive compacted layers at a density of 1300 kN/m^3, in order to completely eliminate the air bubbles formed during installation. Then, two perforated cylindrical copper tubes were inserted into the cell 2 cm from the ends of the transverse walls to serve as electrodes. The experiments were carried out under a voltage gradient of 1.5 V/cm. Different successive tests of duration of 5, 8, 10, and 15 days were carried out for the two soils to measure the different parameters, such as: the intensity of the electric current, the electro-osmotic flow, the pH, the CE, as well as the elimination of ions.

Also, the electro-osmotic flow contained in the cathode compartment was collected in graduated test tubes and measured daily. Under a constant voltage gradient, current intensity was measured at regular time intervals.

At the end of each test, the soil compartment was cut into equal sections from the anode at 4, 8, 12, and 16 cm and then analyzed. After the required electrochemical treatment period, samples from each of the two soils were taken from different sections to analyze their chemical and physical properties. pH and EC were determined using a Hach sension 156 pH/conductivity/dissolved oxygen multi-parameter digital apparatus. The flame spectrophotometer equipment was used to analyze the cations.

3 Results and Discussion

3.1 Variation of Current Intensity

The EK process involves the application of a potential gradient in the soil matrix. This imposed electric field, leads to the movement and migration of ionic species in the soil, which induces changes in electrical intensity. Figure 2 shows the variation of the intensity of the electric current with the treatment time for both each of the two studied soils. The current gradually increased at the beginning of the experiments because the electro-osmotic flow passed through the soil and increased the dissolution of the salts in the interstitial water. Over time, the current flowing through the soils decreased, falling to less than 10 mA in the test period of about 10–15 days. The current distribution is influenced by the concentration of soluble salt ions in the interstitial water. The large initial values are due to the solubilization of the salts contained in the soil, which also leads to an increase of the EC, which is in agreement with the work of Gray et al. [20]. Therefore, soil pH plays an important role in the variation of electrical intensity. The highly alkaline medium, in the cathodic zones,

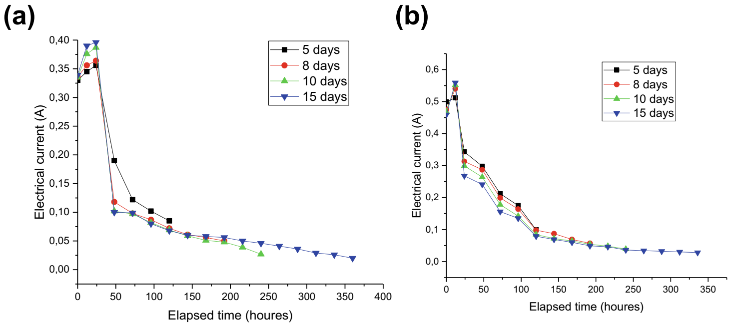

Fig. 2 Variation of electric current intensity with time, **a** Ain Nouissy and **b** Hmadna

causes the precipitation of ionic compounds in the soils, thus leading to a decrease of the current intensity [8, 21].

3.2 *pH Distribution After the Test*

Figure 3 shows the change in soil pH as a function of time for the two tested soils considered. Consequently, it can be observed that the pH value increases over the entire distance between the anode and the cathode for the two soils of Ain nouissy such as that of Hmadna. When an electric field is applied, electrolysis takes place and H^+ and OH^- ions are generated at the anode and at the cathode, respectively. The low pH near the anode allows the solubility and desorption of salts, and consequently its mobility by electro-osmotic and electro-migration mechanisms. The same trend was reported by Li et al., Peng et al., Cho et al., and Kim et al. [1, 22–24].

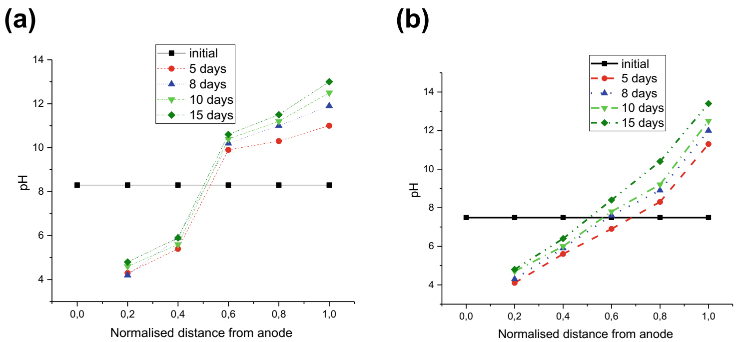

Fig. 3 pH variation along distance from anode after test. **a** Ain Nouissy and **b** Hmadna

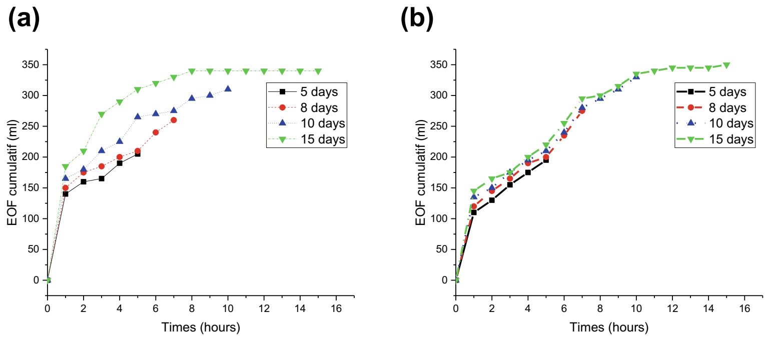

Fig. 4 Evolution of electro-osmotic volume during electrokinetic treatment **a** Ain Nouissy and **b** Hmadna

3.3 Cumulative Electro-Osmotic Flow

The electro-osmotic flow during the electrokinetic process as a function of time for each of the two soils is illustrated in Fig. 4. It may be noted that the flow rate increased with increasing processing time, where flow direction was valid for all anode tests at the cathode. This increase is the result of the mobilization of ionic species to which the applied voltage tends to increase the intensity of the electric current in the soils and thus the electro-osmotic output flow. The same results have been reported by several researchers [8, 24–26].

3.4 Removal Efficiency of Cationic Salts

During EK treatment, the applied electric current includes two phenomena: electro-osmosis and electro-migration, which allows the mobilization of salts and the facilitation of their transport and their elimination. Electro-migration allows the transport of ionic species such as bonds through the cathode, while electro-osmosis is related to the displacement of the pore water from the anode to the cathode, thus providing, the transport of salts in the pore solution. Figure 5 shows the removal of ions (salts) in samples from both soils after treatment with EK. The charged ions are mainly displaced by phenomena, such as: electro-migration, electro-osmosis, electrophoresis, and diffusion in the electrokinetic process. The two mechanisms of electro-osmosis and electro-migration improve the transport of cations (sodium, potassium, calcium, and magnesium) from the anode to the cathode. Electro-osmosis is the key phenomenon, which allows the removal and extraction of contaminants (salts) in the electro-osmotic flow collected to the cathodic compartment.

Also, the soil pH influences the migration and the elimination of the contaminants, an acidic environment near the anode allows the desorption and the dissolution of the contaminants, which lead to their better mobilization and extraction of the latter.

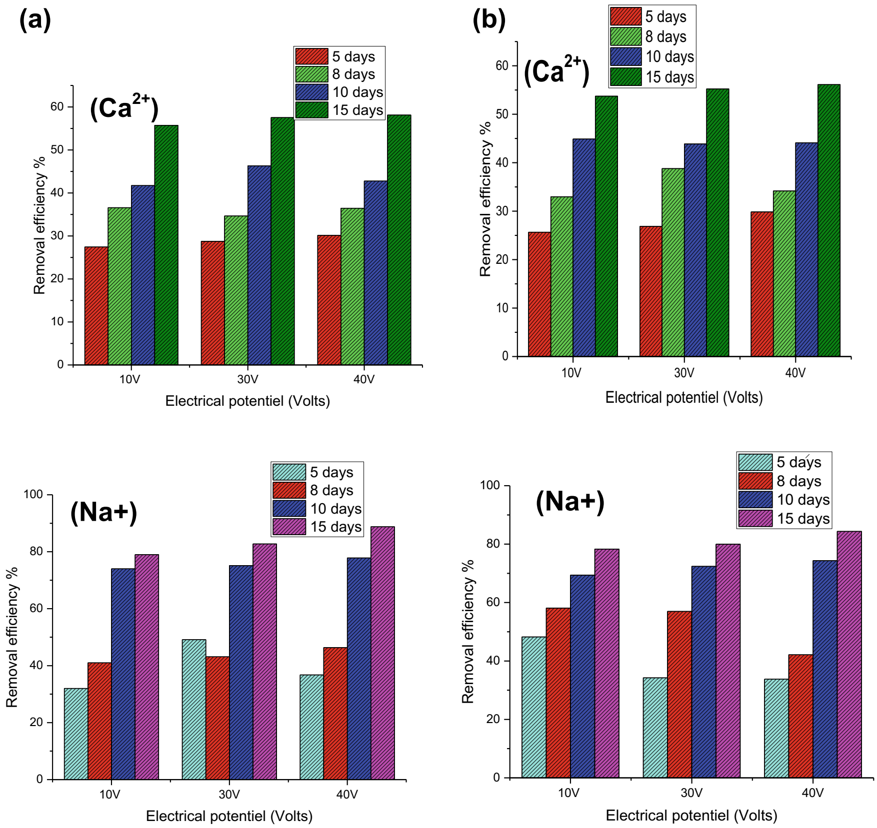

Fig. 5 Salt removal efficiency at the end of treatment. (Sodium and Calcium) **a** Ain Nouissy and **b** Hmadna

With the increase in the duration of the treatment, it is found that the efficiency of the removal of ions increases. This is due to the EOF, which has contributed to the transport and elimination of salts. Ion mobility is a parameter to control the efficiency of salt removal, which is more effective for Na^+ than for Ca^{2+}, even if the ionic mobility of Na^+ is lower. Divalent ions require more energy to be removed than monovalent ions. Divalent cations such as Ca^{2+} appear to be less mobile than monovalent cations, such as Na^+.

It is also necessary to show that monovalent cations have a lower atomic size than divalent cations, resulting in high ionic mobility in aqueous solution, implying a strong extraction of sodium with respect to calcium.

According to the results obtained for each of the two soils, we can say that the Ain Nouissy soil is a very saline clay loam very little plastic.

On the other hand, the soil of Hmadna is an extremely salty silty soil. It can be seen from the parameters obtained that cation extraction is more important for the Ain Nouissy soil than for the Hmadna soil.

4 Conclusion

In our research, sustainable management practices are being considered for application to saline soil remediation at the two study sites to maximize the economic, environmental, and social benefits of the electrokinetic process.

An EK experiment was carried out using a research laboratory-wide cell allowing the treatment and the decontamination of the saline soils from the regions of Ain Nouissy and Hmadna, in order to make profitable these lands for their effective and optimal use.

The results showed that: The pH data for each of the two soils is combined with the removal efficiency at different locations in the soil cell. The influence of the migration of the acid front from the anode to the cathode should be taken into account because of the effect of the dissolution and desorption of the ions.

In addition, it can be noted that the trend of EC soil Hmadna is less, compared to that of the soil of Ain Nouissy and this can be due to many factors, which include: the temperature, the content of water, soil porosity, interstitial fluid resistivity, soil composition, and salinity.

With the application of the continuous electrical potential on both soil samples, the soil-liquid medium undergoes several physical, chemical. and electrical changes, due to several EK processes, which take place in the middle of the soil.

Monovalent cations are strongly eliminated as divalent cations because of their ionic mobility, atomic size, and intensity of attraction. The proposed method achieved a removal rates of 89 and 58% for sodium and calcium ions respectively for Ain nouissy soil and 84 and 56% for Hmadna soil at 40 V electrical potential and a treatment duration of 15 days. It can be deduced that the increase of the treatment time allows a better electrical transport, leading to an optimal transport of the ionic species.

EK treatment is considered as an inexpensive and innovative technology applied in situ and in the laboratory. It is used to treat and remove salts from fine-grained soils to improve agricultural productivity on the one hand, and to protect construction and engineering facilities from deteriorating effects of salinity, on the other hand.

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