Enhancement Of Electro-Osmotic Flow During The Electrokinetic Treatment Of A Contaminated Soil

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ABSTRACT

The electrokinetic remediation of contaminated soils relies in two main transport mechanisms: electromigration and electro-osmosis. The electro-osmotic flow depends on fluid characteristics (dielectric constant and viscosity) and soil surface characteristics represented by Z-potential, as well as voltage gradient. In this work, the influence of voltage gradient in the development and maintenance of electro-osmotic flow is studied. The voltage gradient directly affected the electro-osmotic flow but it also affected the geochemistry of soil that had a critical effect on electro-osmosis. It was demonstrated that 1 V/cm resulted in the development and maintenance of a large electro-osmotic flow. The use of organic acids, such as citric acid, induced large electro-osmotic flow due to the interaction of the organic acids with the soil particles. The use of citric acid was considered to be very promising for large-scale operation.

1. Introduction

Electrokinetic remediation have shown several successes in the remediation of soils, sediments and sludges contaminated with both inorganic and organic contaminants [1]. The principle of electrokinetic remediation relies on the application of a low-intensity direct current through a soil specimen between a couple of electrodes (cathode and anode). The electric field mobilizes charged species, causing ions and water to move toward the electrodes through the soil. The main transportation mechanisms in electrokinetics are called electromigration and electro-osmosis. Electromigration is the movement of ions under the effect of the electric field through the soil towards the opposite charged electrode [2]. This mechanism is responsible for the transportation and removal of free ions such us H^+, OH^- (electrogenerated by water electrolysis on the electrodes), cations (heavy metals, ammonium, . . .) and anions (chloride, cyanide, fluoride, nitrate, . . .), but also ionizable organic compounds.

Electro-osmosis can be defined as the net flux of water towards one of the electrodes induced by the electric field [3]. The electro-osmotic flow depends on fluid characteristics (dielectric constant and viscosity) and soil surface characteristics represented by the Z-potential, as well as the voltage gradient. Z-potential is a function of many parameters including the chemical nature of the soil

particles, pH, temperature and ionic strength of the interstitial fluid [4]. Some of these parameters are affected by the electrokinetic treatment itself. The soil pH and the type and concentration of ions in the interstitial fluid change during the electrokinetic treatment of a contaminated soil, due to the chemical reactions and the transportation induced by the electric field. Those changes clearly affect the development and maintenance of a high electro-osmotic flow (EOF) [5,6].

The electro-osmotic flow is the result of the electrochemical interaction of the electric field, soil particles and interstitial fluid. In general, soil particles are negatively charged. Since the matter is globally neutral, a series of contra-ions neutralize that charge. The contra-ions are concentrated in the diffuse layer of the electrical double layer (Fig. 1). Under the effect of an electric field, the excess of ions in the diffuse layer close to the surface of the soil particle, migrate in a plane parallel to the soil surface in the direction of the opposite electrode. Those ions are in aqueous solution, hence, solvated. In their movement, the ions drag the solvated water molecules. This movement is transmitted to the neighboring molecules due to dipole-dipole interaction, forming a flat rate profile of water flowing through the pore (Fig. 2). In general, soil particles are electronegative, so the counter-ions will be positive, hence, the direction of the electro-osmotic flow be toward the cathode. Electro-osmosis is the dominant transport mechanism for inorganic and organic contaminants in solution or emulsified in the interstitial fluid [4,7].

As it was commented before, EOF is affected by the superficial characteristics of the soil particles, especially the surface charge,

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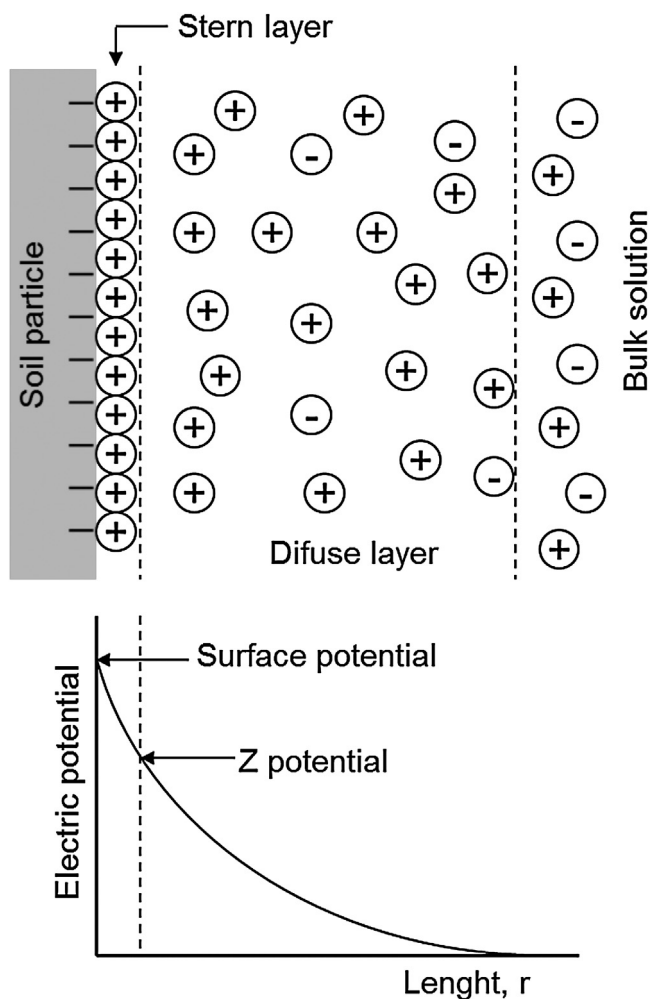E-mail address: claudio@uvigo.es (C. Cameselle).

Fig. 1. Electric double layer in a negatively charged soil particle.

positively charged; as a result, the EOF will reverse to the anode. The EOF is an important factor in the environmental applications of electrokinetics, since the flux of water that flows through the treated soil transports out of the soils any compound (ionic or no ionic) in solution in the interstitial fluid [8–13].

The electro-osmotic flow rate (q_{eo}) [1,4] can be expressed according the Helmholtz-Smoluchowski theory as presented in Eq. (1).

$$q_{eo} = nA\frac{D\zeta}{\eta}E_z = k_{eo}AE_z \qquad (1)$$

Where:

n is the porosity of soil

A is the area of the perpendicular surface to the direction of the flow

D is the dielectric constant of the fluid

ζ is the zeta potential (Fig. 1)

η is the viscosity of the fluid

E_z is the voltage gradient in the direction of the flow (z in this case)

k_{eo} is the coefficient of electro-osmotic permeability

The comparison of the EOF with the hydraulic flow will help to understand the importance of the EOF for the removal of contaminants in low permeability soils. The hydraulic flow only reach practical values for environmental applications in permeable soils, e.g. fine sand, with hydraulic conductivity higher than 10^{-6} m/s. However, the hydraulic flow in kaolin or clayey soils is negligible due to their low hydraulic conductivity (between 10^{-8} y 10^{-10} m/s) whereas the electro-osmotic permeability in a moisten sample of kaolin is $k_{eo} = 5.7\ 10^{-9}$ m^{2}s^{-1}V^{-1} and in clayey silt soil is $k_{eo} = 5\ 10^{-9}$ m^{2}s^{-1}V^{-1} [14]. In low permeability soils, the EOF is much more efficient than a hydraulic gradient. In fact, the hydraulic gradient to reach the same flow than electro-osmosis would be impracticable.

The aim of this work is to evaluate the influence of electrochemical variables in the development and maintenance of EOF with the objective to determine the best operating conditions for the treatment of contaminated soils.

2. Materials and methods

2.1. Soil characteristics and contamination procedure

The soil used in this study was sampled in an agricultural area in the NW of Spain. The soil characteristics are reported in Table 1. The soil was spiked in the lab with seven heavy metals: Cd, Co, Cr, Cu, Pb, Zn and Hg. The final heavy metal concentrations in soil
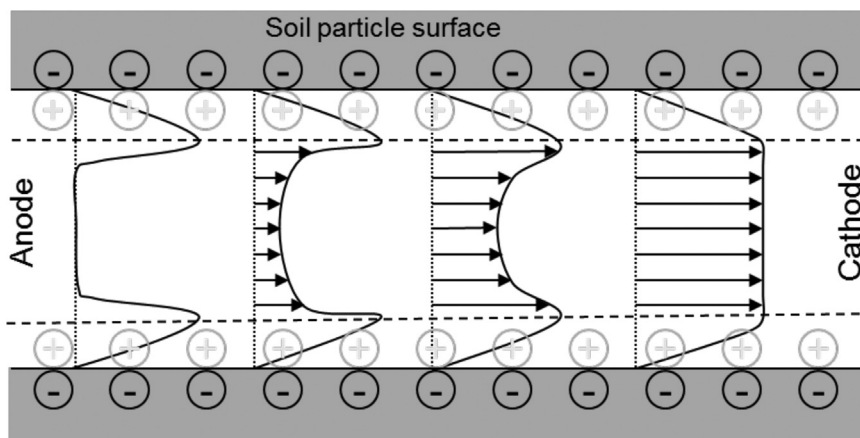
but it is also very important the pH value, the chemical nature and concentration of the ions in the soil, and the total ionic strength of the interstitial fluid. The pH plays a decisive role in the development of the EOF [6] since the pH can largely modify the charge in the surface of the soil particles. In electronegative soil particles, an acidic pH may result in the neutralization of the charge of the soil particles and even in the change to a soil particles

Fig. 2. Development of the electro-osmotic flow in a soil pore.