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Scale Up on Electrokinetic Technology for the Removal of Heavy Metals from Contaminated Soils

Villen-Guzman M and Rodriguez-Maroto JM*

Chemical Engineering Department, Faculty of Sciences, University of Malaga, Spain

Abstract

Electrokinetic remediation has been widely applied to remove contaminants from soils. Results from laboratory tests with spiked real soils have allowed not only to assess the behavior of heavy metals in soils under an electric current application but also to optimize experimental conditions. However, experiments with real polluted soils should be performed to a better understanding of the fundamental transport and transformation processes involved in electrochemical remediation. Scaling-up should be addressed considering the soil characteristics and the site-specific technology development. On this matter, mathematical models are essential to achieve efficient field-scale treatments through a better understanding of the different processes involved. The importance of performing experiments at different scales, implementing mathematical models and characterizing the specific soil to be treated are reviewed in this work. In addition to this, the most relevant field scale applications of electrokinetic have been reported.

Keywords: Soil remediation; Electrokinetic; Scale-up; Field tests; Heavy metal

Introduction

Heavy metal contaminated soils represent a major threat to the environment due to the large number of potentially contaminated sites. According to the U.S. Environmental Protection Agency (EPA), metals are contained at about 65% of Superfund sites registered [1]. The presences of heavy metals in soils have been widely demonstrated to cause adverse effects on human health, plants and animals. In addition, the removal of heavy metals from soils is hindered by its retention in the solid matrix through precipitation, adsorption and ion exchange. Therefore, the technological development to remediate and control the risk of soil contaminated with heavy metals is a high-priority.

Most of conventional remediation techniques are not feasible alternatives for soils with low hydraulic conductivity and inaccessible areas. On this matter, the Electrokinetic Remediation (EKR) has shown a great potential to recover soils. This technology relies on the application of an electrical potential gradient between a set of electrodes placed in the contaminated soil (Figure 1) [2].

The success of the process is based on the solubilisation, mobilization toward the electrodes and extraction of the contaminants to be subsequently treated. The main transport mechanisms of contaminants through the porous media include electromigration, electro-osmosis, electrophoresis and diffusion. The two predominant processes under an electric potential gradient are electromigration, i.e., the movement of dissolved ionic species toward the electrode of opposite charge, and electro-osmosis, i.e., the movement of the pore fluid containing dissolved ionic and non-ionic species toward the electrode. In addition to transport processes, electrolysis reactions typically occur at the electrodes generating an acidic and basic medium at the anode and cathode compartments, respectively. Thus, the soil is divided into two zones: a high pH zone close to the cathode compartment and a low-pH zone close to the anode compartment. These pH changes induced in the soil play an important role on transport, transformation and degradation processes. Specifically, the migration of hydroxides toward the anode side entering the soil will hinder the movement of metals either by precipitation or by complexation. Thus, the use of enhancements to neutralize the basic front generated at the cathode has been widely reported [3,4]. These methods typically are based on reagent addition [5] or use of semi permeable membranes [6-8].

Scale Up Aspects of EKR

The application of EKR to metal contaminated soils started to be explored at laboratory scale since 1990s [2,9]. With the aim of assessing the fundamentals of the technique, many research studies

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***Correspondence:**
Maria Villen-Guzman, Chemical Engineering Department, Faculty of Sciences, University of Malaga, Malaga, Spain.
Tel: *+34 952 133 449*
E-mail: *mvillen@uma.es*

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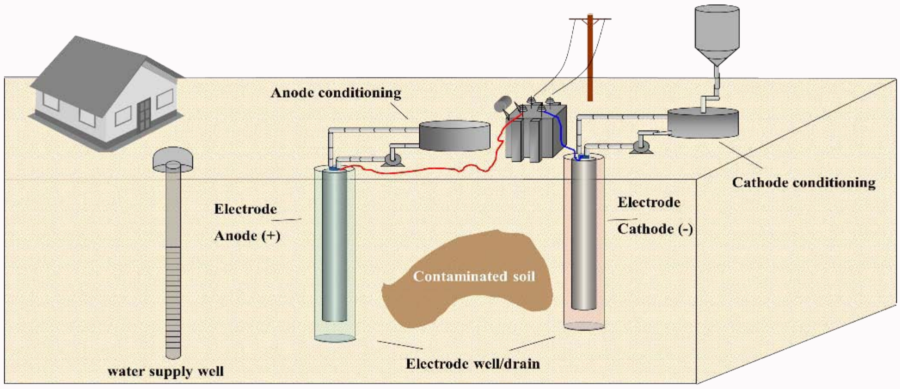

Figure 1: Experimental setup of *in situ* electroremediation system.

Table 1: Field demonstrations of electrokinetic to remediate metal contaminated soils.

Field scale	Key features	Metal removed	References
Geokinetics International, Inc.	Use of electrode wells for anode and cathode, and the management of the pH and electrolyte levels in the electrode streams of both electrodes. Use of additive to solubilize contaminants and to improve the transportation and removal of metals from polluted soils.	Pb, Cu, Zn, As, Cd, Ni, Cr	Lageman (1993) [16] Lageman, Clarke, and Pool (2005) [17]
Electrokinetics, Inc by Louisiana State University	Accomplish extraction and removal by electrodeposition, evaporation/condensation, precipitation and ion exchange. Use of CADEX™ electrode system to promote transport of species into the cathode compartment.	Pb, Cd, Cr, Hg, Fe, Mg, U, Th, Ra	USEPA (1997) [1]
Isotron Corporation	Application of Electrosorb® process with a patented cylinder to control buffering conditions *in situ* and use of an ion exchange polymer matrix called Isolock® to trap metal ions.	Hg, Pb, Cr	USEPA (1995) [18]
Electroacoustical soil decontamination by Battelle Memorial Institute of Columbus	Combination of electrokinetic with sonic vibration to enhance soil dewatering andsolubilisation of metals.	Zn, Cd	USEPA (1994) [19]
Naval Air Weapons Station, Point Mugu, California (2000)	New disposition of electrodes: three cathodes were centred between six anodes to concentrate the contaminants around the cathodes.	Cr, Cd	USAEC (2000) [20]

reported the use of kaolinite to model a low hydraulic conductivity soil [10-12]. However, the data obtained from these studies could not be directly used to optimize field applications. Hence, feasibility studies with real soils were required to optimize the design and operation of the technique before exploring the full-scale application. The use of laboratory spiked real soils has been also widely used to develop the technique. Nevertheless, the behavior of trace metals in real soils could not be compared with trace metals adding as soluble metal salts. M.Villen et al., (2018) compared the behavior of lead present as “naturally-aged” and as “spiked” in a real soil. From EKR application, they concluded that the energy requirements could not be extrapolate from spiked soils to field soils. The experimental setup also plays an important role in the results. With the aim of reducing the controlled variables during treatment, simple cylinders or prismatic cells are conventionally used as electrokinetic cells. As that experimental approach differs from field conditions, the scaling-up of the process is required. Lopez-Vizcaino et al., (2016) reproduced the field conditions of real soil, such as moisture content and degree of compaction, to submit it to EKR process at two scales. They concluded that phenomena such as evaporation and possible leaks played an important role in the electrokinetic processes and, consequently, these processes should be evaluated. In addition, the energy consumption was considerably influence by the scale, which involved divergences in the electrokinetic processes developed [13]. M. Villen et al., (2015,2018) proposed a generalized model based on the soil fractionation for the prediction of the energy requirements for removal of metals at different scales. This approach allows not only to optimize experimental conditions, such as electrode distance and remediation time, but also to evaluate the viability of applying the technology at different scales [14,15].

Field Applications

The first field-scale application of electrokinetic reported was applied for metal concentration and mineral exploration since early 1970s in the former Soviet Union. However, it was not until 1987 that Geokinetics International designed the technology called “Electroreclamation” for soil remediation. At first, the electrokinetic technology was based on the basic electrochemical transport processes without implementing any enhancement. A list of some of the most relevant field-scale projects with a brief description is given in Table 1. These technology demonstrations are characterized by implementing some modifications in the electrokinetic processes to improve the removal of metals [16-20].

Although electrokinetic process has been demonstrated to be successful in the removal of heavy metals from soils and other solid matrices, the technology performance is limited by some factors. Soil characteristics could limit the applicability of the technique for a specific case. For instance, high concentration of ions apart from the target contaminants entails higher energetic consumption and lower removal efficiency. For soils containing carbonates and hematite, as well as rocks or other objects, the removal efficiency is drastically reduced due to discontinuities in the current flow path. Other factors limiting the field-scale application of the technology includes large remediation times, formation of by-products and electrode corrosion. In addition to this, electric heating, phenomena negligible at smaller scales, have been reported to be important in application at field scale [21,22]. As standard procedures could not be applied to predict field application results of the technique, the combination of trials at different scales and the use of mathematical models are key factors to deal with the application of the technique at large scales. From the analysis of a real polluted soil in Southern Spain, M.Villen et al., (2019) proposed a scaling-up methodology based on key aspects, such as buffering capacity of soil, properties of enhancing agents, behavior of metals present in the soil at different experimental conditions and energy consumption obtained from a mathematical model [23]. This promising procedure for the treatment of soils polluted with heavy metals could be used as complementary tool in the sustainable design and optimization of field scale demonstrations.

Conclusion

The application of electrokinetic technologies to remediate soil contaminated with heavy metals has been widely demonstrated to be a feasible alternative. The influence of experimental conditions and soil characteristics on metal mobilization has been assessed to improve the effectiveness of the treatment. Although most of studies have been performed at laboratory scale, the direct extrapolation of these results to field scale is questionable. The analysis of field scale demonstrations reported reveals the importance of evaluating the specific site characteristics to successfully design the technology application. Therefore, detailed soil analysis and bench-scale studies together with mathematical models represent a valuable tool to overcome limitations associated with the applicability of electrokinetic technology.

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