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INTEGRATED ELECTROKINETIC REMEDIATION TECHNOLOGIES: OPPORTUNITIES AND CHALLENGES

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Remediation of contaminated sites is a top priority of environmental professionals to protect public health and the environment. Unfortunately, many conventional in-situ remediation technologies are found to be ineffective and/or expensive to remediate sites with low permeability and heterogeneous subsurface conditions[1]. In-situ electrokinetic remediation is continuing to be extensively investigated for over a decade as a potential technology to remediate such difficult subsurface environments. The objectives of this paper are: (1) to present difficulties in implementing the standard electrokinetic remediation process; and (2) to outline the opportunities and challenges in developing and implementing promising integrated electrokinetic remediation technologies.

Numerous bench-scale studies have been reported which use ideal soils such as kaolin spiked with a selected single contaminant (e.g., lead or phenanthrene) to understand the contaminant transport processes. However, only a limited number of studies have been reported on real-world soils contaminated with a wide range of aged contaminants, and these studies have been helpful in recognizing complex geochemical interactions under induced electric potential. All of the bench-scale studies have clearly documented that non-uniform pH conditions are induced by applying a low direct current or electric potential, complicating the electrokinetic remediation process. Low removal of contaminants was observed in these studies, and detailed geochemical assessments were made to understand hindering mechanisms leading to low contaminant removal. In low acid buffering soils, high pH conditions near the cathode cause adsorption and precipitation of cationic metal contaminants, whereas low pH conditions near the anode cause adsorption of anionic metal contaminants. In high acid buffering soils, high pH conditions prevail throughout the soil, causing cationic contaminants to precipitate without any migration and anionic contaminants to exist in soluble form and migrate towards the anode. Removal of organic contaminants is dependent on the electroosmotic flow which varies spatially under applied electric potential. Initially, flow occurs towards the cathode, but it gradually decreases as electric current decreases due to depletion of ions in pore-water. If the soil pH reduces to less than point of zero charge (PZC), electroosmotic flow direction can reverse and flow could cease. Depending on the ionic strength, the electroosmotic flow may increase towards the cathode or the anode.

Several studies have investigated strategies to enhance the contaminant removal by using different electrode conditioning solutions, changing the magnitude and mode of electric potential application, or both. The electrode conditioning solutions aim to increase the solubility of the contaminants and/or increase electroosmotic flow. When dealing with metal contaminants (including radionuclides), organic acids (e.g., acetic acid) are introduced in the cathode to neutralize alkaline conditions, thereby preventing

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[1] Sharma, H.D., and Reddy, K.R. (2004), Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies, John Wiley & Sons, Hoboken, New Jersey, USA, 992p.

high pH conditions in the soil. This allows the cationic metal contaminants to be transported and removed at the cathode. Alkaline solutions are introduced in the anode to increase pH near the anode. This allows anionic contaminants to exist in soluble form and be transported and removed at the anode. Instead of using acids, complexing agents (e.g., EDTA) can be used in the cathode. When these agents enter the soil, they form negative metal complexes that can be transported and removed at the anode. When addressing organic contaminants (including energetic compounds), solubilizing agents such as surfactants, cosolvents and cyclodextrins are introduced in the anode. When transported into the soil by electroosmosis, these agents solubilize the contaminants. Alkaline solutions are also introduced to maintain soil pH greater than PZC to enhance electroosmotic flow.

Mixed contaminants (combinations of cationic and anionic metals and organic contaminants) are commonly encountered at contaminated sites. In general, the presence of multiple contaminants is shown to retard the contaminant migration and removal. Synergistic effects of multiple contaminants should be assessed prior to the selection of an enhancement strategy. It is found that the removal of multiple contaminants in a single step-process is difficult. Therefore, sequential conditioning systems have been developed to enhance removal of mixture of cationic and anionic metal contaminants and/or a mixture of metal and organic contaminants. In addition to the use of electrode conditioning solutions, the magnitude and mode of electric potential application is altered. An increase in the magnitude of electric potential increases the electromigration rate and initial electroosmotic flow rate. Pulsed mode of electric potential application is found to increase the electroosmotic flow due to polarization of soil surfaces and it also allows rate-limited dissolution of contaminants to occur.

Although excellent removal efficiencies can be achieved by the use of different enhanced electrokinetic remediation strategies, several practical problems arise in using them at actual field sites. These problems include: high cost of electrode conditioning solutions, regulatory concerns over injecting conditioning solutions into subsurface, high energy requirements and costs, longer treatment time, potential adverse effects on soil fertility, and costs for treatment of effluents collected at the electrodes. As a result of all these problems, the full-scale field applications of electrokinetic remediation are very limited.

Despite the challenges, in-situ electrokinetic remediation holds promise to remediate difficult subsurface conditions, particularly low permeability and heterogeneous subsurface environments, where most of other conventional technologies fail. The electrokinetic remediation technology can also be applied to remediate diverse and mixed contaminants even when they are non-uniformly distributed in the subsurface. Standard electrokinetic remediation method is essentially an electrokinetically enhanced flushing process. However, the electrokinetic remediation can be made efficient and practical as well as less expensive by integrating or coupling it with other proven remediation technologies. Such integrated technologies include electrokinetic-chemical oxidation/reduction, electrokinetic-bioremediation, electrokinetic-phytoremediation, electrokinetic-thermal desorption, electrokinetic- permeable reactive barriers, electrokinetic-stabilization, electrokinetic-barriers (fences), and others. These integrated technologies have potential for the simultaneous remediation of mixed contaminants in any subsurface environment. Several successful bench-scale and demonstration projects have been reported recently on integrated electrokinetic remediation technologies; such integrated electrokinetic projects are expected to grow in the near future.