

## A Review of Electrokinetic Treatment Technique for Improving the Engineering Characteristics of Low Permeable Problematic Soils

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**ABSTRACT:** The use of electrokinetic (EK) treatment which is a comparatively new methodology is being investigated in some parts of the world as a viable in situ soil remediation and treatment method. The principles of EK treatment method involve applying a low direct current or a low potential gradient to electrodes inserted in the low permeable soils that cannot readily drained. The transportation of charged species across the soil involves several complex mechanisms such as electrolysis, electro-osmosis, electro-migration and electrophoresis. This technique can also be applied/enhanced by introducing desirable non-toxic chemical compounds such as lime or cement solutions to the soil by introducing them at the appropriate electrode. The combined effect of these processes together with various geochemical reactions alters the chemical composition of the soil porous medium and thereby alters the physicochemical properties of the soil. Although the technology has been approved to be practical in many laboratory bench scale experiments and small-scale pilot field tests, complicated features such as many electrochemical reactions and soil contaminant interactions are still not fully understood, therefore there is a need for further research to be conducted for a better understanding of physicochemical changes in problematic soils and efficiency of this newly developed technology.

**Keywords:** Electrokinetic treatment, Electrochemical, Electro-osmosis, Problematic soil

### 1 INTRODUCTION

In recent years, major settling or tilting of buildings and bridges, instability of dams and road embankments have been observed and many attempts have been made in order to mitigate such damages. In this regard, it is necessary to determine the soil improvement alternatives, technically and economically, from the ultimate state design in accordance with geotechnical categories, to stabilize and remediate the existing soft problematic soils prior to the commencement of any construction activities. The aims of improving soils (as foundation and construction materials) are to increase strength, reduce distortion under stress, reduce compressibility, control shrinking and swelling, control permeability and reduce water pressure (redirect seepage), prevent detrimental physical or chemical changes due to environmental conditions, reduce susceptibility to liquefaction, reduce natural variability of borrow materials and etc.

Conventional remediation methods have been known successful in minimizing several damages, however, they are expensive, time-consuming and may be difficult to implement in some existing structures. In this regard, electrochemical or electrokinetic (EK) treatment method can be used as an alternative soil treatment method for remediation of those deficiencies underneath building foundations, roads, railways or pipelines. The use of this technique involves an approach with minimum disturbance to the surface while treating subsurface contaminants and improving the engineering characteristics of subsurface soils.

The use of EK treatment which is a comparatively new methodology is being investigated in some parts of the world for the potential application through several laboratory experiments to verify the versatility and

effectiveness of this technique in practice as a viable in-situ soil remediation and treatment method [1-7]. Therefore, this review represents an overview of the EK phenomena, as well as previously performed research activities on this technique. Besides, advantages and disadvantages (limitations) of this technique are discussed and some recommendations and directions for future needs are described for this newly developed technique.

### 2 LOW PERMEABLE PROBLEMATIC SOILS

The EK method is applicable to fine grained soils because this process takes place basically due to the presence of clay particles in the low permeable soil (that cannot readily drained), possessing specific mineralogical properties, hence electrically and chemically active. Low permeable problematic soils have been distributed all over the world as expansive soils, dispersive soils, high compressible clays, marine clays, sensitive clays, quick clays, saline/sodic soils, soft peat and etc.

Soft clay soils are commonly found in many parts of the world. In coastal areas of Australia, the soft soils often outlying the estuaries of creeks and rivers [8] and pose serious problems in design and construction of roads and foundations. The soft problematic clays of Southeast Queensland (SEQ) are classed as very soft to soft, moist to wet and with medium to high plasticity. Their general characteristics include low shear strengths in the order of 10kPa to 15kPa, natural moisture contents between 60 and 120% and high compressibility [9]. As the population increases, the demand for new land increases at a similar rate, therefore in order to prevent excessive settlements, increasing their bearing capacities and control seepage, some ground improvement techniques are required.

In Bangkok, the upper soft clays are of low strength and high compressibility, with natural moisture content between 65 and 90% and high plasticity index (Ip) of 40-63% [10]. When subjected to flood in rainy seasons, the

land heaves and this cause settlement in the compressible soft clay layer [10]. The shortage of land around the large conurbations in Japan has resulted in various coastal engineering schemes and reclaimed land developments, which these are often located on soft marine clay deposits [11]. Moreover, settlement problem is prominent in Holocene clay deposits of coastal regions near the shore in Osaka, one of the industrial/commercial areas in Japan having relatively shallow water table [12].

In this regard, soil improvement techniques become significant especially in Southeast Asian countries, which most of these countries are laid within the coastal areas of South China Sea, having poor engineering properties.

### **3 ELECTROKINETIC (EK) TREATMENT**

“Electrokinetics is defined as the physicochemical transport of charge, action of charged particles, and effects of applied electric potentials on formation and fluid transport in porous media [13]”. Electrokinetic (EK) remediation, also termed as electrochemical soil processing, electro-migration, electro-reclamation or electro-restoration, is an emerging technique which uses intensity direct current (DC) or a low electric potential difference to an array of electrodes placed in the soil, for removing organic, inorganic and heavy metal particles from low permeable soils, mud, sludge, slurries, sediments and groundwater by electric potential [14]. When a DC is applied to soil, it stimulates the migration of electricity, pore fluid, ions and fine particles across the soil towards the oppositely charged electrode, thus creating a combined effects of a chemical, hydraulic and electrical (CHE) gradients [15]. As this method has widely been used to remediate contaminated soils, with the application of electrical DC, contaminants in the aqueous phase or contaminants desorbed from the soil surface are transported towards electrodes depending on their charge. Heavy metals are one of the main contaminants that are removed by the EK process. Heavy metals and other positively charged species are highly attracted and sorbed on the negatively charged clay surfaces. The migrated species can then be removed by several different methods such as electroplating, adsorption onto the electrode, precipitation and co-precipitation at the electrode or pumping near the electrode.

EK soil treatment induces several changes in the pore fluid chemistry, diffuse double layer (DDL), soil fabric and the hydraulic conductivity [13]. In this regard, the presence of DDL of clay minerals gives rise to several EK phenomena in soil. This EK process can also be enhanced by use of some non-toxic enhancement solutions (stabilizing agents) such as lime or calcium chloride solutions. These chemical solutions can be fed at either anode or the cathode depending on the ions to be transferred into the soil. By the addition of an appropriate enhancement agent, some properties of the soil such as texture, plasticity, compressibility and permeability will be altered; therefore they can be very effective in improving soil characteristics by reducing the amount of clay size particles and increasing the shear strength.

#### **3.1 History/development of EK treatment**

The demand for innovative and cost-effective in-situ and ex-situ remediation technologies in waste management

encouraged some attempts to apply conduction phenomena in soils under an electric field to remediate and remove chemical species from soils [16], while very few studies have investigated the role of EK technology on strengthening and improving the engineering characteristics of the problematic clay soils. In-situ EK treatment has been developed largely to address several contaminants in low permeable soils particularly with high clay content. Although this application is relatively new, some oil industries have employed electrokinetics for enhanced recovery over the past several decades.

Ruess (1808) first observed the EK phenomena when a DC current was applied to a clay-water mixture. In 1879, Helmholtz first treated electro-osmosis phenomena analytically and provided a mathematical basis; then after in 1921, Smoluchowski modified it to apply it to electrophoretic velocity. In the early 1930's Casagrande started his studies in electro-osmosis in order to stabilize clays mainly by removal of the water. Several Russian researchers used electro-migration in prospecting for metals in 1960's [17]. The first successful demonstration of the use of EK technique for soil remediation was performed in the Netherlands in 1986 and some other places in Europe and US for the removal of the toxic chemical species. These successful studies and applications encouraged some other researchers and in-situ studies, resulting in some breakthroughs in the understanding of EK phenomena to improve physical properties of low permeable soils for many approaches such as: improving stability of excavations and unstable embankments [18], [19], backfill strengthening and slope stabilization [18], [20], stabilization of soils by consolidation [21-29], soil drainage and ground water lowering [30], soil improvement stabilization of fine-grained soils [31-38], remediation of salt affected soils [1], dewatering of sludge [39-41], assisting pile driving [42-45] and treatment of dispersive soils [46], [47].

#### **3.2 Geochemical reactions**

Due to fluid and solute transport through soil, several geochemical reactions take place within the porous media. These interactions may include diverse processes such as sorption-desorption, precipitation/dissolution, and oxidation-reduction (Redox) behavior during the EK process. Sorption refers to partitioning of contaminants from the solution to the solid phase or soil surface. Sorption mechanisms include surface complexation (i.e. adsorption) or ion exchange. Desorption is the reverse process and is responsible for the release of contaminants from the soil surface. These mechanisms are dependent upon the surface charge density of the clay mineral, characteristics and the concentration of the cationic species and the existence of organic matter and carbonates in the soil [16].

Transport of fluid and solute through a porous media is highly influenced by precipitation and dissolution reactions which are dependent on the soil and pore fluid pH and the concentration of the species. For efficient contaminant removal and to enhance the EK process, it is necessary to avoid any precipitation/dissolution, and to have the contaminants in the solubilized form [16], [17]. Dramatic changes in the soil electrochemistry throughout EK treatment also result in different chemical reactions, including oxidation and reduction of the species, which are

highly dependent on the soil pH. In this regard, the buffering capacity of the soil (resistance to change in pH) is an important soil characteristic which can significantly influence the highly pH dependent geochemical reactions in the porous media.

### 3.3 Electrochemical reactions

The migration of charged species through the soil involves 4 complex mechanisms such as electrolysis, electro-osmosis, electrophoresis and electro-migration (Fig 1). In the other words, the formation of electric DDL at the charged surface of clay particles is responsible for EK phenomena, namely electrophoresis, electro-migration and electro-osmosis [48]. The effect combinations of these complex electrochemical processes cause several changes in physicochemical, hydrological and engineering properties of the soils under an electric field.

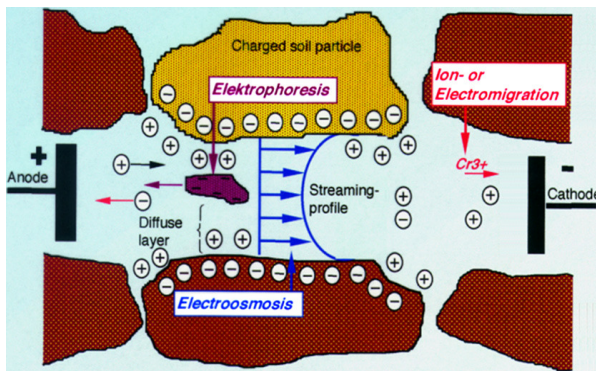
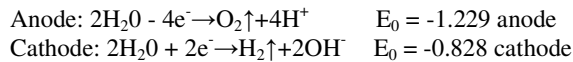


Fig.1 Schematic diagram of various electrochemical processes under EK treatment technique, after [49]

Electrolysis stands for chemical reactions associated with the electric field which generate  $H_2$  and  $OH^-$  at the cathode (reduction) and  $O_2$  and  $H^+$  at the anode (oxidation) as follows:



As a result of these reactions, an acid front will be generated near the anode and a base front will be produced near the cathode and that migrate towards each other. The acid front moves faster than the base front due to the higher mobility of  $H^+$  than  $OH^-$ , as a result, the acid front dominates the chemistry across the specimen except for some small parts close to the cathode. Helmholtz–Smoluchowsky’s model is widely used for the theoretical explanation of electro-osmosis phenomena [50]. Electro-osmosis is the migration of the pore fluid from anode to cathode through the capillary influence of an electric field. Electrophoresis is the motion of charged particles (usually micelles or colloids) relative to a fluid under an electric gradient, while electro-migration is the gradual movement of the ions or charged electrical species under an electric gradient. The rate of movement and direction of an ionic species is dependent upon its charge, both in magnitude and polarity, plus the magnitude of the electro-osmosis-induced flow velocity. Non-ionic species, both inorganic and organic, will also be carried along with the electro-osmosis induced water flow [51].

### 3.4 Contaminant transport mechanisms

Theoretical understanding and simulation of the EK treatment requires the mathematical formulation of transport processes, which are controlled by different variables such as pH and soil-surface chemistry, electrolysis reactions at the electrodes, equilibrium chemistry of the aqueous system, and geotechnical/hydrological characteristics of the porous medium [13], [21]. The coupled fluxes of different species due to different driving forces (CHE gradient) can be formulated as:

$$J_i = \sum_{j=1}^n L_{ij} X_j \quad j=1,2, \dots, n \quad (1)$$

Where  $J_i$  is the flux of species I,  $X_j$  is the driving force (the potential gradient),  $L_{ij}$  are the uncoupled conductivity coefficients under the driving forces of  $X_i$  and  $L_{ij}$  are the coupling coefficients. Under this section, some theoretical formulations are provided for further explanation of transport mechanisms under electric fields. Contaminant transport mechanisms include hydraulic or fluid flux, species or mass flux, and charge transport. Fluid flux ( $J_w$ ) per unit area of the porous medium due to hydraulic and electric gradients is expressed as:

$$J_w = k_h \nabla(-h) + k_e \nabla(-E) \quad (2)$$

Where  $J_w$  is the fluid flux per unit area of the porous medium ( $L^3 L^{-2} T^{-1}$ ),  $k_h$  is the coefficient of hydraulic conductivity ( $L T^{-1}$ ),  $k_e$  the coefficient of electro-osmotic permeability ( $L^2 V^{-1} T^{-1}$ ),  $h$  is the hydraulic head (L) and  $E$  is the electrical potential (V). The total mass transport of chemical species per unit cross-sectional in a saturated soil medium under CHE gradient is illustrated by the following formula [13]:

$$J_i = D_i^* \nabla(-c_i) + c_i(u_i^* + k_e) \nabla(-E) + c_i k_h \nabla(-h) \quad (3)$$

where  $J_i$  is the total mass flux of the  $i_{th}$  chemical species per cross sectional area of the porous medium ( $ML^{-2} T^{-1}$ ),  $c_i$  is the molar concentration of the  $i_{th}$  chemical species ( $ML^{-3}$ ),  $D_i^*$  is the effective diffusion coefficient of the  $i_{th}$  chemical species being transported in porous media ( $L^2 T^{-1}$ ),  $u_i^*$  is the effective ionic mobility of the  $i_{th}$  transported species in porous medium ( $L^2 TV^{-1}$ ),  $k_e$  is the coefficient of electro-osmotic permeability ( $L^2 V^{-1} T^{-1}$ ),  $E$  is the electrical potential (V),  $k_h$  is the hydraulic conductivity of the porous media ( $L T^{-1}$ ) and  $h$  is the hydraulic gradient (L). Finally the charge transport (current density) in the pore fluid due to electrical gradients is governed by Ohm’s law via:

$$I = \sigma^* \Delta(E) \quad (4)$$

Where  $I$  is the electric current density ( $CL^{-2} T^{-1}$ ), and  $\sigma^*$  is the effective electric conductivity of the soil which is given by:

$$\sigma^* = \sum_{i=1}^N F z_i u_i^* c_i \quad (5)$$

Where  $F$  is Faraday's constant (96,485 C/mol electrons),  $z_i$  is the charge of the  $i_{th}$  species,  $u_i^*$  is the effective ionic mobility and  $c_i$  is the molar concentration of the  $i_{th}$  chemical species ( $ML^{-3}$ ) [13].

**3.5 Factors affecting EK treatment**

There have been limited studies investigating the practical considerations for field implementations and the factors affecting EK processing [15]. The primary controlling factors are listed in Table 1.

**4 ADVANTAGES AND DISADVANTAGES/ LIMITATIONS OF EK TREATMENT**

Compared to conventional remediation technologies, EK remediation has several advantages, such as being less expensive (cost-effective), being applicable both in-situ and ex-situ, rapid installation and easy to operate (simplicity), having silent operation, having the advantage of not disturbing the site activities, and relatively short treatment duration.

Based on the results of laboratory tests and field applications, electrokinetics has been shown to be a promising method to remediate low permeable soils. However, the process has the following limitations, such as in some cases, during the EK treatment; excessive heat generated in the vicinities of electrodes can cause some adverse effects such as desiccation or cracking in the specimen. Some undesirable products (e.g., chlorine gas) may also be generated at the electrodes during the process as a result of electrolytic decomposition (redox) reactions of water [4]. In addition, it is also recommended by some researchers [52] to control variation changes in pH of the soil, caused by the application of EK treatment in order not to harm the biodegradation process, because high acidic conditions and electrolyte decay can corrode some anode materials. Another major concern is to use the proper chemical stabilizer (enhancement agent) to enhance the EK soil treatment.

As a remediation technique, some studies showed that heavy metals in their metallic state have not been successfully dissolved and separated from soil samples. The EK process is also not efficient when the target ion concentration is low and nontarget ion concentration is high. Also in some cases, the migration path could be very long or there might be stagnant zones between wells where the rate of migration is particularly slow resulting in incomplete remediation of the contaminated soil [17]. Electrolysis reactions in the vicinity of the electrodes may cause changes in pH that may change the solubility of the contaminants in the soil. Heterogeneities or subsurface anomalies at sites, such as rubble, building foundations, large quantities of iron or iron oxides, buried conductors/insulators, large rocks or gravel, or submerged cover materials such as seashells, can reduce the effectiveness of the process.

**5 SOLUTION FOR LIMITATIONS/ DISADVANTAGES**

Some techniques can be used in order to increase the efficiency of the EK technique such as: (1) injection of

Table 1. Factors affecting the EK treatment

	Factors	Characteristics
Soil condition	Soil type and mineral type	<ul style="list-style-type: none"> <li>• Effective on clay soils with particle size &lt; 2µm is 30% or more</li> <li>• More effective on silty clays with moderate plasticity (kaolinite) than illite and montmorillonite</li> <li>• Preferably soils not having high adsorption and high cation exchange capacities (CEC), e.g., illitic and bentonitic clays,</li> <li>• Not effective in soils with high buffering capacity</li> <li>• Not effective in soils containing high carbonate buffers, e.g., glacial till</li> </ul>
	Water content	<ul style="list-style-type: none"> <li>• Soil moisture should be conductive and adequate to permit electro-migration but optimally, not saturated, to avoid the competing effects of tortuosity</li> </ul>
	pH and electro-conductivity (EC) of the pore water	<ul style="list-style-type: none"> <li>• Effective on soils with high pH value (pH &gt; 9)</li> <li>• More effective in soils with higher EC</li> </ul>
Designing system	Voltage and current	<ul style="list-style-type: none"> <li>• Electric current intensities should be in the order of a few amperes per square meter</li> <li>• Variation depends on electrochemical properties of the soil, e.g., soils with higher EC require more charge and higher currents than lower EC soils</li> </ul>
	Nature of electrodes	<ul style="list-style-type: none"> <li>• In-expensive inert electrodes are preferred such as graphite and "pressed carbon-coated" electrodes</li> <li>• Use of metal from steel, iron, and copper are more effective rather than black carbon, lead and platinum</li> </ul>
	Processing time	Depend on the current and voltage levels, rate of transport, electrode spacing and configuration
	Cost	Depend on the type and depth of the contaminant, the EC of the soil and pore water, spacing of electrodes, type and process designed employed, site preparation requirements, and electricity and labor costs

appropriate chemical stabilizers (enhancement solutions) to strengthen the soft clay soil as coupled with EK treatment technique to prevent production of hydrogen ions in a relatively short time which will lead to the reduction of electro-osmosis flow and cationic contaminants removal; (2) prevent desorption and precipitation of the contaminants; (3) optimize all variables (e.g. current and voltage levels, processing time, installation and operation costs, etc) before selecting a configuration and spacing arrangements to enhance both electro-conductivity and cost-effectiveness of the process; (4) using inexpensive non-reactive electrodes such in carbon forms (graphite, activated carbon or carbon fibers) which are available in almost all countries, especially in third world countries where environmental controls have been absent or lacking; rather than expensive nonreactive metals such as electrodes like titanium or titanium coated metals; (5) using hollow electrodes preferably with some drilled holes through their walls, in order to allow the liquids to move freely into the sample and enhance the EK process; (6) conquering or managing the development of non-conductive regions as a result of soil drying is another important issue which requires careful considerations in developing appropriate practical methods and guidelines for full scale implementation of the EK process; (7) avoid toxic effects on the soil.

## **6 RESEARCH GAPS AND DIRECTIONS FOR FUTURE RESEARCH**

A review of the EK technique, as well as the previous research performed on EK has been carried out. This review indicated that some laboratory tests and field applications have proven to have practical application and technical effectiveness of the EK treatment for the industries. However, there are still a lot of scopes to be covered and research gaps need to be closed in this newly developed technology. The following highlight some of the reasons: (1) most of the studies focused on contaminant removal and remediation of the contaminated soils, while very few studies have investigated the role of EK technology on strengthening and improving mechanical and engineering characteristics of the problematic clay soils; (2) the understanding of complex micro-structural behavior of different clay minerals and chemical species under coupled chemical, hydraulic and electrical (CHE) gradients is limited and (3) a solid theoretical understanding based on experimental investigations and evidences does not still exist. Based on the review, a fundamental research question that needs to be posed is: can EK treatment method be technically effective and practically viable as an exsitu and insitu methods, for improving the engineering characteristics of the low permeable problematic soils? In short, can this method be considered as a good ground improvement technique?

Therefore, in order to address the question: (1) several field and laboratory studies need to be conducted on different problematic soils in order to investigate several alterations in soil composition, physicochemical and engineering characteristics of the soil under EK treatment; (2) there is even a greater need to build up new models in order to predict the modification of soil chemo-mechanical properties, which would be of great assistance in

infrastructure management and development applications; (3) the effects and degree of improvement of the soil with and without permeating different enhancement (stabilizing) agents through the soil should also be discussed; (4) several changes in soil composition and chemistry, soil physical properties (water content, consistency limits, etc), pH, nature and spacing of the electrodes, processing time, levels of voltage, current and many optimizations need to be further investigated and optimal design concept should be verified through the EK treatment of the problematic soils; (5) additional research is also needed to gain a better understanding of the relative importance of the transport mechanisms involved and to develop methods of identifying, quickly and simply, the most important factors affecting the EK treatment process at each specific site.

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