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# Influence of degree of compaction on electrokinetic remediation of unsaturated soil

**Chengwei Yin[‡], Liguo Jiang[‡,†], Keming Sun, Weiji Sun, and Bing Liang**

School of Mechanics & Engineering, Liaoning Technical University, Fuxin, Liaoning Province, 123000, China

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**Abstract**−In order to evaluate the electrokinetic process for unsaturated soil with different compacted conditions, six remolded soil samples containing the same water content (16 wt%) were compressed to obtain the various degrees of compaction (96.87% to 103.37%). All the lab-scale experiments were performed by applying a constant electrical voltage (1 V/cm). The electrical parameters related to the electrokinetic process were monitored to evaluate the influence of the soil degree of compaction on this process. The obtained results indicate that the soil compaction degree could influence the electrical current, the migration velocity of the voltage front, and the controlling mechanism of water transport during the electrokinetic processes. Followed by the initial decline, the electrical current of soil with a lower degree of compaction (96.87%) would increase at 0.7 mA/h, which was about seven times larger than that of the soil with a higher degree of compaction (103.37%). The migration velocity of voltage front in the soils increased with decreasing compaction degree. The voltage front migrated from the cathode towards the anode at 6.66 mm/h in the soil with a lower degree of compaction (96.87%). In comparison, the migration velocity decreased to 1.75 mm/h in the soil with a higher degree of compaction (103.37%). Both hydraulic and electrokinetic driving forces could influence the water transport in unsaturated soil. The results demonstrate that the catholyte entering the soil under the hydraulic gradient could be opposite to electro-osmosis. The electrokinetic driving force would be a major controlling mechanism for the unsaturated soil with a higher degree of compaction. For the soil with a lower degree of compaction, the hydraulic driving force would affect the water transport in the soil during its initial saturation period. Moreover, with the increase in soil saturation, the effects of hydraulic driving force were weakened, and the electrochemical properties of the pore solution appeared to be the dominant factor for the electrokinetic process.

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Keywords: Electrokinetic Remediation, Unsaturated Soil, Degree of Compaction, Apparent Electrical Conductivity

## INTRODUCTION

Soil contamination is one of the most important concerns for environmental engineers worldwide. Several contaminants, such as heavy metals, radionuclides, and organic matter, exist in the environment. It is considered a serious problem since it affects the environment, living organisms, and human health and the economic activities associated with soil usage. During the last 20 years, scientists and technicians have put considerable effort into developing innovative technologies for soil remediation. The electrokinetic (EK) method has been proven innovative in removing soil pollutants with low hydraulic permeability [1-6]. The principle of the EK method relies on the application of low-intensity direct current or low voltage gradient through the soil specimen between a couple of electrodes (cathode and anode). During EK treatment, the applied current causes both oxidation and reduction at the anode and the cathode, respectively. Therefore, it leads to a series of coupled transport phenomena, including diffusion, electro-osmosis, electro-migration, and electrophoresis [7-10].

The EK method has significant advantages among the rest, which include: 1) flexibility to use either as *ex-situ* or *in-situ* method; 2) applicability to both heterogeneous soil and soil with low permeability; and 3) applicability for heavy metals, radionuclides, and organic contaminants. Depending on the establishment of numerical models and the act of conducting experiments, the effectiveness of the EK method in mobilizing different pollutants in soil with other enhanced technologies has been widely discussed [11-13]. As a type of novel remediation technology, the previous studies have primarily focused on the transport and removal efficiency of contaminants under lab-scale conditions. The contaminated soils used in laboratory experiments are commonly spiked with certain pollutants first and then remolded in specially designed cells. However, there are currently no standard test methods that can be used to design and conduct the EK remediation experiment, especially lacking the standard procedures for preparing saturated remolded soil specimens in the laboratory. At present, there are main two preparation methods for remolded soil specimen in the laboratory: 1) by consolidating in a high liquid to solid ratio of slurry with a free drainage boundary [14-16]; and 2) by compressing the soil with a specific weight of water in mass fraction into the experimental mold under undrained condition [17-20]. The former method based on [21] could obtain the fully saturated soil specimen by applying back pressure before consolidation. However, the soil specimens prepared by the latter method, commonly based on [22] or [23], are always partially saturated because the air within the soil pore cannot be displaced entirely during the compaction. More importantly,

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[†] To whom correspondence should be addressed.
E-mail: princell@163.com

[‡] The author contributed equally to this work and should be considered co-first authors.

the pore structure and degree of saturation of the soil specimens compacted by different amounts of compaction energy would be quite different. Most literature related to soil EK remediation, which selected compaction method to prepare remolded soil specimen, did not clarify the detailed compaction process. The compacted unsaturated soil specimens are usually assumed to be fully saturated. The saturation of the compacted soil mainly depends on its dry density and water content [24]. Dry density is one parameter that describes soil pore structural and textural properties (e.g., porosity, void ratio, and pore volume). The water content is a significant influence factor of the soil electrical resistivity [25]. The constitutive relationships between the flux and the associated parameters demonstrate that the soil porosity would produce varying degrees of impact on diffusion, electro-migration, and electro-osmotic advection [26]. Furthermore, mass transport flux driven by hydraulic gradient is usually considered negligible compared to the EK processes in low permeability soil. However, for unsaturated soil, various investigations confirmed that matrix suction mainly depends on soil pore structure, and water content may significantly influence mass transport during EK remediation [27-29]. Yustres et al. observed that there are two well differentiated stages of water transport mechanism across the unsaturated soil. The hydraulic gradient is the fundamental driving force for the initial saturation process, and the electro-osmotic driving force becomes predominant when the soil reaches a degree of saturation close to one [30]. Xie et al. discussed the effect of the degree of saturation on the electric permeability coefficient. They concluded that the fluid is affected by the position water head, the pressure head and the matrix suction water head [31]. Moreover, according to classical Archie's law, the relationship between soil electrical resistivity ($\rho_a$), porosity (n), degree of saturation (S), and pore water electrical resistivity ($\rho_w$) is:

$$\rho_a = \mathrm{a} \cdot \rho_w \cdot \mathrm{n}^{-m} \cdot \mathrm{s}^{-2} \tag{1}$$

where m is the cementation factor and a is the tortuosity [24]. This relationship implies that both water content and porosity variations could change soil resistivity, which, in turn, affect electrical field local distribution [25].

Overall, many uncertainties remain in our knowledge on the EK remediation processes involved in contaminated soil in lab-scale experiments. The repeatability of soil specimens prepared by the compaction method is almost questionable. Therefore, further discussions considering the influences of the properties of remolded soil specimens prepared by compaction method on the EK processes are necessary. The degree of compaction is determined as the ratio between the field dry density and the maximum dry density of the soil, which is dependent on many factors, such as bulk density, porosity, moisture content, the shape of grains, and the granulometric composition of soil [24]. The objectives of this series of experiments were: (1) to evaluate the differences between the electric current and the apparent conductivity of the soils with different degrees of compaction; (2) to provide an insight into the impact of the degree of compaction on the voltage front of the inner segments of soil; and (3) to evaluate the water movement across the unsaturated soil with different degrees of compaction during the EK method.

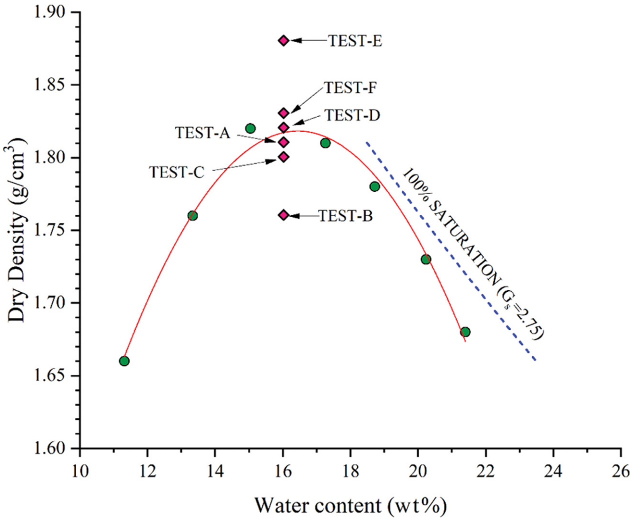

**Fig. 1. Comparison of the dry densities achieved in the soil compaction of the tests (diamond maker) and the standard protector compaction results (circle maker and solid line).**

## MATERIALS AND METHODS

### 1. Soil Sample Characterization

Commercial kaolinite produced in Jiangsu Province of China was selected as the model soil for this experiment. The clay soil mainly contained $SiO_2$ (45.4%), $Al_2O_3$ (37.5%), CaO (1.8%), $K_2O$ (1.7%), MgO (1.58%), and $Fe_2O_3$ (1.6%) appearing as brown-yellow with more than 98 wt% passing through 0.02 mm of standard mesh. The plastic limit is defined as the minimum moisture content at which the soil can be deformed plastically, and the liquid limit is defined as the water content at the transition of liquid state to a plastic state. The plastic limit and liquid limit of the model soil were 18.62 wt% and 40.75 wt%, respectively, which were determined based on [32]. According to the plastic limit and liquid limit results, six soil samples with different initial water content (11 to 22 wt%) were prepared. Then the standard protector compaction tests were performed following [22]. The maximum dry density and the optimum water content of the soil were found as 1.82 g/cm$^3$ and 16.5 wt%, respectively (see Fig. 1). The specific gravity of the soil was 2.75, which was tested according to [33]. The cation exchange capacity (CEC) of the soil was 4.4 coml$^+$/kg, which was determined following [34].

### 2. EK Experimental Apparatuses

The EK experimental apparatuses used in this study mainly consisted of four different parts. The configurations of these apparatuses were primarily based on the test system designed by Yeung et al., while their geometries were changed (see Fig. 2) [8]. The open fluid flow boundaries were implemented both on the anode and the cathode. The water could flow in or out from the electrode chambers to eliminate the effects of pore pressure and hydraulic conductivity [35]. Stainless steel rods with 8 mm diameter and 50 mm length were selected as electrodes for the anode and the cathode. Additionally, seven voltage monitoring holes (0#~6#) were set on the sidewalls of the EK extraction unit. The spacing between the monitoring holes was evenly distributed along the length of

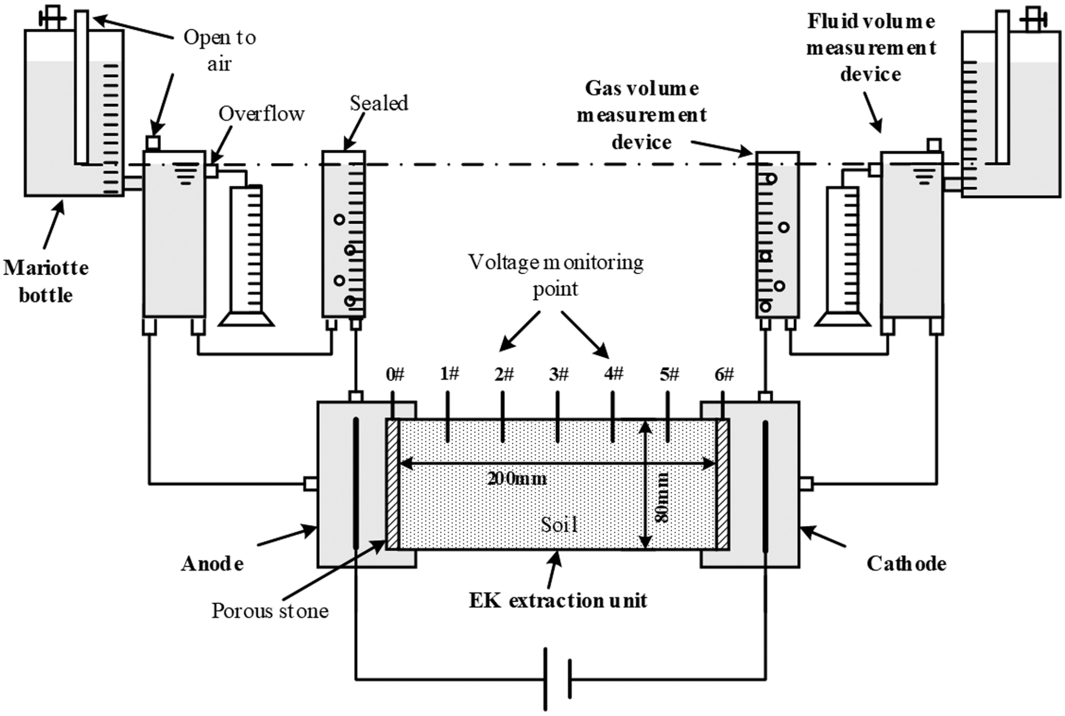

**Fig. 2. Experimental setup for the EK process (modified with [8]).**

the EK extraction unit. Those holes were sealed with stainless steel bolts during the soil packing process. To prevent the influence of the soil specimen on pore structure during the packing of soil into the EK extraction unit, the bolts were screwed just to fill those holes so that they could not penetrate the sidewalls of the EK extraction unit. Before the voltage was applied to the EK extraction unit, the bolts were tightened further to make the end enter into the cross-sectional center of the soil specimen.

### 3. Soil Sample Preparation and Compaction

To get closer to the chemical properties of the actual soil pore solution, 1 M $Ca(NO_3)_2$ solution was prepared by the municipal tap water and added to the air-dried soil to adjust its water content to 16 wt%. Then they were mixed thoroughly and sealed in a plastic container for 24 h (aging time) for homogenization. The reason for selecting $Ca(NO_3)_2$ was to avoid the generation of hazardous gases in the solution during electrolysis (e.g., $Cl_2$ would be generated when $CaCl_2$ was used). The municipal tap water adjusted the water content of the soil used in TEST-F for the control test. Before the compaction into the EK extraction unit, three soil samples were randomly selected to check the homogeneous moisture distribution. Subsequently, the soil was placed in the EK traction unit in three layers having heights between 7.5 cm and 8.5 cm. The compaction process for those layers was performed using a manual compaction hammer with a mass of 2.5 kg and a diameter of 51 mm, corresponding with the [22]. Before adding the next layer, the top of the previous layer was scratched to ensure close contact between the layers. Note that the height of outward projections of the EK unit of the final layer should not be greater than 6 mm. In addition, after the sample preparation, the EK unit was carefully separated from the mold. The soil beyond the EK unit was manually removed and then connected to the electrode chambers during this process. Here, six soil samples with different parameters were

**Table 1. Parameters and designs of the experiments**

| Parameters | TEST-A | TEST-B | TEST-C | TEST-D | TEST-E | TEST-F |
|---|---|---|---|---|---|---|
| Volume of unit ($cm^3$) | 954.56 | 954.56 | 954.56 | 954.56 | 954.56 | 954.56 |
| Sample loading layers | 3 | 3 | 3 | 3 | 3 | 3 |
| Number of blow | 25 | 20 | 25 | 30 | 40 | 25 |
| Total compaction energy ($kJ/m^3$) | 587.72 | 470.17 | 587.72 | 705.26 | 940.34 | 587.72 |
| Dry density ($g/cm^3$) | 1.81 | 1.76 | 1.80 | 1.82 | 1.88 | 1.83 |
| Degree of compaction (%) | 99.19 | 96.87 | 98.91 | 100.22 | 103.37 | 100.38 |
| Void ratio | 0.52 | 0.56 | 0.53 | 0.51 | 0.46 | 0.51 |
| Initial saturation (%) | 91 | 85 | 90 | 93 | 100 | 94 |
| EK duration time (day) | 2 | 4 | 6 | 8 | 10 | 10 |

used to study the impact of the degree of compaction on the EK process. The information and parameters of the final soil specimens are given in Table 1.

### 4. Procedure for the EK Experiment

The EK extraction unit was connected to the electrode chambers, followed by the soil compaction. The fluid and gas measuring devices were connected to the electrode chambers and then filled with municipal tap water. The water level elevation in the fluid measuring devices connected to the anode and the cathode was maintained at a constant level during the EK extraction process so that no hydraulic gradient could exist across the specimen. The electrodes, anode, and cathode were connected to the power supplier, and 20 V of direct current (DC) was applied (i.e., 1 V/cm). The flow of water and gas generated by the electrode solution during electrolysis was measured manually throughout the experiment. TP700 paperless recorder (TOPRIE electronics) with the TP1738 DC acquisition module (maximum support DC 0-10 A, accuracy 0.5%, resolution 1 mA) was used to record the amount of electric current passing through the specimen. According to [36], the apparent electrical conductivity ($EC_a$) of the soil can be calculated as:

$$EC_a \text{ (semens/cm)} = \text{I (amp) L (cm)/V (volt) A (cm}^2\text{)} \qquad (1)$$

Here, I is the electric current; L and V are the distance and voltage potential differences between 1# and 5#, respectively (see Fig. 2); A (=50.24 $cm^2$) is the cross-sectional area of the soil specimen. Municipal tap water was used for adjusting the water content of the soil and electrolyte both in the anode and cathode reservoirs. The pH, redox potential, and electrical conductivity of the tap water were 7.6±0.3, 175±25 mV, and 350±20 μS/cm, respectively.

The liquid samples were taken from the cathode and anode chambers when the specified processing time was reached. Then the electrode chambers were removed to push out the soil specimen from the extraction cell carefully. The whole soil specimen was divided into six sections according to the distance between the voltage monitoring points (0#-6#, from the anode to the cathode). Each section was analyzed for determining its water content, pH, and EC.

## RESULTS AND DISCUSSIONS

### 1. Soil pH and EC Distribution

The difference between the initial and the final pH distributions across the test samples with different EK processing times is shown in Fig. 3(a). The development of a relatively low-pH environment around the anode as well as a high-pH environment surrounding the cathode was the consequence of hydrogen and hydroxide ions transported from the anode and the cathode, respectively, into the soil under its applied electric potential. The pH values of most of the soil areas did not change much, excluding the surroundings of the electrode chambers. The pH values around the anode were decreased by about 1 unit for all the tests with different processing periods, though the pH values of both the anode compartment and reservoir were relatively low (pH=2.1-2.7). This observation was possibly due to the higher acid neutralization capacity of the selected soil [37,38]. The reason for the higher pH value appearing at the location of 0.6 normalized distance from the anode of TEST-E might be due to operator error. Because the part of the soil specimen adjacent to the cathode chamber was pushed out from the extraction cell, which may have been contaminated by the electrolyte with high pH.

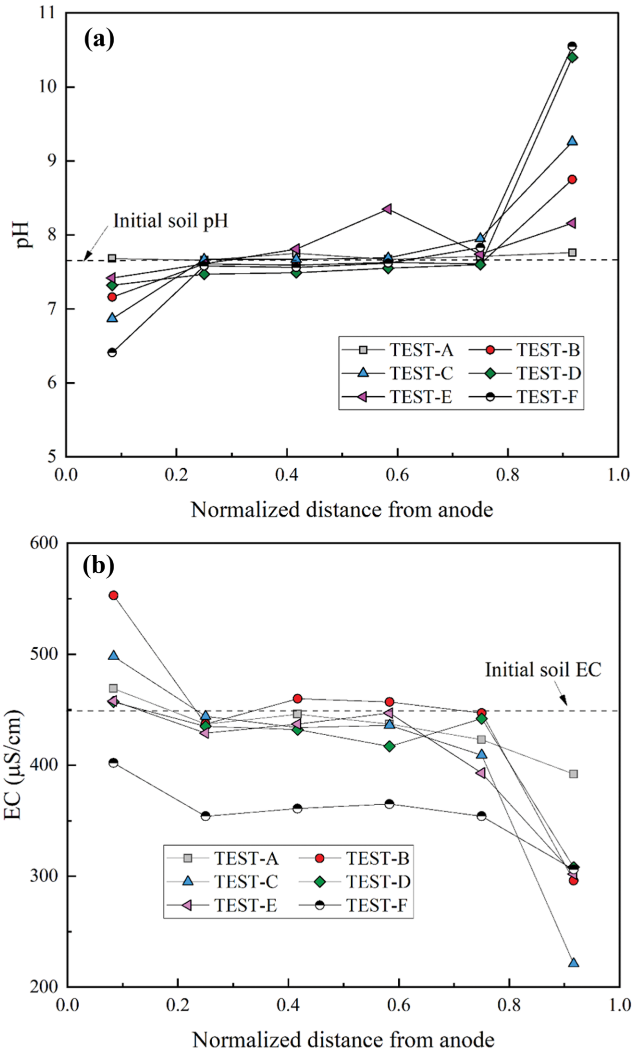

**Fig. 3. Distribution of soil pH and electrical conductivity after the EK treatment.**

Fig. 3(b) shows the distribution of EC values for the soil under different testing conditions after the EK treatment. The final distribution was non-linear along with the specimen, though the initial distribution was linear. The non-linearity might have been caused by the migration of ions in the pore fluid, resulting in a different EC distribution across the specimen [39]. The EC value is proportional to the ionic concentration that includes the number of ions produced from the electrolysis of water, and the ions present naturally in the soil [40]. Therefore, the difference in the EC values nearby the anode and the cathode might be attributed to their different pH values. Relatively low pH near the anode implies the presence of more $H^+$ ions there, which could dissolve some reactive minerals (e.g., carbonate minerals) and result in a higher EC value. In comparison, the higher pH near the cathode suggests the presence of more $OH^-$ ions there, which could combine with some cations

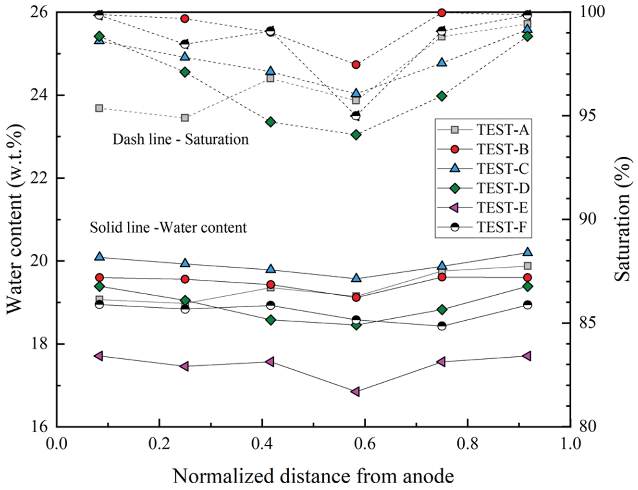

**Fig. 4. Saturation and water content distribution of soil after the EK treatment.**

to form precipitation and lower its EC value. Such changes represented the capabilities of the electrodes of forming compounds by reacting with the other ions [41].

**2. Water Content and Soil Saturation Distribution**

Fig. 4 shows the soil water content and saturation profiles of soil samples after the EK process. For the present study, the water content of the soil before compaction was the same (i.e., 16 wt%). Because the soil specimens were compacted under undrained conditions, the initial water content for all compacted soil specimens should be equal to 16 wt%. By comparing the final water content distribution results of different soil specimens with their initial water content, it can be seen that the water content of the soil with a lower degree of compaction showed significant variations. After four days of treatment, the average water content of the soil in TEST-B, which degree of compaction was 96.87%, increased by 3.5 wt%. The average water content of the soil in TEST-E, which degree of compaction was 103.37%, only increased by 1.5 wt%, although it had been treated for ten days. While the average water content of the soil in TEST-F, which had the same treatment time as TEST-E but with lower compaction (i.e., 100.38%), increased by 2.8 wt%. Increasing the compaction helps in reducing the voids that are filled with air [42]. Therefore, the initial saturation of the soil compacted in the present study increased with the degree of compaction (see Table 1). The higher initial saturation indicates that more soil voids were filled with water, and thus the water content changed little during the EK treatment. On the other hand, if the soil specimen compacted under lower compaction energy, more air would be retained in the pore space. Thus the unsaturated soil would absorb more water from anode and cathode chambers.

The result of saturation distribution implies that all the specimens were not fully saturated at the end of the EK processing period. The degree of saturation near the cathode and the anode was higher than that near the middle area. A similar saturation profile of an unsaturated soil sample during its EK treatment was also observed [30]. The region adjacent to the cathode had higher saturation than the region adjacent to the anode. Under the action of electro-osmosis, the movement direction of water in soil is from anode to cathode. Therefore, the area near the cathode (with the initial unsaturated condition) will receive the water transported from other regions in the soil under the action of electro-osmosis and the water supplied from the cathode electrolysis chamber at the same time. While the area near the anode only received water supply from the anode electrolysis chamber. With the increase of electrokinetic treatment time, the saturation near the cathode and anode gradually tended to be consistent. After electric treatment for ten days, the regions near the cathode and anode were nearly fully saturated. According to the results, interestingly, the zone with a lower degree of saturation appeared at the same position for all the tests (i.e., approximately at 0.6 normalized distance from the anode), though the initial saturation levels varied between different soil specimens (see Table 1). However, the reason behind this phenomenon is still unclear. A reasonable explanation for this could be the compaction process that would not completely discharge the gas within the pores of the specimen. The gas, initially present in the pores connected to the electrodes, would be displaced to move towards the cathode when water from the anode compartment entered there through electro-osmosis and/or matrix suction as the driving force. On the other hand, water from the cathode compartment would flow into the specimen by matrix suction. Finally, the gas might be entrapped in some areas of the specimen. According to some other studies, the impacts of the gas entrapped in solid skeleton on soil saturation were also observed by Tamagnini et al. and Gabrieli et al. [5,43].

**3. Electrical Parameters during the EK Process**

3-1. Variations in the Electric Current

The amounts of current measured for all the tests performed at different treatment periods are shown in Fig. 5(a). With the initial application of electric potential, the electrical currents in all tests decreased quickly in the first 10 h and then increased gradually at different rates. The electrical current results during 10 h to 96 h in different soil specimens indicate that the electrical current increase rates were inversely proportional to the degree of compaction. The increased rates of the soil with lower (TEST-B), standard (TEST-C and TEST-D) and higher (TEST-E) degrees of compaction were 0.7 mA/h, 0.4 mA/h and 0.1 mA/h, respectively.

Similar electrical current change has been reported by other literature which considers the EK processes in unsaturated soils [41, 44]. Such a trend in electrical current variation among the unsaturated soil samples was quite different from that in most saturated soil samples. Sauer et al. proposed that there are three electrical conducting paths acting in parallel in soil: (1) alternating layers of series-coupled solid-liquid (the aqueous phase in the fine pores), (2) solid element (conductance along the surface of the soil particles), and (3) continuous liquid element (the aqueous phase in the large pores) [45]. Rhoades et al. claimed that the contribution of the solid element is negligible because soil structure does not allow for enough direct particle-to-particle contact [46]. For entirely saturated soil, both large pores and fine pores are filled by water. Thus the ions in the pore solution would be the primary electrical carriers, which means that the concentration of ions in the pore solution would be the only influence factor of the variations in the electrical current. With the electric field applied, the ions would migrate to the electrode under the electric field, and the number

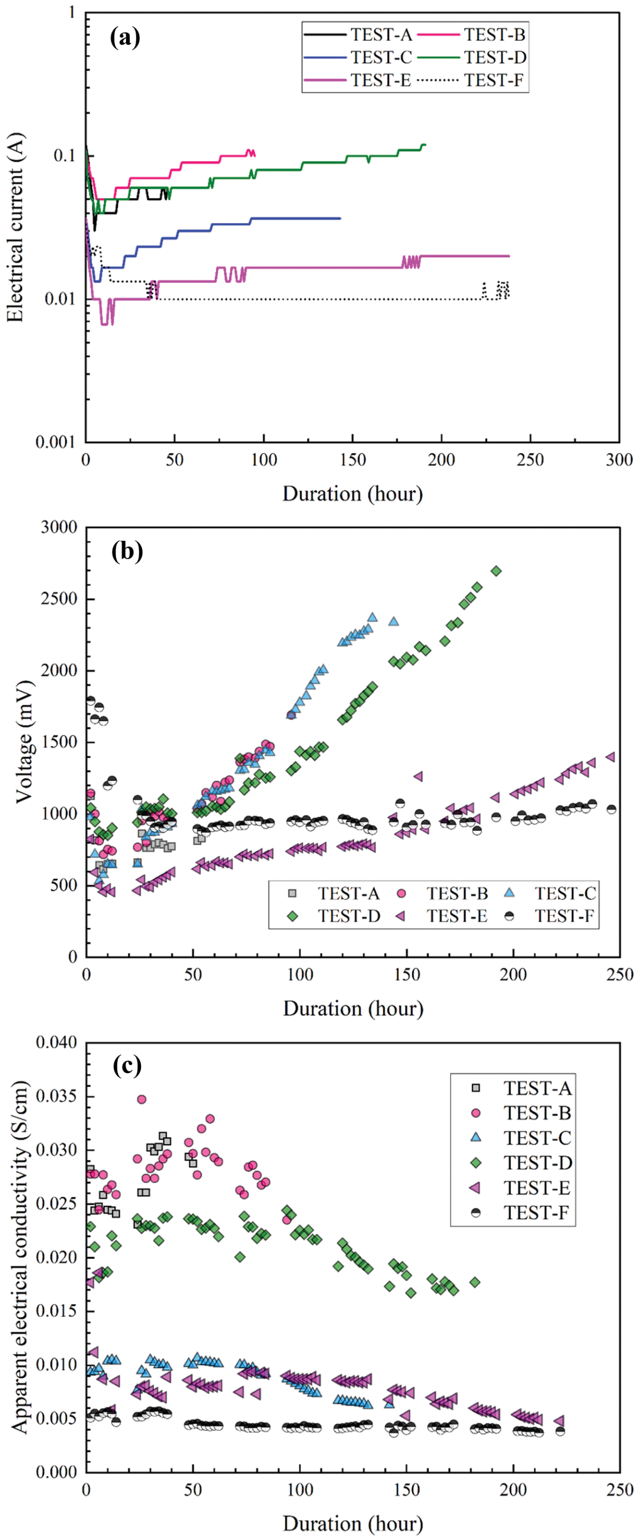

**Fig. 5. The current passing through the soil during the EK treatment.**

of ions in the pore solution would decrease. Therefore, in the initial stage of the EK treatment, the electrical current in saturated soil reaches the peak initially and then gradually decreases to constant [38,40,47]. For unsaturated soil, both the ions in the pore solution and the air phase in the voids should be considered the influence factors of the electrical current conducting. Under different compaction conditions, air could exist in fine pores and large pores, depending on the pore structure of the compacted soil. Thus, the electrical current variations in unsaturated soil would depend on the size of the pores with the air existing. In the present study, all soil specimens had a degree of compaction of >95% and an initial saturation of >85%. This implies that most air initially existed in the fine pores because the air in large pores would be more easily expelled during compaction. Thus, the properties of the aqueous phase in the fine pores would be major influence factors for the variations of electrical current in unsaturated soil. During the EK processes, the water entering into the fine pores could reduce the relative proportions of air and water. The increased water could provide additional electrical current conducting paths. Meanwhile, the increased water would alter the local distribution of ions between the solid and liquid phases in the fine pores. Thus, more adsorbed ions on small particles might transfer into the aqueous phase to promote electrical current conducting. The results shown in Fig. 5(a) show that the electrical current of the control test (TEST-F) gradually decreased from the initial peak value (0.03 A) to constant (0.01 A) without any increasing trend. While the electrical current of TEST-D decreased from the initial 0.11 A to 0.04 A, and then increased gradually to 0.12 A. It should be mentioned that the degree of compaction (see Table 1) and the final water content distribution (see Fig. 4) of the soil in TEST-D were similar to TEST-F. This implies that the rising electrical current followed by the initial decline of TEST-D may contribute to the increased pore solution ions. Other researchers have also discussed the influences of adsorbed ions on small particles on electrical current conduction in soils [48,49].

### 3-2. Variations in $EC_a$ of the Soil

The calculated results of $EC_a$ varied with the soil specimens by depending on the current (i.e., the results shown in Fig. 5(a)) and the total voltage values between point 1# and point 5# (i.e., the results shown in Fig. 5(b)) are demonstrated in Fig. 5(c). The $EC_a$ of soil showed a tendency to decrease with the increase in soil compaction. When the degree of soil compaction was increased, the medium porosity was decreased (i.e., the volumetric ratio of water to soil solid was decreased) by reducing the influence of the pore solution EC on the soil $EC_a$ [50]. In addition, according to the well-known Archie equation, there was an inverse relationship between porosity and resistivity. $EC_a$ and resistivity were also reciprocal to each other [51]. Hence, there was a negative relationship between the soil $EC_a$ and the degree of soil compaction.

The $EC_a$ of the soil with a higher degree of compaction (TEST-C, TEST-D, and TEST-E) was observed to decrease gradually and approached the value of the control test (TEST-F). However, the $EC_a$ of the soil with a lower degree of compaction (TEST-A and TEST-B) was increased initially within the first 50 h and then decreased. The initial increase of TEST-A and B might be attributed to the more catholyte flowing into the soil both from the anode and cathode under hydraulic effect. Friedman concluded that the EC of soil solution and the soil volumetric water content were the two main factors affecting the $EC_a$ of the soil and causing an increase in its dependence on the water content [52]. This conclusion might only be suitable for soils with a low initial saturation level

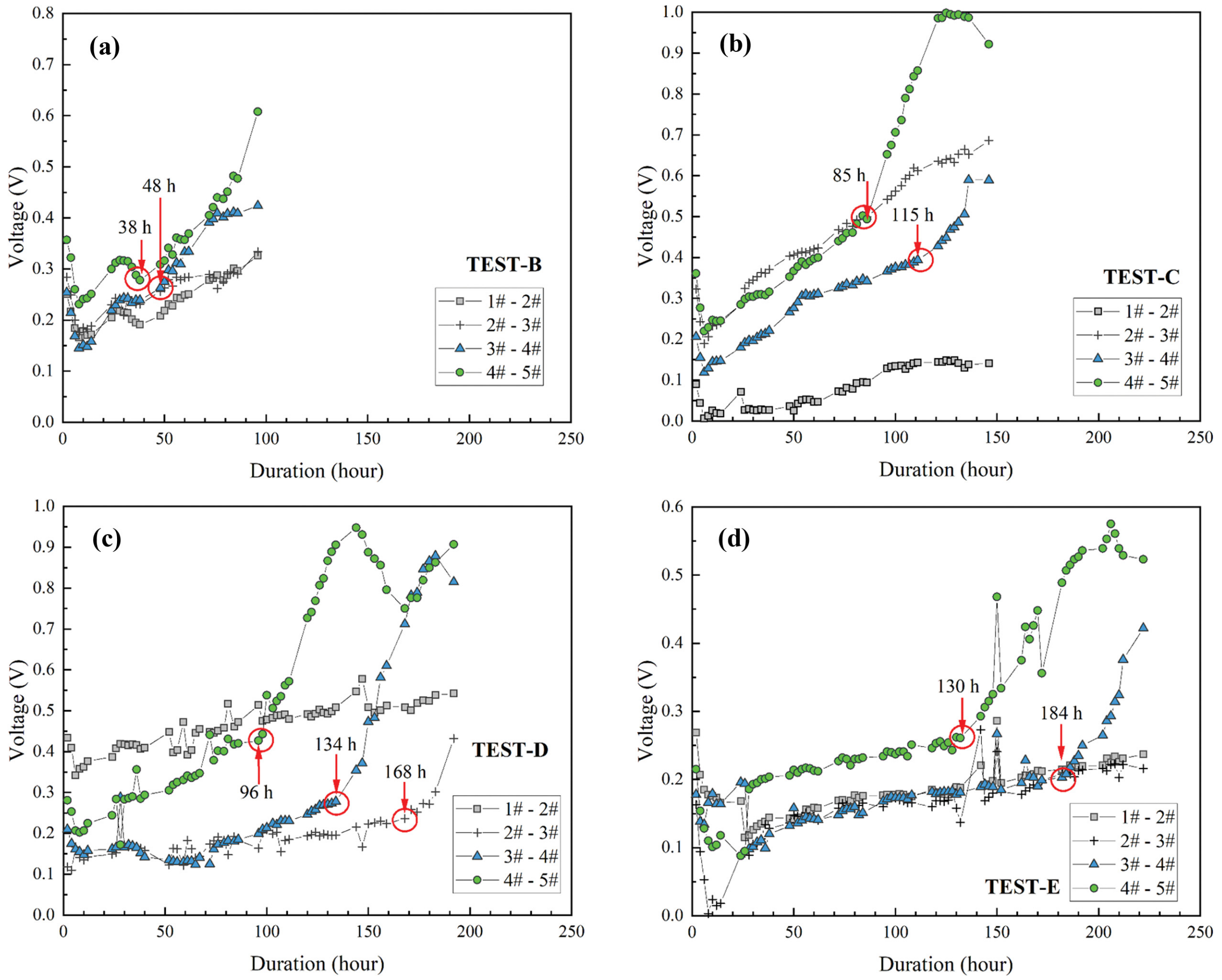

**Fig. 6. Electric potential distribution through soil during the EK treatment.**

and low degree of compaction. When the soil was close to saturation, the influence of saturation level on the $EC_a$ was weakened, and the concentration of the charged ions in the soil pore solution would play a significant role.

### 3-3. Movement of the Voltage Front

The evolution of electric potential between different voltage monitoring points in the soil specimens during the EK treatment is shown in Fig. 6(a) to 6(d). Although different soil samples showed different voltage values across the monitoring points at the same location, an obvious voltage front (i.e., the position shown by the arrows in the figure) was found to move from the cathode to the anode during the EK process. The voltage front indicated the depletion region within the soil [35]. Therefore, the moving speed of the voltage front might represent the migration velocity of the ions. The velocity of the voltage front moving in unsaturated soil decreased with the increase in soil compaction. For example, the time when the voltage front appeared in the section between point 4# and point 5# of TEST-B (Fig. 6(a)) with a lower degree of compaction was about 38 h. On the other hand, in the case of TEST-E, the time when the voltage front was observed at the same region (Fig. 6(d)) with a higher degree of compaction was about 130 h. Moreover, in the soil samples with a similar degree of compaction, the time required for the appearance of voltage front at the same section was close. For example, the time of the voltage front passing through the section between point 4# and point 5# in TEST-C and TEST-D was 85 h and 96 h, respectively. Furthermore, the time of the voltage front passing through the section between point 3# and point 4# was 115 h and 134 h, respectively (see Fig. 6(b) and Fig. 6(c)).

The migration velocity of the voltage front could be estimated according to the total length of the two adjacent voltage monitoring sections and the time difference of the first appearance time of the voltage front in the two sections. Here, the section data between point 4# and point 5# and the section data between point 3# and point 4# were selected to compare different soil specimens. The total length of the selected two sections, i.e., the distance between point 3# and point 5#, is 66.6 mm. The estimated values of the migration velocity of voltage front in the specimens with different degrees of compaction were, in descending order, TEST-B (6.66 mm/h), TEST-C (2.22 mm/h), TEST-D (1.75 mm/h), and TEST-E (1.23 mm/h), which was consistent with the order in the degree of compaction.

According to the constitutive relationship between the fluxes and the associated parameters affecting transport, the effective diffusion coefficient ($D_j^*$) and the effective ionic mobility ($\mu_j^*$) of the $j$th chemical species in the porous medium were defined as $D_j^* = D_j \tau n$ and $\mu_j^* = \mu_j \tau n$ respectively. Where $D_j$ and $\mu_j$ are the diffusion coefficient and ionic mobility in free solution at infinite dilution, respectively; $\tau$ and n indicate the tortuosity factor as well as the porosity of the porous medium [19]. The relationship between the porosity and tortuosity factor could be found elsewhere [19,54,55]. Consequently, the soil with a higher initial degree of compaction indicated that the solid particles were arranged more tightly, so it could have the lower values of both $\tau$ and n.

## 4. Water Movement during the EK Treatment

Both matrix suction and electro-osmotic flow can influence the water transport in unsaturated soil. Thus, it was difficult to distinguish between the contributions of the two effects until the soil reached its saturation level (or matrix suction could be ignored). Hence, only the total water movement could be analyzed according to the variation in the liquid volume of the electrolytic reservoirs and fluid measuring devices.

The dynamic response of the incoming and outgoing water flux (one day average values) from both the anode and cathode compartments was calculated as follows:

$$q = \frac{\Delta V_{water}}{A \cdot \Delta t}$$

where q (m/s) is the average water flux from the anode or cathode compartment, $\Delta V_{water}$ ($m^3$) is the volume of water entering/leaving electrolytic compartment during the monitoring time interval $\Delta t$ (s), and A ($m^2$) is the cross-sectional area of the soil specimen. The calculation results are shown in Fig. 7. The sign of the flux indicates its direction: the positive values correspond to the outflux of the anolyte entering the soil (i.e., from the anode to the cathode), whereas the negative values indicate the outflux of the catholyte entering the soil (i.e., from the cathode to the anode). The results demonstrate that most of the absolute values ranged from $2\times10^{-7}$ to $8\times10^{-7}$ m/s, which is consistent with the data reported by [30]. It was observed that the analytic fluxes were maintained at their positive values and were progressively increased. However, most of the catholyte fluxes were maintained at negative values. It should be noticed that the catholyte fluxes of TEST-B and TEST-C were changed to positive values during the later periods of the specified time. In contrast, the catholyte fluxes of TEST-D and TEST-E were maintained at the negative values during the whole test period. The initial increased catholyte fluxes represented the water entering into the soil under the matrix suction effect. Then the progressively decreasing fluxes indicated the gradual reduction in hydraulic driving force and the enhanced electro-osmotic driving force. The positive values of the catholytic fluxes indicated the beginning of the outflux of soil pore solution to the soil under electro-osmotic effect [30]. According to the catholyte flux variation, it was found that soil compaction was a major factor influencing factor for water transport. It was observed that the saturation time (i.e., the required time for the catholyte flux that got changed to a positive value) increased with the increase in soil compaction. The soil specimen of TEST-E, which had the highest compaction degree, was not saturated even after ten days of processing. The same phenomenon was also reported by other researchers [5,30,55].

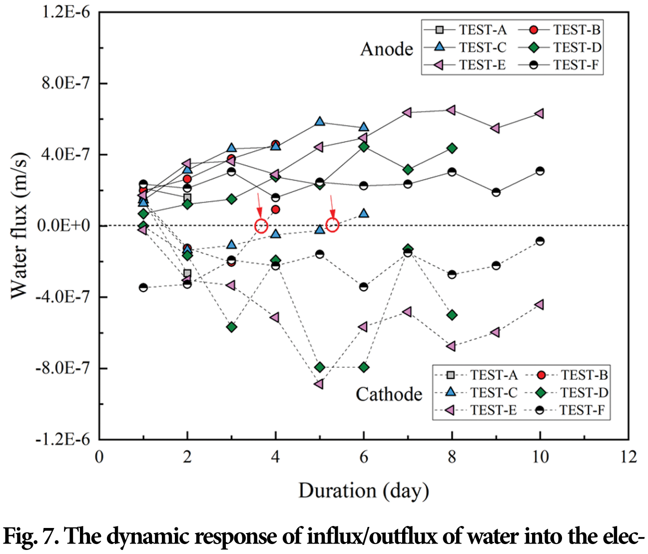

**Fig. 7. The dynamic response of influx/outflux of water into the electrolytic compartments.**

It was believed that the main reason for the fluctuations in the flow was a test equipment error. The gas generated by the electrolytic reaction might not immediately enter the gas measuring device, but instead first got aggregated somewhere at a high position of the electrolytic chamber. When the gas aggregation area was connected to the gas measuring device, it would start entering the device, and such an important thing was found to happen randomly. During this experiment, the phenomenon of discontinuous gas collection in the gas measuring device was observed. Therefore, although the gas production process of the electrolytic reaction was continuous, the capturing mechanism of the gas measuring device was discontinuous. Since the liquid discharged from the gas measuring device would enter the fluid measuring device, the flow-rate result tested by the fluid measuring device would fluctuate. Such test equipment errors might be solved in the future by reducing the volumes of the electrolytic chambers.

## CONCLUSIONS

The present study was designed to investigate the effects of degree of compaction on the EK remediation processes when the remolded unsaturated soil was selected as the object for the laboratory experiment. This investigation indicates that the degree of compaction of the remolded soil has significant influence on the electrical current and the voltage distribution in the soil. During the application of the EK process to an unsaturated soil, the hydraulic gradient produced by the matric suction was its fundamental driving force of water transport at the initial stage. When the soil reaches its saturated condition, the EK transport, including electro-osmosis, electro-migration, and diffusion, would become the predominant ones. The degree of compaction of soil showed an impact on both stages. Under the condition of having the same water content by weight, a higher degree of compaction meant a higher saturation level, lower matrix suction, and slower entry of electrolytes into the soil at the initial stage. However, at the same time, a higher degree of compaction represented lower porosity and tortuosity-like factors of the soil. Therefore, when the soil reached the degree of saturation close to one, the flux of electro-migration and diffusion became relatively small, which was reflected by the velocity of the depleted regions moving towards the anode.

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