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Effects of variations of voltage and pH value on the shear strength of soil and durability of different electrodes and piles during electrokinetic phenomenon

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ABSTRACT

Electrokinetic (EK) treatment is an effective method in accelerating the consolidation and improving the geotechnical properties of fine-grained soils. This method stabilizes the soil and increases the bearing capacity of piles by improving the soil shear strength. Changing the soil pH, due to the occurrence of chemical reactions of electrolysis in the soil, can increase its shear strength. However, the electrodes used in this method corrode due to the change in the soil pH, which in turn reduces the electrical potential. Electrode corrosion and loss of electrical potential can significantly reduce the efficiency of the EK method. In addition, when using the EK method to increase the bearing capacity of piles, changing the pH can cause corrosion and damage to the piles. One of the most important factors influencing the change in the pH of soil is the voltage applied during the EK process. It was reported that increasing the voltage affects the intensity of chemical reactions and electroosmotic flow and thus increases the efficiency of EK. However, very limited research has been conducted on the effect of voltage on the performance of EK method. In the present study, the effects of three voltages on soil pH and corrosion resistance of four types of electrodes including iron (Ir), stainless steel (St), copper (Co), and aluminium (Al) were studied. In addition, the effects of pH variations on the corrosion rate of three types of piles including steel pile (SP), reinforced cement concrete pile (RCCP), and reinforced lime-cement concrete pile (RLCCP) were investigated. It was observed that increasing the voltage from a specific limit had no effect on the intensity of electrolysis reactions and the soil pH adjacent to the electrodes did not change more than a specific limit. Moreover, increasing the voltage to higher than 35 V (i.e. 45 V) did not increase the volume of drained water from the soil, but caused more electric current than the allowable current for Ir, St, and Al electrodes, and the corrosion intensity of these electrodes increased significantly. RCCP reduced the soil pH to 2.4 within 7 d of curing due to severe corrosion (13% corrosion rate). The soil pH values adjacent to RCCP and RLCCP within 28 d of curing reduced to 3.7 and 3.8, respectively, but the two piles were not damaged. In general, the results of this research showed that selecting an optimized voltage had a significant effect on the efficiency of EK, and increasing the voltage did not always lead to increase in the efficiency of EK process.

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1. Introduction

Consolidation of soft clayey soil has always been a major problem in geotechnical engineering. The consolidation settlement in low permeable soft clayey soil occurs after a long period of time, which significantly delays the construction of infrastructures (Changizi and Haddad, 2015; Vali et al., 2019). Therefore, it is important to accelerate soil consolidation (Win et al., 2001;

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Kolwalkar, 2009). Hydraulic modification has been widely used to accelerate the consolidation of soft clayey soils, which requires the introduction of a hydraulic gradient. The hydraulic gradient can be provided by either applying an additional load to increase the soil pore pressure or using vacuum pressure to reduce the soil pore pressure. However, the hydraulic modification always requires additional materials such as fill materials or geo-membranes for sealing (Win et al., 2001).

A more recent environmentally friendly and cost-effective soft soil treatment technique is the electrochemical or electrokinetic (EK) treatment method. This method treats the subsurface contaminants and improves the engineering characteristics of subsurface soil with minimum disturbance to the surface (Acar et al., 1997; Reddy and Chinthamreddy, 2003; Mosavat et al., 2012; Yukselen-Aksoy and Reddy, 2013; Karim, 2014; Ramadan et al., 2018; Asadollahfardi and Rezaee, 2019; Zhang and Hu, 2019; Li et al., 2020; Ghobadi et al., 2021). EK method improves soil permeability through electro-osmosis (movement of water), electrophoresis (movement of soil particles), and change in the chemical properties of soils (Teng et al., 2017). Electrochemical effects in soils caused by EK treatment include electrolysis, hydrolysis, oxidation, ion diffusion, ion exchange, the formation of osmotic and pH gradients, desiccation by heat generation across the electrodes, mineral decomposition, precipitation of salts or secondary minerals, physical and chemical adsorptions, and fabric changes (Mitchell and Soga, 1993). These electrochemical changes are the basis for strengthening clayey soil by electrochemical injection (Ozkan et al., 1999; Zhang et al., 2017). EK treatment improves the soil strength and properties, and significantly decreases the treatment cost by eliminating the pumping process (Lo et al., 1991). Lo et al. (1991) reported that within 32 d, the undrained shear strength of soil under EK treatment increased uniformly by 50%; however, the required power consumption during this period was only 1% of the total project cost.

Several researchers have used the EK method for soil treatment, including soil consolidation (Esrig, 1968; Shang et al., 1996), soft clay strengthening (Bjerrum et al., 1967; Lo et al., 1991), soil stabilization (Casagrande, 1952; Chappell and Burton, 1975), and increasing the capacity of friction piles (Soderman and Milligan, 1961; Butterfield and Johnston, 1980). Soderman and Milligan (1961) reported a significant increase in the bearing capacity of steel pile (SP) anodes. Butterfield and Johnston (1980) also reported the modification of the stress field around a metallic friction pile in clayey soil by applying a modest and direct current electrical potential across the system with the pile used as one electrode. The shaft bearing capacity increased by about two times by increasing the voltage from 30 V to 90 V applied across the electrode system at 1.5 m distance from an anodic pile; however, the shaft load capacity of the cathodic pile decreased by five times. El Naggar and Routledge (2004) studied the effect of electro-osmotic treatment on increasing the axial and lateral capacities of metallic piles in a soft clayey soil. The result of a small-scale test showed a 36% increase in the lateral capacity and a decrease in the pull-out capacity of piles. The overtreatment (due to high voltage gradient and long-time treatment) of soil in the vicinity of the pile was the main reason for decreasing the pull-out capacity by causing soil shrinkage and pile-soil interface separation. By decreasing the voltage gradient and treatment duration in a large-scale testing program, the pull-out capacity of piles increased by up to 45%. Kolwalkar (2009) reported a nine times increase in the bearing capacity of SP in kaolinite clay subjected to an electric voltage of 30 V for 100 h.

The previous studies have only focused on evaluating the effectiveness of EK method on the bearing capacity of metallic piles. A very recent study published by the authors demonstrated that the

use of EK method could significantly increase the bearing capacity of both metallic and even concrete piles (Sadeghian et al., 2021). In this study, the impact of EK method on the bearing capacity of three pile types including reinforced cement concrete pile (RCCP), reinforced lime-cement concrete pile (RLCCP), and SP in kaolin clay was evaluated. The voltage of 25 V was applied to RCCP and SP for 1 d, 3 d, 5 d, and 8 d and the pile bearing capacity under static load was measured. This procedure resulted in a 38.1% increase in the bearing capacity of 7-d cured RCCP with 3-d EK treatment. The bearing capacity of RCCP without EK treatment only increased by 1% within 3 d. The bearing capacity of 7-d cured RCCP with 5-d EK treatment decreased due to failure in the pile body and the reduction in the bonding between the pile and the surrounding soil. To improve the corrosion resistance of RCCP under EK treatment, the effects of increasing the curing time and adding lime to RCCP materials were evaluated. By increasing the curing time, the bearing capacity of 28-d cured RCCP with 8-d EK treatment increased by 53%, and no damage was observed in the pile body. The bearing capacity of RLCCP increased by 57.8% with 8-d EK treatment without significant corrosion in the pile body. The bearing capacity of SP with 8-d EK treatment, and RCCP and SP without EK treatment increased by 95.4%, 11%, and 16%, respectively. The result showed that adding lime to cement concrete piles can effectively increase the pile bearing capacity and prevent damage in the pile body. EK method is often used to increase the bearing capacity of prefabricated piles. However, in the laboratory and in small dimensions, the piles are kept in water during the curing period and then installed in saturated soil for the EK treatment process. The saturation of soil and the wetness of pile can contribute to the electrical conductivity. The relatively small thickness of the pile is not a barrier to electric current. Besides, the thickness of concrete cover on the rebar is often limited to a few centimeters so that the ingress of water to a dry pile and the consequent electric current can also be provided.

As discussed earlier, EK treatment consists of four phenomena: electro-osmosis, electrophoresis, electrolysis, and electro migration (Lamont-Black et al., 2015; Asadollahfardi and Rezaee, 2019). Electro-osmosis is the water transfer from positive electrodes to negative electrodes. Therefore, water is collected in the vicinity of the cathode, which is drainable. Electrolysis in the EK treatment process is the result of decomposition of pore water molecules in the electrodes. In addition, the transfer of ions in the soil is also carried out during the process (Jones et al., 2011). The decomposition of water molecules leads to the formation of H^+ ion (acidic agent) in the anode and OH^- ion (alkaline agent) in the cathode (Asadollahfardi et al., 2016). Chemical equilibrium equations in the electrolysis process that breaks down water molecules are as follows (Jeyakanthan et al., 2011; Feijoo et al., 2017):



According to the equilibrium equations, the EK treatment process results in pH change of clayey soils, and during this process, the pH of the soil in the vicinity of anode decreases and in the vicinity of cathode increases.

A review on the literature shows that the basic aim of using the EK method is to accelerate the consolidation and to increase the shear strength of clayey soil, which results in the soil improvement, and increases the pile bearing capacity. Increasing the soil shear strength is mostly due to the pH variation and reduction of water content. The voltage value (potential gradient) affects the pH variation in the EK treatment process. In addition, these two parameters result in corrosion in the electrodes. Although the EK

efficiency mostly depends on the shear strength of the soil, the corrosion of material during the EK treatment increases the costs and accordingly decreases the EK efficiency. Moreover, in the EK method, the pile is used as an anode (positive electrode), and the reduction of pH in the soil adjacent to the pile can make corrosion in the pile body, which in turn ends up to the structural failure. To date, previous studies have shown that during the EK treatment process, the pH of clayey soil changes (Estabragh et al., 2014; Malekzadeh and Sivakugan, 2016; Moghadam et al., 2016). However, the effects of voltage and pH variations on the EK efficiency, such as corrosion intensity of piles and electrodes and shear strength of soil, have not been investigated yet. Moreover, the effectiveness of EK on increasing the bearing capacity of concrete piles, as well as SP, has recently been proved by the authors (Sadeghian et al., 2021). Therefore, the focus of the current study is to evaluate the impacts of different voltages and pH variations on the shear strength and corrosion resistance of four types of metallic electrodes, including iron (Ir), copper (Co), stainless steel (St), and aluminium (Al), three types of piles including SP, RCCP, and RLCCP under the EK treatment process.

2. Materials and methods

2.1. Properties of materials

Two types of soils, i.e. clay and sand (ASTM D2487-11, 2011), were used in the current testing program. A series of laboratory tests was carried out based on the American Society for Testing Materials (ASTM) standards to determine the basic properties of these soils as summarized in Table 1. Chemical analysis was carried out by X-ray fluorescence (XRF) analysis using Bruker S4-Explorer. The chemical composition of the clay, cement, and lime used in this study is summarized in Table 2. The properties of the clayed soil, lime, and cement used in the present research as well as the mix designs to prepare the concrete piles are the same as those used by Jahandari et al. (2019a). Fig. 1 shows the particle size distribution curves of the soils in this study. The water quality can also affect the mechanical properties of cementitious materials (Hajforoush et al., 2019; Kazemi et al., 2020; Mohammadi et al., 2020; Rasekh et al., 2020; Saberian et al., 2020; Mehrabi et al., 2021). In this research, deionized water was used for characterization tests and tap water for molding the specimens (Sadeghi-Nik et al., 2011; Jahandari et al., 2019a,b, 2020, 2021; Ghasemi et al., 2019; Bengar et al., 2020; Kazemi et al., 2020; Toghroli et al., 2020).

Table 1
Properties of tested soils (Jahandari et al., 2019a).

Soil type	Basic soil property	Value	Method
Sand	Effective size, D_{10}	0.005	ASTM D422-63 (1998)
	Uniformity coefficient, C_u	200	ASTM D422-63 (1998)
	Coefficient of curvature, C_c	18	ASTM D422-63 (1998)
	Plastic limit, PL	22%	ASTM D424-54 (1971)
	Liquid limit, LL	27%	ASTM D423-66 (1972)
	Plasticity index, PI	5%	Das (2013)
	Mineral	Kaolinite	Das (2013)
Clay	Activity degree	0.47	Das (2013)
	D_{10}	0.0015	ASTM D422-63 (1998)
	C_u	18	ASTM D422-63 (1998)
	C_c	0.4	ASTM D422-63 (1998)
	PL	23%	ASTM D424-54 (1971)
	LL	33%	ASTM D423-66 (1972)
	PI	10	Das (2013)
	pH value	6.8	Jahandari et al. (2017)
	Optimum water content, W_{opt}	15%	AASHTO T180 (2010)
	Dry specific weight, $\gamma_d \max$	18.74	AASHTO T180 (2010)
	Specific gravity, G_s	2.46	ASTM D854-10 (2010)

Table 2

Chemical compositions of the clay, lime, and cement used (Jahandari et al., 2019a).

Oxide compound	Content (%)		
	Clay	Lime	Cement
CaO	13.2	73.7	63.41
SiO ₂	41.75	1.15	21.66
Al ₂ O ₃	15.15	0.11	4.21
Fe ₂ O ₃	5.2	0.24	3.1
MgO	5.13	1.619	2.82
SO ₃	3.48	0.015	2.61
NaCl	0.08	0.011	
Mn		0.005	
LoI	12.58	23.15	0.81

Note: LoI is the loss on ignition.

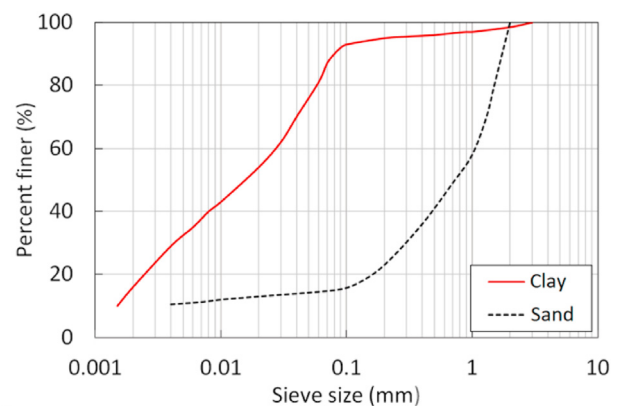


Fig. 1. Particle size distribution curves of the soils used (Jahandari et al., 2019a).

2.2. Test setup and procedure

A fully sealed glass box with the dimensions of 200 mm × 200 mm × 150 mm (length × height × width), made of glass plates with a thickness of 6 mm was used in the experiments. Two electrodes with a distance of 140 mm from each other were installed vertically. Two water drainage valves were attached to the bottom of drainage electrodes to drain the water accumulated near the electrodes. Metal electrodes with a length of 200 mm, an internal diameter of 18 mm and an external diameter of 20 mm (thickness of 2 mm) were used. A filter layer was also used to prevent soil penetration into the electrodes. For better drainage, all the electrodes were filled with sand. A layer of filter was placed at the intersection between the electrodes and the bottom of the box to prevent sand from entering the drainage valves. The shape and scale of the apparatus were designed and inspired by the experiments conducted by Zhou et al. (2015) and Sadeghian et al. (2021).

As shown in Fig. 2a, water (5% more than the liquid limit of soil) was added to the air-dried kaolinite. The soil-water mixture was kept in a closed container for 24 h to gain a uniform water content distribution (Estabragh et al., 2014; Malekzadeh and Sivakugan, 2016). Then, the soil mixture was uniformly placed into the box and a thin metal plate was placed on the specimen for preloading. The preloading phase with 27 kPa of load was completed when the soil settlement was stopped after 8 d. During this phase, excessive water was drained through the electrodes and the drain valves and the soil became saturated.

Initial shear strength of soil was measured by the vane shear test according to ASTM D4648-05 (2005) in the vicinity of electrodes. In general, there are two types of electrodes arrangement: one-dimensional (1D) configuration (linear arrangement) and two-dimensional (2D) configuration. The 1D configuration refers

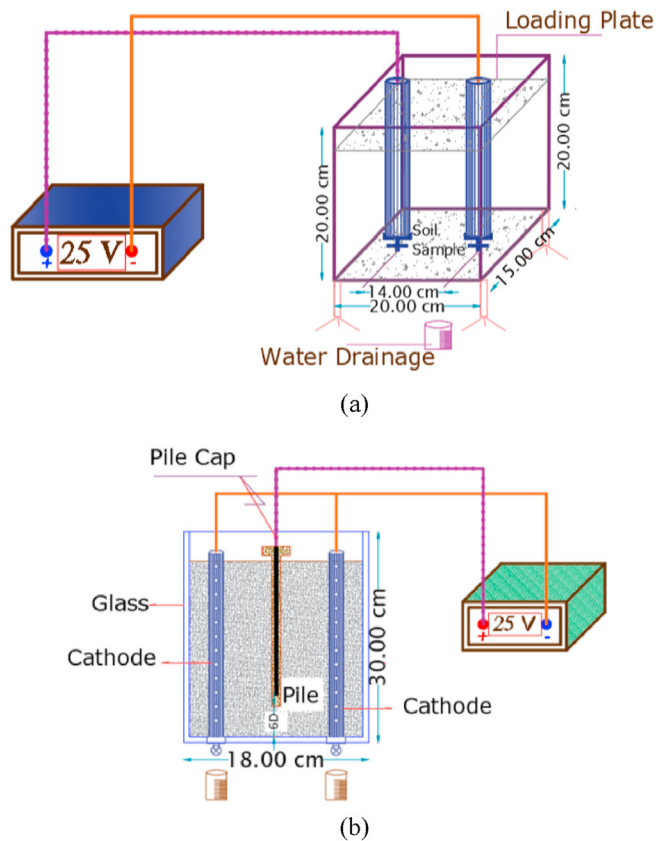


Fig. 2. Schematic design of the laboratory experimental apparatus for investigating (a) corrosion resistance of electrodes and (b) corrosion resistance of piles.

to the cases when one cathode is used for every anode. In 2D configuration, more than one cathode is installed for every anode (Alshawabkeh et al., 1999; Vociante et al., 2016). In the current study, three constant voltage potentials (i.e. 25 V, 35 V, and 45 V) were applied to the electrodes for 840 min with 1D configuration (Alshawabkeh et al., 1999; Zhou et al., 2015; Vociante et al., 2016). The pH of the soil in the vicinity of the anode and cathode was measured every 120 min. At the end of the EK treatment process, the shear strengths in the vicinity of the anode and cathode were measured as shown in Fig. 2a. These steps were repeated four times for four pairs of electrodes, including Ir, Co, St, and Al. In the second phase of the experiments, a glass box with a 180 mm × 180 mm cross-section and 300 mm height was used. Iron electrodes with 300 mm in length, 200 mm in external diameter and 180 mm in internal diameter were used in the experiments. The electrodes were mounted at 2D (D is the pile diameter) distance with a square arrangement (2D configuration) in order to concentrate the treatment effort in the vicinity of the pile and to maximize the efficiency. It is worth mentioning that the distance of $2D$ is reported to be appropriate in the field application that involves the EK treatment of a pile group (El Naggar and Routledge, 2004). A distance of $6D$ between the pile tip and the bottom of box was also selected to avoid the exit of stress isobars off the bottom and eliminate the effect of scale (El Naggar and Routledge, 2004; Sadeghian et al., 2021). Table 3 presents a summarized description of the cases involved in the set-up and tests. Sample preparation and preloading were performed as in the previous steps shown in Fig. 2b. All the tested piles had a length of 180 mm and a diameter of 20 mm. Iron rebar with a diameter of 6 mm was located inside the RCCP and RLCCP as an anode to supply the conductivity of these non-

Table 3
Summary of the test variables.

Variable	Value	
	Pile	Electrode
Treatment time (h)	64	14
Applied voltage (V)	25	25, 35, 45
Length of element (cm)	20	20
Dimension of element (cm)	2	2
Tests box dimensions (cm × cm × cm)	18 × 18 × 30	20 × 15 × 20

metallic piles. Therefore, no metal band (in the form of a spiral, for example) was required for the pile conductivity.

A series of uniaxial compressive strength (UCS) tests was conducted on RCCPs and RLCCPs at 7 d and 28 d of curing, respectively using nine cylindrical samples with 45 cm in diameter and 90 cm in length. The UCS of RLCCPs after 28 d at room temperature (25 °C) was less than that of RCCPs in the similar situations. Therefore, to reach similar compressive strengths, RLCCP piles were cured for 3 d at 50 °C (Jahandari et al., 2018, 2019a). In addition, because the quality of water used in the construction of the RLCCP piles is an important factor, tap water was used in RLCCP specimens according to the recommendations provided by Jahandari et al. (2017, 2019b, 2021) and Saberian et al. (2017). UCS tests were conducted on samples and the main results showed that the average UCSs of RCCP samples cured for 7 d and 28 d were 46.4 kPa and 69.1 kPa, respectively, and the average UCS of RLCCP samples cured for 3 d at 50 °C was 76.01 kPa.

3. Results and discussion

3.1. Effects of voltage and pH variations on the shear strength of soil and corrosion resistance of electrodes

In the first step, the pH change of the soil adjacent to the electrodes during EK treatment and its effect on the shear strength of kaolinite clay were investigated using four types of metal electrodes at 25 V. In addition, the effect of pH on the corrosion rate of the electrodes, and the effect of increasing the voltage from 25 V to 35 V and 45 V on the pH of soil and corrosion of electrodes were investigated.

3.1.1. pH variation of the soil adjacent to the anodes under 25 V

The change rate of the soil pH during the EK treatment process indicates the intensity of the reactions (Bjerrum et al., 1967; Estabragh et al., 2014). The intensity of reactions depends on the type (materials) of electrodes and the intensity of the electric current generated between the electrodes (Mohamedelhassan and Shang, 2001). Fig. 3 shows the change in the pH of soil adjacent to the anodes during 14 h of EK treatment under 25 V. This test was performed on four pairs of electrodes including Ir, Co, St, and Al. As can be seen in Fig. 3, during the process, the pH of the adjacent soil decreased for all four pairs of electrodes. In the early hours (nearly the first 2 h), the reduction rate of soil's pH was low, which increased significantly at the later hours. The reason for this change in the reduction rate of soil's pH can be explained by the fact that clay particles carry negative electrical charges at their surface. In dry clay, these negative charges are in equilibrium with the cations (ions with positive charge) of the metals in the soil due to the electrostatic attraction force. When water is added to the soil, these cations and a number of negatively charged clay particles float to form an electrolyte system. In addition, when clay is in contact with water, a double layer of water is formed (Yeung and Datla, 1995; Kolwalkar, 2009). If electrodes are installed in this electrolyte

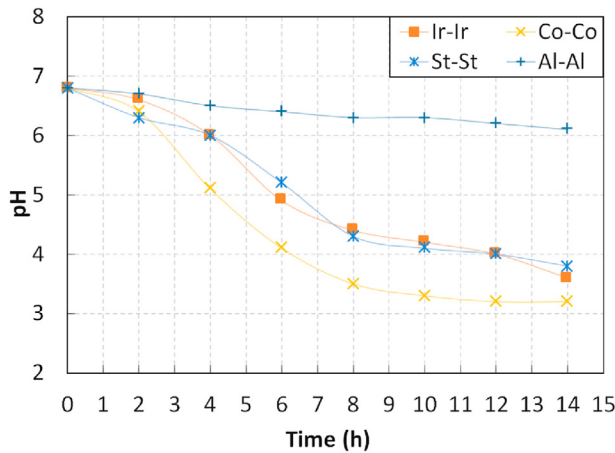


Fig. 3. Variations of pH value of soil adjacent to the anodes with time under 25 V.

system, negatively charged particles move towards the positive electrode and water polar molecules also move. This mechanism can be the beginning of the EK treatment process. It takes time to complete this process of creating an electrolyte system and a double layer of water. Therefore, in the first 2 h, the pH value decreased at a lower rate. As the process continued, the pH value decreased again until the end of the process. The reason for this decrease is the effect of H^+ ion on the double layer of water along with the reduction of electric current. A parameter called the zeta potential for clay is defined in the EK phenomenon. The negative zeta potential affects the amount of double layer of water and is defined as the tendency of soil to move water in soil volume during the EK treatment process (Chen et al., 1996; Shang, 1997; Kaniraj et al., 2011). In other words, soils with an initial negative zeta potential promote more chemical electrochemical reactions. H^+ production and reduction of soil pH cause compaction of the double layer of water and reduction of reaction intensity (Malekzadeh and Sivakugan, 2016). There are different factors that can affect the electrokinetic phenomenon and the speed of its chemical reactions such as zeta potential, water, double layer, electrical current, and electrode material. For example, at the first stage of EK treatment, double layer and negative zeta potential were high, which resulted in the promotion of the reactions. Electrical current increased to a certain density and then decreased gradually, and soil and electrode resistance were low at the first stage of process. Therefore, the chemical reactions related to the production of H^+ and OH^- were at higher rates at the beginning of the process.

As a result, the pH decreased at a slower rate until the end of the process. In addition, corrosion of the electrodes reduces the electric current and decreases the electromagnetic current and reactions. The greatest decrease in the soil pH was observed when a pair of copper electrodes was used. Copper electrodes are more conductive, and as a result, the electric current generated in the soil is higher. Zhou et al. (2015) also reported a similar result. However, the reduction in the pH of soil caused a decrease in the thickness of the double layer of water, resulting in a faster reduction in intensity of reaction. The reduction rate of pH was almost horizontal and constant, as shown in Fig. 3. The pH of soil adjacent to the anode decreased slightly when stainless steel electrodes were used. The reason for this is the lower conductivity of stainless steel compared to that of iron and copper.

Stainless steel is more resistant to corrosion due to the galvanized coating and thus a less current loss occurred. This result is similar to the findings of the research conducted by Afshar et al. (2020). As a result, the pH reduction became constant or stopped

at later periods of time. The lowest rate of decrease in the pH of soil adjacent to anode was observed when aluminium electrodes were used. The conductivity of aluminium was lower than that of the other three types of the electrodes, and thus more electrical resistance was generated in the soil and less electroosmotic flow occurred. From these observations, it can be concluded that the trend or rate of change in the soil pH as a factor affecting the shear strength of soil depends on the types of electrodes due to the current generated in the soil. In addition, over time, the rate of change in pH decreased and gradually became constant. Constant pH indicates a decrease in the intensity of electrolysis reactions. Although the electric current is reduced, it is not cut off, and the soil does not completely lose its moisture as a result of the electroosmotic current. The reactions are slowed down due to the reduction of the double layer of water and the zeta potential of the soil. As a result, basic soil characteristics such as negative soil zeta potential and initial soil moisture percentage along with the electrode material are effective in changing the pH of soil.

3.1.2. Effect of pH variation on the shear strength of soil adjacent to the electrodes under 25 V

Acidification and alkalization of soil due to change of pH increase the shear strength of clayey soil. In addition, the movement of water from anode to cathode reduces the moisture content of the adjacent soil. Decreasing the moisture content of soil also results in an increase in the shear strength of soil. Fig. 4 shows the changes in the shear strength of soil adjacent to anodes with pH, and Figs. 5 and 6 show the shear strength variations of soil adjacent to electrodes with time. As can be seen, the shear strength of the soil increased with decreasing pH. Although the pH reduction rate was low as shown in the early hours, the electroosmotic flow generated at the early stage of process was higher due to the high current. As a result, the water transfer from the anode to the cathode was higher and the decrease in higher moisture content increased the rate of shear strength increment. Over time, despite a further decrease in pH, the rate of increase in the shear strength decreased. The reason for this reduction can be explained by the decrease in electric current, which leads to the reduction of electroosmotic flow (Zhou et al., 2015; Xue et al., 2017). In addition, corrosion of the electrodes to some extent caused the current loss. The use of copper electrodes resulted in the highest shear strength of the soil adjacent to the anode. The performance of iron and stainless steel electrodes was nearly similar. Aluminium has lower conductivity and, thus, a greater current drop occurred. As a result, less pH change and lower shear strength were observed when aluminium electrodes were

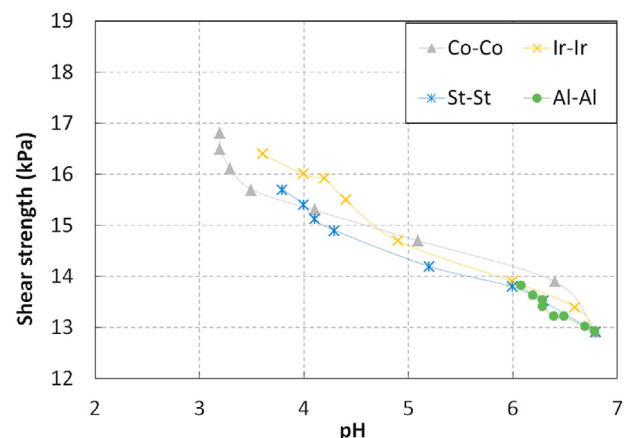


Fig. 4. Shear strength variations of soil adjacent to anodes with pH under 25 V.

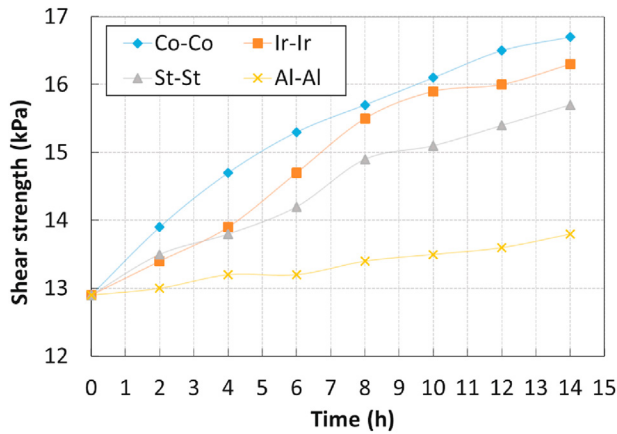


Fig. 5. Shear strength variations of soil adjacent to anodes with time under 25 V.

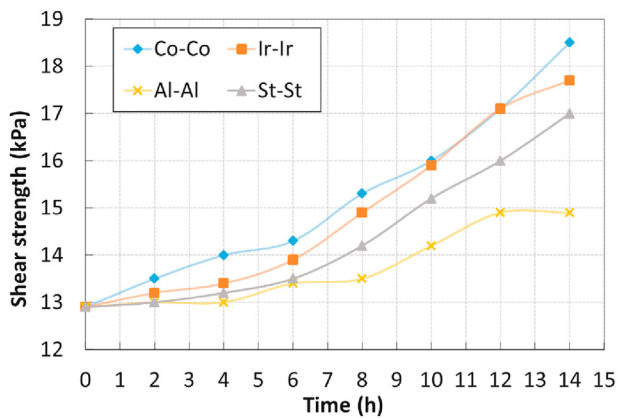


Fig. 6. Shear strength variations of soil adjacent to cathodes with time under 25 V.

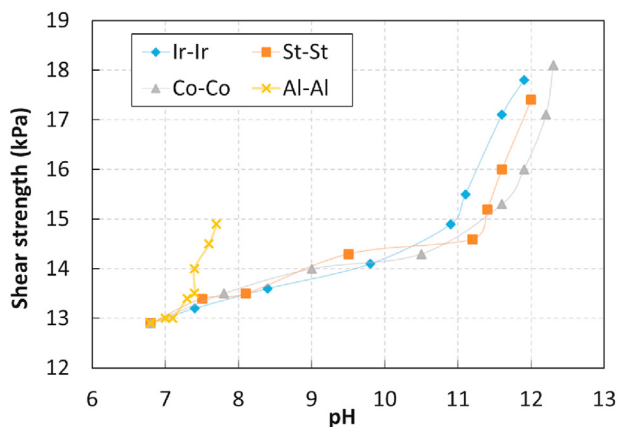


Fig. 7. Shear strength variations of soil adjacent to cathodes with pH under 25 V.

used compared to the other three electrode materials. OH^- production caused alkalinization and pH increased.

Alkalinization of soil causes cementation and increases the shear strength. The intensity of OH^- production depends on the electric current and the material of the electrodes. Fig. 7 shows the change in the shear strength of soil adjacent to cathodes based on pH. As can be seen, with increasing pH, the shear strength of the soil adjacent to the cathodes increased during the EK treatment process. As the EK treatment process progressed, the gain in shear

strength in the last hours increased more significantly compared to that at the beginning of the process, while the rate of increase in the shear strength of soil adjacent to the anodes was higher in the early hours. In the early hours, the amount of water being collected around the cathode and the drainage rate is low. Therefore, despite the upward trend of cementation of the soil adjacent to the cathodes in the later hours, the shear strength increases with a steeper rate. This is because, in the later hours, the water drainage process is completed and the percentage of soil moisture is further reduced. In general, the shear strength of the soil adjacent to the cathodes increased more than that of the soil adjacent to anodes. Accumulation of OH^- ions affects the clay and causes more cementation than that of H^+ . In addition, although in the last hours, the electrical resistance of the soil and electrodes was higher and the electro-osmotic flow decreased, the process of water drainage from the cathodes and the reduction of water content continued. In addition, the heat generated by the electrical resistance of the soil and electrodes is effective in reducing the water content. Therefore, the increasing rate of the shear strength increased. From the observations, it can be concluded that in addition to pH changes, decreasing the moisture content plays a significant role in increasing soil shear strength during the EK treatment process. In addition, the shear strength of adjacent soils reaches the highest amount in the early hours of EK; however, a significant increase in the shear strength of soils adjacent to cathodes occurs in the last hours of EK treatment. By now, the purpose of soil stabilization by EK method in previous studies has been stabilizing the soil adjacent to anodes (Yee and Kaniraj, 2011). However, these results show that in the case of proper drainage of water from the cathode, this method can also be used to stabilize the soil adjacent to the cathode largely.

3.2. Effects of voltage and pH variations on the corrosion resistance of electrodes

Electrode corrosion is inevitable during the EK treatment process, which is one of the controlling factors affecting the EK efficiency. When a metal is used as an electrode, the electrode corrodes due to the electrolysis phenomenon. The electrolysis and consequently the anode corrosion occur due to the following reaction (Malekzadeh and Sivakugan, 2016):



where M is metal electrode and MO is metal oxide. For example, when using a copper anode, this reaction occurs adjacent to the anode and results in different chemical reactions within the soil. Moreover, the pH changes accelerate the chemical reactions related to electrolysis near the electrodes.

In addition to changing the soil pH, the applied voltage and the resulting generated current also affect the corrosion of the electrodes. Eq. (4) was used to calculate the corrosion intensity of metal electrodes (Malekzadeh and Sivakugan, 2016).

$$\text{Degree of corrosion}(\%) = \frac{M_0 - M_1}{M_0} \quad (4)$$

where M_0 is the initial mass of the electrode and M_1 is the final mass of the electrode after corrosion.

Table 4 shows the corrosion rate of the electrodes under 25 V, 35 V, and 45 V. As can be seen from Table 3, the corrosion intensity of the anodes was higher than that of the cathodes in all four pairs of electrodes. For example, under 25 V, the corrosion rate of iron anode was 2.1% while that of iron cathode was 0.4%. Therefore, decreasing the pH of soil causes more corrosion than increasing it. Among the anodes, the copper anode had the highest corrosion and

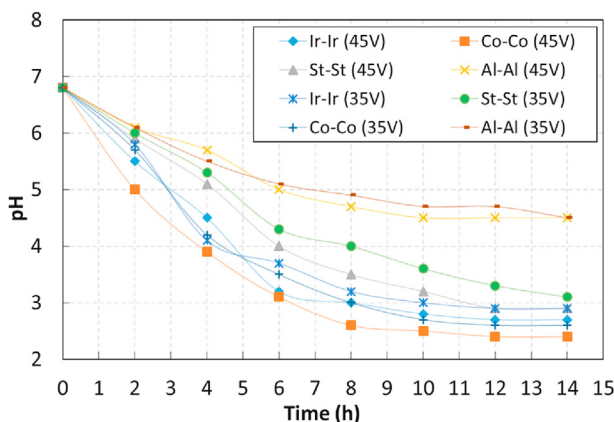
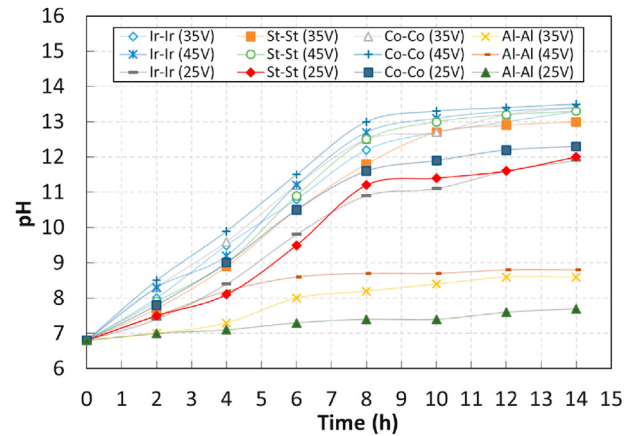
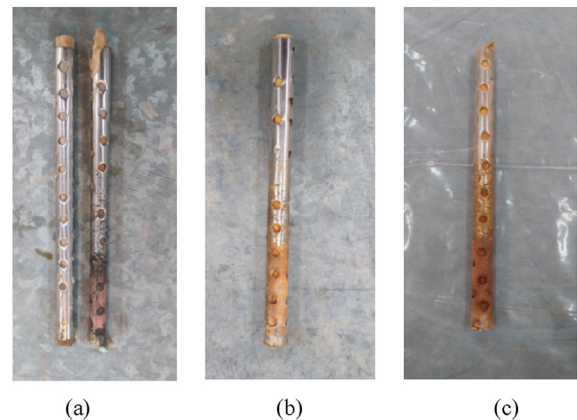
Table 4

Corrosion rate of electrodes under 25 V, 35 V, and 45 V.

Anode	Cathode	Corrosion of anode (%)			Corrosion of cathode (%)		
		25 V	35 V	45 V	25 V	35 V	45 V
Iron	Iron	2.1	2.7	4.1	0.4	1.3	1.6
Copper	Copper	2.6	2.8	3	0.5	0.6	0.6
Stainless steel	Stainless steel	1.5	2	3	0.4	0.9	1.1
Aluminium	Aluminium	0.5	0.06	0.5	0.3	0.8	0.4

the lowest resistance in an acidic environment in comparison to iron and stainless steel anodes. Although the pH of soil adjacent to the iron and stainless steel anodes was nearly similar, stainless steel anode was less corroded. The low corrosion intensity of aluminium can be attributed to the low pH change, not the high resistance of aluminium to the acidic environment of the soil. Alkalinization of soil caused corrosion in the cathodes, but the intensity of corrosion was much lower than that of the anodes.

Figs. 8 and 9 show the pH change curves of the soil adjacent to the electrodes over time under 35 V and 45 V for four pairs of electrodes, i.e. iron, copper, stainless steel and aluminium. As shown in Fig. 8, with increasing voltage, a greater decrease in the soil pH adjacent to all anodes was observed compared to that under 25 V. Increasing potential gradient from 25 V to 45 V caused 23% decrease in the pH of soil adjacent to copper anode. In addition, the speed and intensity of the reactions in the early hours were higher than those under 25 V. A notable point was that the pH change became constant at a higher rate with increasing voltage. Although with increasing voltage, the pH of the soil adjacent to anodes increased slightly, the process of pH changes to become constant or slow down became faster. In other words, by comparing the final pH of soil adjacent to the anodes under three voltages, a significant change in pH was observed by increasing the voltage from 25 V to 35 V. However, increasing the voltage from 35 V to 45 V caused no significant reduction in the pH of soil. As mentioned earlier, the initial negative zeta potential of soil plays an important role in the intensity of reactions and pH changes. From these observations, it can be concluded that the percentage of initial soil moisture and the formation of a double layer of water have a significant effect on the change of pH during the EK treatment process. Therefore, increasing the voltage to a certain amount increases the intensity of EK reactions. Increasing the voltage from a certain amount slightly increased the pH of the soil adjacent to the anodes during the EK treatment; however, it has a greater impact in accelerating reactions than the intensity does. This was observed to some extent in

**Fig. 8.** Change in the pH value of soil adjacent to anodes with time under 35 V and 45 V.**Fig. 9.** Change in the pH of soil adjacent to cathodes with time under 35 V and 45 V.**Fig. 10.** Stainless steel anodes (a) before EK treatment and after applying 25 V, (b) after 35 V, and (c) after 45 V.

the case of cathodes. Increasing voltage accelerated the change rate in the pH of the soil adjacent to all four cathodes, and the change rate in the pH of the soil near cathode was higher compared to that under 35 V. From these observations, it can be concluded that although the electrode material affects the intensity of the current produced at different voltages and this current intensity affects the pH, the negative zeta potential of the soil and the double layer of water of the soil (basic soil characteristics) are also effective factors in changing the pH and soil shear strength due to the EK treatment. In addition, increasing the voltage to a certain level does not have much effect on lowering the pH value.

Comparing the corrosion intensity of the anodes under 25 V, 35 V, and 45 V (Table 4) shows that increasing voltage aggravated the corrosion of all four types of anodes due to the acidification of the soil adjacent to the anodes. The pH of the soil adjacent to the iron anode was 3.6 and 2.9 under 25 V and 35 V, respectively. Changing the voltage from 25 V to 35 V increased the corrosion of the iron anode from 2.1% to 2.7%. The pH value under 45 V was 2.8 and did not change much compared to the pH under 35 V; however, the corrosion of this anode aggravated significantly (4.1%). The same result was also achieved in the case of stainless steel and aluminium anodes, as corrosion aggravated significantly from 35 V to 45 V with a small change in the pH (see Fig. 10).

The pH values of soil adjacent to the copper anode were determined as 3, 2.8, and 2.6 at 25 V, 35 V, and 45 V, respectively. The cause of copper anode corrosion aggravation can be explained by increase in soil acidification. In addition to increase in soil

acidification, another factor can be expressed for a significant change in the corrosion of three anodes (i.e. iron, stainless steel, and aluminium) against low pH change. Different metals have different allowable currents depending on factors such as current cross-section, environmental conditions and type of metal. When the electric current passing through a metal exceeds its allowable current, the metal becomes corroded and proceeds to the melting point (Vikharev, 2019). So far, no specific value has been defined or determined for the allowable or maximum current passing through a conductor without damaging it because the maximum current depends on the specific electrical resistance. Various factors, such as conductor's temperature, ambient temperature in which the conductor is located, environmental conditions, affect the specific resistance of a conductor. Therefore, the allowable or maximum currents are variable parameters and there are no fixed values. For example, increasing the temperature of the conductor and the environment increases the electrical resistance. Increasing the electrical resistance reduces the conductivity and thus reduces the maximum current passing through the conductor (Pozar, 2005; Halliday et al., 2013; Giambattista, 2019; Vikharev, 2019).

There are several reasons for the increase in the corrosion of the electrodes due to the increase in the voltage. During EK treatment, the rising temperature of the soil and the electrodes increased the resistance of the soil and the electrodes and decreased the conductivity. In addition, the acidification of the environment, along with the increase in electric current generated by the increase in the voltage, intensified the corrosion of the electrodes. In general, an electrical circuit defines a phenomenon called galvanic corrosion. Corrosion is the difference in the electrical potential between metals in relation to each other. The potential difference causes electrons to flow between the two electrodes. In this case, the metal with less equilibrium potential and anode forms the electrochemical cell and becomes more corroded, and less corrosion in the cathode metal occurs. Galvanic corrosion can be another cause of most electrodes corroding at 45 V.

In this study, increasing the voltage from 25 V to 35 V increased the current generated in the soil and between the electrodes. Due to the saturated soil and the distance between the electrodes, the current passing through the iron, stainless steel, and aluminium electrodes was more than their allowable current. Therefore, although the pH change with the voltage from 35 V to 45 V is not substantial, the corrosion due to electric current was significant. The decrease in the pH of soil adjacent to copper anode was 7% when the voltage increased from 35 V to 45 V. Among the four selected electrodes, the copper electrode had the highest allowable current. Therefore, the current produced at 45 V was less than the allowable current of copper and the copper was not damaged by electricity. However, the copper electrode showed less resistance to acid. As a result, in addition to changing pH and the amount of chemical ions in the soil, the passing current plays a significant role in the corrosion of the electrodes during EK treatment. By considering the allowable current of the electrodes and controlling the electric current, the corrosion in electrodes can be prevented to a great extent. In addition, although increasing voltage accelerates the reactions in EK treatment and increases the intensity of the reactions, it has no effect on changing the pH above a certain amount. Therefore, determining the appropriate voltage to optimize the EK efficiency is important; and increasing the voltage does not always increase the EK efficiency as a result of increasing intensity of the reactions. In addition, the applied voltage plays an important role in selecting the electrode material when using EK method. In other words, the electrolysis reactions during EK treatment, despite the retention of moisture in the soil and the uninterrupted flow of electricity, do not exceed a certain limit and increasing the voltage does not necessarily lead to an increase in the EK efficiency.

Table 5

Volume of drained water from the soil, percentage of soil moisture near the electrodes, and power consumption under 25 V, 35 V, and 45 V.

Voltage (V)	Variation	Value			
		Iron	Stainless steel	Copper	Aluminium
25	Water drainage (mL)	227	225.11	250.3	129.3
	Water content close to anode (%)	28.8	27.3	25.8	29.3
	Water content close to cathode (%)	28.8	27.6	25.6	29.9
	Electricity consumption (kW h)	95.15	102.55	116.98	60.09
35	Water drainage (mL)	250	239	263.9	152.32
	Water content close to anode (%)	25.8	24.54	24.1	25.2
	Water content close to cathode (%)	26	24.66	24.3	26
	Electricity consumption (kW h)	169.85	182.53	190.19	98.04
45	Water drainage (mL)	248.49	241.82	266.4	153.4
	Water content close to anode (%)	24.7	24.1	23.95	24.3
	Water content close to cathode (%)	25.1	23.95	23.63	24.12
	Electricity consumption (kW h)	258.11	270.85	262.86	120.9

Table 5 shows the volume of water drained from soil, water content of soil adjacent to the electrodes, and the electricity consumption by the electrodes. As can be seen, increasing the voltage from 25 V to 35 V increased the water drainage; however, increasing the voltage from 35 V to 45 V, contrary to expectations, had no effect on the volume of water drained from the soil. Despite not increasing the volume of drained water, with increasing the voltage to 45 V, the water content of soil adjacent to the electrodes decreased significantly. Part of the decrease is due to rising temperatures during the EK treatment process. The reason for the rise in the soil temperature in EK treatment is the electrical resistance of the soil and the electrodes, which occurs with increasing current.

Fig. 11 shows the current change curves during EK treatment for all four pairs of electrodes. Increasing the voltage to 35 V and 45 V increased the electric current in the early hours of the EK treatment process, but there was more current drop in the final hours under 35 V and 45 V than under 25 V. Considering the amount of water drained from the soil, it can be concluded that the increase in the electric current did not increase the electromagnetic current, contrary to expectations. In addition, the drop in the current under 45 V was greater than those under 25 V and 35 V. Therefore, although increasing the voltage increases the electric current, which can promote the chemical reactions of electrolysis to some extent, and as a result, the electromagnetic current will increase, the corrosion in the electrodes and the drop in current will be more significant.

From these observations, it can be concluded that increasing the voltage beyond a certain limit does not increase the drainage of water, and on the contrary, causes a decrease in the current and further corrosion of the electrodes. In addition, the electrical energy consumption increases with increasing current, which reduces the EK efficiency and increases the cost.

3.3. Effect of pH variation on piles

The change in the soil pH and the corrosion of SP and 7-d cured RCCP installed in the clayey soil under 25 V are investigated in this section. The piles went through EK treatment process for 1 d, 3 d, 5 d and 8 d and at the end of these time periods, pH and the shear

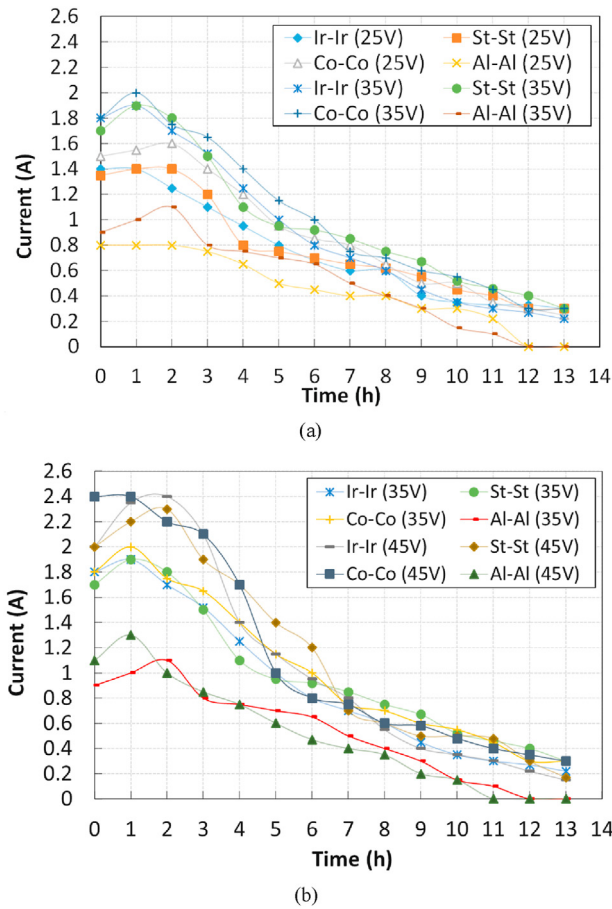


Fig. 11. Relationships between the change in current and time under voltages: (a) 25 V versus 35 V, and (b) 35 V versus 45 V.

strength of soil adjacent to the pile (anode) were measured. At the end of 8 d, corrosion in piles was also measured. Table 6 shows the pH, shear strength, and corrosion resistance of the piles during the 8 d of the EK treatment process. As can be seen, the pH value of soil adjacent to the SP decreased during 8 d of EK treatment. In the first 3 d, the pH decreased with a higher rate and in the following days, the pH continued to decrease at a lower rate. The shear strength of the soil adjacent to the iron anode increased from the beginning of consolidation until the end of 8 d. Although the reduction rate in pH decreased after 3 d, the increase in the shear strength due to increased drainage of water from the cathodes was significant. At the end of the 8th day, the corrosion of the SP was 3.2%, which did not affect the bearing capacity of the pile. At the end of the 1st and 3rd days of EK treatment on the 7-d cured RCCP, the pH values were 5.3 and 4, respectively. On the 5th day, deep cracks were observed in the soil adjacent to the pile in four directions and the pH value of the soil adjacent to the pile was 2.4 (see Fig. 12). After removing the

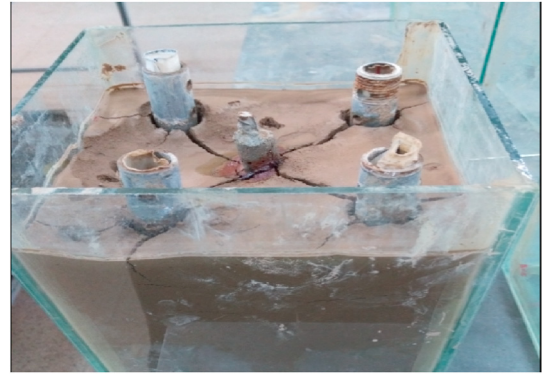


Fig. 12. Cracks of soil adjacent to 7-d cured RCCP at the end of the 5th day of EK treatment process.

RCCP from clayey soil, a significant corrosion was observed in the body of the pile as shown in Fig. 13; and the rate of corrosion was 12%. Despite the increase in the shear strength of the soil adjacent to the pile on the 5th day, the bearing capacity of the pile decreased significantly. Fig. 14 shows the load-settlement curves for 7-d cured RCCP. As can be seen, the bearing capacity of RCCP on the 5th day was significantly reduced (Sadeghian et al., 2021). The cause of the decay of RCCP body after 5-d EK treatment is low resistance of concrete against the acidic environment (Fig. 12). The conditions of EK treatment process for RCCP and SP were similar in terms of soil characteristics, applied voltage, dimension, size, and type of cathode. However, the decrease in the pH value of soil adjacent to the RCCP was greater in 5 d compared to the SP. The reason for this can be stated that with the corrosion of the pile and the penetration of existing ions in cement, the intensity of electrolysis reactions increased and the pH value of the soil further decreased. Decreasing the pH value due to the entry of cement ions with increasing intensity of the reactions increased and accelerated the electroosmotic flow and a low percentage of soil moisture caused the soil to dry out and crack.

Then, 28-d cured RCCP and RLCCP were exposed to 25 V for 5 d and 8 d, respectively. Increasing the curing time of RCCP reduced the conductivity of this pile; therefore, the pH value of the soil adjacent to this type of pile decreased less compared to that with 7-d cured RCCP and SP. At the end of the 5th and 8th days of EK treatment, soil pH values adjacent to 28-d cured RCCP were 3.9 and 3.6, respectively and no corrosion was observed in the body of the pile. The pH values of the soil adjacent to the RLCCP at the end of the 5th and 8th days were 3.7 and 3.6, respectively and no corrosion/damage was observed in the body of piles after removing from the soil. Results show that the curing duration of RCCP affects the acid resistance. Therefore, the EK method is an effective way to increase the bearing capacity of RCCP, but corrosion of the RCCP may occur over time. Therefore, it is suggested to inject lime into the soil adjacent to the RCCP when using the EK method to increase the bearing capacity of RCCP. Lime injection increases soil

Table 6
Change of pH value in the adjacent soil and corrosion rate of pile.

Parameter	SP				RCCP (7-d curing)				RCCP (28-d curing)		RLCCP (3-d curing)	
	<i>d</i> = 1	<i>d</i> = 3	<i>d</i> = 5	<i>d</i> = 8	<i>d</i> = 1	<i>d</i> = 3	<i>d</i> = 5	<i>d</i> = 8	<i>d</i> = 5	<i>d</i> = 8	<i>d</i> = 5	<i>d</i> = 5
pH value	5.1	3.9	3.4	3.3	5.3	3.5	2.4		3.9	3.6	3.7	3.6
<i>C_u</i> (kPa)	16.6	18.2	21.4	25.6	17.1	19.4	21.6		20.6	22.4	21	22.4
Corrosion (%)	3.2				13				0		0	

Note: *d* represents the EK treatment duration.



Fig. 13. The 7-d cured RCCP at the end of the 5th day of EK treatment process (Sadeghian et al., 2021).

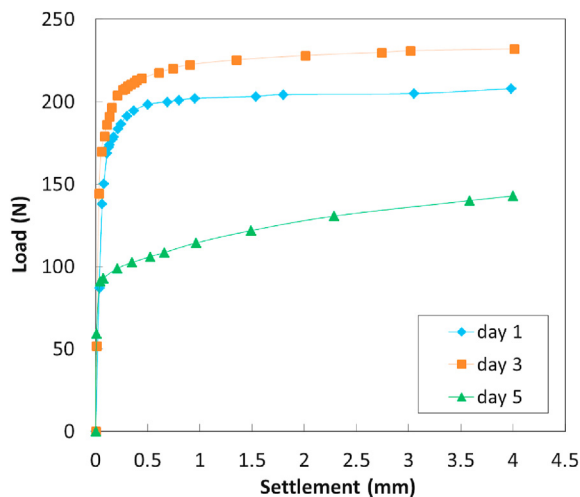


Fig. 14. Load-settlement behavior for 7-d cured RCCP after 1 d, 3 d, and 5 d of EK treatment (Sadeghian et al., 2021).

cementation and decreases the pH value of soil adjacent to RCCP. In addition, the period of EK treatment on RCCP can be controlled to prevent potential pile damage that may occur over time (Sadeghian et al., 2021). The use of lime in RCCP material is also an effective way to prevent a possible RCCP failure that may occur over time.

4. Conclusions

EK treatment is one of the effective methods for consolidating fine-grained soils, which stabilizes the soil and increases the bearing capacity of piles by improving the shear strength of soil. Increased shear strength largely determines EK efficiency. The change in the soil shear strength in EK treatment is because of the change in soil pH value, which is due to chemical reactions of electrolysis. However, changing the pH value causes the electrodes to corrode and thus reduces the EK efficiency. One of the effective factors on changing the soil pH value in EK treatment is the intensity of applied voltage. In this study, the effects of voltage and pH variations on the soil shear strength and corrosion intensity of

four types of electrodes during 14 h of EK treatment were investigated. The effect of pH change on the corrosion of three types of piles including SP, RCCP and RLCCP was also investigated under 25 V of voltage during 8 d of EK treatment. The main results of the present study are as follows:

- (1) The change in the pH of soil adjacent to the cathodes during EK treatment was greater than that adjacent to the anodes at all three applied voltages, and the shear strength of the soil adjacent to the cathodes increased more than that adjacent to the anodes. Therefore, although the purpose of EK treatment is mainly to strengthen the soil adjacent to the positive electrode, by proper draining of water adjacent to the cathode, this method can be used to significantly increase the shear strength of the soil adjacent to the cathode.
- (2) Increasing the voltage from 25 V to 35 V increased the speed and intensity of the electrolysis reactions and thus the pH changed for all four types of electrodes. In addition, the corrosion of the electrodes increased slightly. Increasing the voltage to 45 V had no significant effect on changing the pH of the soil adjacent to the electrodes for all four types of electrodes; however, it greatly aggravated the corrosion of iron and stainless steel electrodes (anode and cathode) despite the low change in pH. Corrosion of copper electrodes did not significantly increase with increasing voltage to 45 V.
- (3) Increasing the voltage from 25 V to 35 V increased the volume of water drained from the soil for all four pairs of electrodes; however, contrary to expectations, increasing the current to 45 V did not cause an increase in the electromagnetic current. In addition, the increase in voltage led to a further drop in electric current and increased power consumption.
- (4) The pH value of soil adjacent to SP on the 8th day of EK treatment was 3.3, and the corrosion of this pile at the end of the 8th day of EK treatment was 3.2%, which had no effect on the bearing capacity of this pile. The pH of the soil adjacent to the 7-d cured RCCP was 2.4 on the 5th day of EK treatment; deep cracks and corrosion (12%) were observed in the body of the pile, and the bearing capacity of this pile decreased despite the increase in its shear strength. The reason for the corrosion in the pile was due to the low strength of 7-d cured concrete in an acidic environment. In addition, deep cracks were observed in the soil around the 7-d cured RCCP on the 5th day of EK treatment. Decomposition of the body of the RCCP showed the penetration of the ions in the cement into the soil. These ions intensified the electrolysis reactions and increased the electroosmotic flow. As a result, a large decrease in the soil moisture and dryness caused cracks.
- (5) Increasing the curing time of RCCP increased the resistance of this pile in an acidic environment. At the end of the 5th and 8th days of EK treatment, despite the pH value of 3.7, no corrosion was observed in the body of 7-d cured RCCP. Increasing the curing period of RCCP or adding lime to the material of this pile increases its resistance in the acidic environment resulting from EK treatment. Therefore, it is recommended to inject lime into the soil around the concrete pile during EK treatment to prevent possible damage to the pile that may occur over time.
- (6) The applied voltage plays a significant role in selecting an appropriate electrode material for EK treatment. If the applied voltage causes more current than the allowable current of the electrode, severe corrosion occurs in the electrode, which increases the cost and drastically decreases the current in the EK treatment.

Data availability statements

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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