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Dehydrating subsurface clayey soils using plastic electrodes: a simple, fast, and yet reliable technique

Ronald Beyner Mejia Sanchez[1], José Tavares Araruna Júnior[2#], Roberto Ribeiro de Avillez[3], Hongtao Wang[4], Shuguang Liu[5]

Article

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Abstract

The electrokinetic process seems to be interesting to the earthwork portion on the construction of buildings, and transportation projects since this simple, fast, yet reliable technique could expedite dehydrating of soil and reduce delays in the construction schedule. This paper examined the technical feasibility and a brief cost analysis of using plastic electrodes for electrokinetically dehydrating clayey soils with high moisture content were also carried out. The results from the experimental program carried out on a marine clayey soil with copper and plastic electrodes showed a great deal of soil improvement since positive changes in undrained shear strength occur due to the free water dehydration process induced by electro-osmosis and to the adsorbed water dehydration process induced by electromigration. It was also observed that values of the undrained shear strength remained stable at the final stages of the electrokinetic process indicating a permanent soil improvement. Finally, it was noticed that dehydrating could be achieved at lower costs by employing plastic electrodes.

1. Introduction

Water has always been the largest obstacle in terms of constructability and time efficiency for as long as mankind has been building on natural soils (Zhuang, 2021; Rao et al., 2021; Indraratna et al., 2019; Zhang et al., 2019). In Brazil and other tropical countries, where extended periods of wet weather usually prevail, surface soils become wet or saturated through infiltration and adsorption of water to clay minerals (Ngo et al., 2021; Mahmoud et al., 2010). As a consequence, higher porewater levels reduce soil strength, increase soil compressibility, and hinder soil ability to be compacted (Zhang & Hu, 2019; Ammami et al., 2020; Babu et al., 2020; Martin et al., 2019; Wang et al., 2021). The excessive water moisture in soil delays the earthwork as current construction equipment cannot operate in such conditions and may cause the project to become off schedule and create an undue hardship for contractors (Lamont-Black et al., 2012; Rittirong et al., 2008). On most construction projects, time constraints preclude relying on nature. To satisfy construction plans and specifications, foundation soils must meet certain levels of strength and compressibility, and to attain such characteristics, a dehydrating technique is necessary to meet design specifications.

It is generally believed that clayey soils have very weak drainage characteristic (Peng et al., 2015). To overcome this challenge, in recent decades different processes have been proposed, such as mechanical-electrical drainage, mechanical-electroacoustic drainage, mechanical-thermal drainage, among others (Mahmoud et al., 2010). However, the complexity, cost, and energy consumption of these methods prevented their implementation in construction projects. Among the most promissory techniques is the electrokinetic process, which is based on the properties of the electrical charges inherent in the particles that make up clayey soils (Zhang et al., 2019). In this process, the electric field is applied to the soil mass, taking the negatively charged constituents toward the anode and the elements positively charged toward the cathode. Several authors, including Bourgès-Gastaud et al. (2015), argue that the versatility of the process is due to the possibility of removing interstitial water that usually cannot be removed by conventional mechanical processes.

The electrokinetic mechanism involves the phenomenon of electro-osmosis, electromigration, and electrophoresis. In a porous medium, electro-osmosis is defined as the net water flow from the positive electrode towards the negative electrode, when an electrical voltage gradient is applied. Electromigration is defined as the transport of the ions in

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[#] Corresponding author. E-mail address: araruna@puc-rio.br
[1] Pontifícia Universidade Católica do Rio de Janeiro, Instituto Tecgraf de Desenvolvimento de Software Técnico-Científico, Rio de Janeiro, RJ, Brasil.
[2] Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Engenharia Civil e Ambiental, Rio de Janeiro, RJ, Brasil.
[3] Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Engenharia Química e Ciência dos Materiais, Rio de Janeiro, RJ, Brasil.
[4] Tongji University, College of Environmental Science and Engineering, Shanghai, P.R. China.
[5] Tongji University, Department of Hydraulic Engineering, Shanghai, P.R.China.

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solution in the interstitial fluid in the soil matrix towards the opposite charge electrode when the electric field is applied (Cameselle & Gouveia, 2018). The phenomenon of ionic migration or electromigration depends on the size and charge of the ions, as well as the intensity of the applied electric field in accordance with Cameselle (2015). Finally, electrophoresis is the transport of charged particles of colloidal size or contaminants in the soil under the influence of an electric field (Virkutyte et al., 2002). According to Cameselle & Gouveia (2018), its magnitude is insignificant in soil systems with low hydraulic conductivity when compared with electroosmosis and electromigration.

In electrokinetic, the selection of the material and the arrangement of the spatial distribution of the electrodes have a great influence on the process efficiency. Chemical reactions, heat resistance capacity, and cost are the main considerations to be taken into account when it comes to the selection of the type of material for electrodes. From the studies reported in the literature, there is no consistent conclusion about which electrode can achieve the best efficiency of the electrokinetic process since experiments in different soil types can lead to different or even contradictory conclusions (Zhou et al., 2015). Moreover, the generation of gases due to electrolysis causes oxidation of metal electrodes generating a reduction in the efficiency of the electrical conduction, and increasing the costs of the process. For the reasons mentioned above, it is interesting to consider corrosion-resistant and economically viable materials for electrokinetic applications for construction purposes (Bourgès-Gastaud et al., 2015).

In this sense, the electrokinetic process seems to be interesting to the earthwork portion on the construction of commercial, industrial and residential buildings, and transportation projects since this simple, fast, yet reliable technique could expedite dehydrating of soil and decrease delays in the construction schedule. This paper examined the technical and economic feasibility of using plastic electrodes for electrokinetically dehydrating clayey soils with high moisture content, and a brief cost analysis was also carried out.

2. Materials and methods

A soft clayey soil of marine origin obtained at a construction site from the Metropolitan Center in the west zone of the city of Rio de Janeiro was used in the experimental program. The disturbed soil sample was collected from the bucket of an excavator at a depth of approximately 6 meters, stored in 1 m^3 big bags, and transported to the Geotechnical Laboratory where it was later stored in the humid chamber. This material was subjected to geotechnical and mineralogical characterization, and its chemical composition was determined. The geotechnical characterization comprised the determination of moisture content (ASTM, 1998), particle density (ASTM, 2009), Atterberg limits (ASTM, 2017a), and organic matter content (ASTM, 2020b). The soil grain distribution curve was determined following the procedures established in ASTM D7928 (ASTM, 2017c). Its chemical composition was determined using the inductively coupled plasma mass spectroscopy (ICP-MS) technique as detailed in ASTM D1976 (ASTM, 2020a). The procedure used the Agilent spectrometer, model 7500CX. The mineralogical characterization of the clayey soil was performed by the X-ray diffraction technique (ASTM, 2007; Burnett, 1995; Moore, 1970). Two samples were analyzed: the first sample constitutes the natural clayey soil and the second sample is a fraction of this soil that passed through sieve #40 (i.e., 0.42mm).

Dehydrating tests were carried out using a plastic water tank with 100L volumetric capacity as observed in Figure 1. Changes in the pH of the effluent during tests were monitored with an AKSO digital pH meter model AK90 which has calibration in three points and automatic temperature compensation. The electrical current intensity was monitored with a MULTILASER digital multimeter model AU325 that has a range of 200 µA up to 10A operating in direct current mode. The electric field was induced using a Minipa MPC3030 DC source that provides a maximum potential difference of 30V, which allowed the application of a potential gradient of 1.5 V/cm. For the tests with the voltage of 150 V DC, a DC source was used that generates a maximum potential difference of 220 V DC, developed by the Laboratory of Conversion and Electrical Machines of PUC-Rio. The use of this electrical source allowed the application of a voltage gradient of 7.5 V/cm maintaining the same geometric configuration.

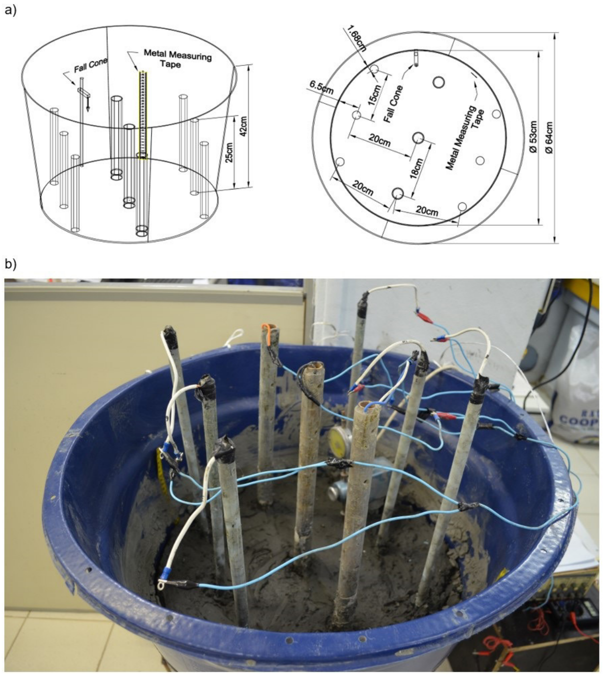

Figure 1. Electrokinetic test device: (a) general arrangement; and (b) test layout.

Remolded samples were obtained by drying the natural soil in an oven for 24 h at a temperature of 60 °C. After the drying process, 29.6 Kg of soil were weighed, and tap water with an electrical conductivity of 127.8 μS/cm and a pH of 7.6 was then added until a moisture content equivalent to 1.25 times the soil liquid limit was observed. The authors decided to use tap water in order to enhance the repeatability of the sample fabric even though, as stated by Jardine et al. (1984), it is preferably that the chemistry of the water be similar to that of the pore water in the clayey soil in order to preserve its natural state (i.e., structure). Tap water chemical composition was determined using the ICP-MS technique as detailed in ASTM D1976 (ASTM, 2020a) for inorganic constituents and ion chromatography for anionic constituents using the procedure described in ASTM D4327 (ASTM, 2017b). The sample was then mixed for 30 minutes in an orbital mixer until the soil reached a soft soil consistency. The assembly of the test consisted of positioning the electrodes in the previously designated locations for each type of spatial configuration in the water tank described in Figure 1.

Cathodes were wrapped by #40 Whatman filter paper to prevent the intrusion of soil particles through their drainage holes. During tests, the volume drained from the effluent was measured using Pyrex graduated cylinders with a volumetric capacity of 1,000 mL with a 10 mL resolution, and the soil settlement was measured by two metal measuring tapes fixed at opposite sides of the tank inner wall with a 1 mm resolution. Drainage was measured at regular intervals of 6 hours, and soil settlement was measured at regular intervals of 24 hours. Although tests were carried out in a temperature-controlled environment, the relative humidity and ambient temperature values were determined with an HTC DIGITAL equipment model BFHTC-1 at pre-established time intervals of 24 hours.

An electrokinetic soil dehydration testing program was performed using two gradient potentials. In the first batch, a 1.5 V/cm potential gradient was applied in three tests with plastic electrodes developed by Mejia (2018) to assess repeatability. Plastic electrodes consist of a composite comprised of brass filaments embedded in a BB2004 epoxy resin and a 3154BB hardener. An additional test was carried out applying the same potential gradient with copper electrodes to assess electrolysis-induced corrosion and to appraise the efficacy of the plastic electrodes. The effect of electrolysis was measured by determining the weight loss of anodes using an analytical scale TOLEDO Prix AS with 0.01 g resolution. The second batch comprised two tests employing a 7.5 V/cm potential gradient to assess plastic and copper electrodes efficiency.

Soil strength was evaluated using the fall cone apparatus using a Wykeham Farrance apparatus following the procedures described in BS1377-2 (BS, 1990). The device was adapted within the plastic tank and measurements were carried out at regular intervals. To assess fall cone tests results unconsolidated undrained triaxial tests were performed with samples collected after the completion of the dehydrating process following the procedures described in ASTM D2850 (ASTM, 2015).

Power consumption was measured during each test and the dehydrating cost was calculated assuming the electricity rate of 0.035 US$/kW.h charged by the local distributor in November 2018.

3. Results and discussion

The grain size distribution curve of the clayey soil is shown in Figure 2 and its index properties are described in Table 1. Based on the aforementioned results it was possible to classify the soil according to the Unified Soil Classification System (ASTM, 2000) as MH-OH. Table 2 presents the chemical composition of the tap water and the marine soil.

The concentration of the tap water anionic constituents was well bellow to those commonly found in sea water (i.e., fluoride 0.44 mg/L; chloride 16.1 mg/L; bromide <0.05 mg/L; nitrate 17.9 mg/L; phosphate <0.05 mg/L, and sulphate 22.7 mg/L). It is clear that the use of tap water changed the original structure of the marine soil but since the experimental program was carried out in a different environment, it seems that the adopted strategy did not play an important role in the examination between plastic and copper dehydrating performance.

The mineral characterization of the soil sample indicates the presence of calcite, quartz, and kaolinite, as can be seen in Figure 3. The X-ray diffractogram indicates that the sample is a mixture of clay minerals that make up the amorphous

Table 1. Values of index properties.

Property	Value
Natural moisture content	132%
Particle density	2.61
Plastic limit	32%
Liquid limit	55%
Organic matter content	7.4%

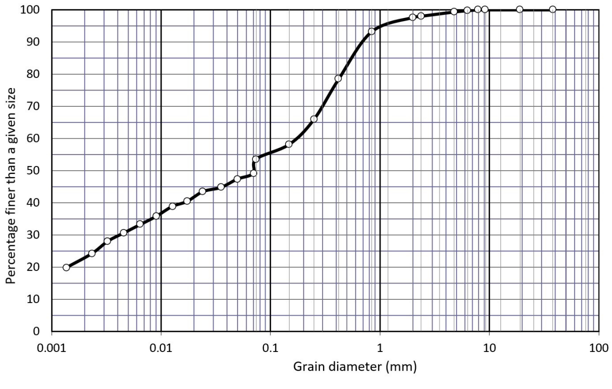

Figure 2. Grain size distribution curve.

Table 2. Chemical Composition.

Parameter	Tap Water Concentration (mg/L)	Soil Concentration (mg/kg)
Al	n.a.	720
V	<0.01	0.564
Cr	<0.001	0.515
Mn	0.002	3.88
Fe	0.033	480
Ni	<0.002	0.182
Cu	0.004	0.143
Zn	0.11	0.818
Cd	<0.001	0.0034
Ba	0.024	1.01
Pb	<0.01	0.191

n.a. – not available.

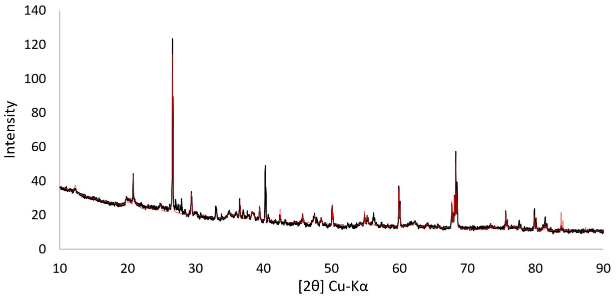

Figure 3. X-ray diffractogram of the sample under study.

part and minerals that represent the crystalline phase of the sample under study.

Soil dehydrating during the electrokinetic process as a function of time is presented in the sequence of photographs shown in Figure 4 for tests with a voltage gradient of 1.5V/cm and, in Figure 5, for the tests with a voltage gradient of 7.5 V/cm. One can observe the variation in soil consistency due to dehydration since the electroosmotic phenomenon generates a water flow from the regions near the cathode towards the regions of the anode where the water is drained. The soil mass near the cathodes shows a greater increase in soil solids compared to the soil mass close to the anode since the water molecules from the double layer move preferentially towards the anode (Mahalleh et al., 2021; Vocciante et al., 2016; Menon et al., 2019; Martin et al., 2019).

The volume drained and soil settlement as a function of time are shown in Figures 6 and Figure 7 respectively. The dehydrating process is faster when copper anodes are used since they possess a higher electrical conductivity (i.e., the measured electrical conductivity of plastic electrodes is 5.64 x10^{3} Ω^{-1}m^{-1} and the measured electrical conductivity of copper electrodes is 6.0x10^{7} Ω^{-1}m^{-1}). When the voltage gradient of 1.5 V/cm was applied, soil settlements in the test that used copper anodes were higher compared to the tests that employed plastic anodes. This behavior also leads to higher drainage due to the higher electrical conductivity of copper electrodes. On the other hand, when the voltage gradient of 7.5 V/cm was applied, higher settlement values were observed

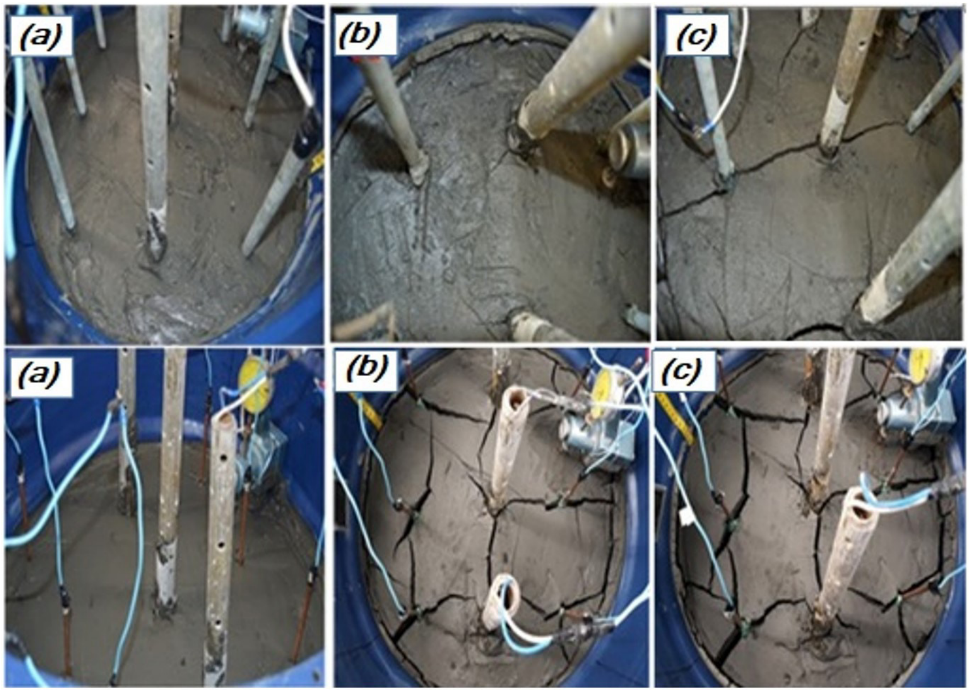

Figure 4. Sequence of photographs for test with voltage gradient of 1. 5 Volts/cm: First row with plastic anodes in which: (a) 1 hour; (b) 6 days; and (c) 10 days. Second row with copper anodes, where: (a) 1 hour; (b) 4 days; and (c) 6 days.

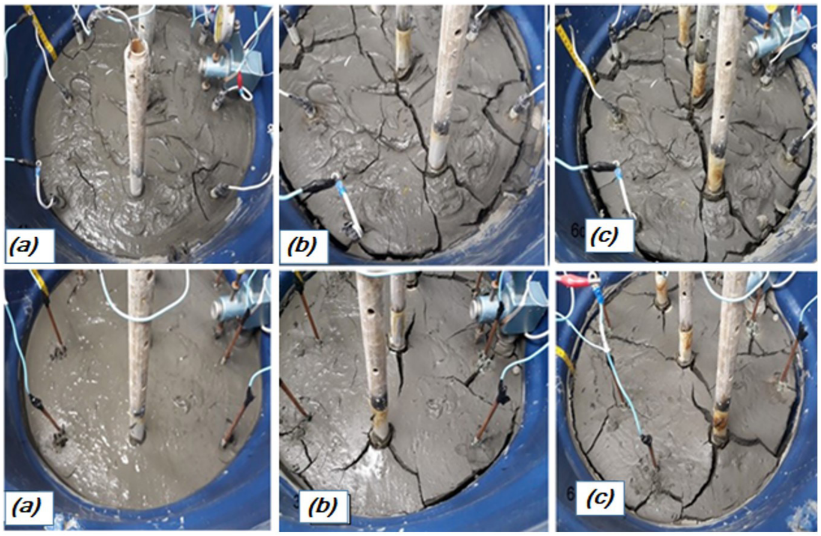

Figure 5. Sequence of photographs for tests with voltage gradient of 7.5 volts/cm: First row with plastic anodes. Second row with copper anodes, in which: (a) 1 hour; (b) 3 days; and (c) 6 days.

in the initial moments of the tests. However, the settlement rate decreased considerably with time in tests that employed copper anodes since the increase in the voltage gradient caused a rise in the magnitude of electrolysis in the vicinity of the anodes, which, in turn, generated greater corrosion that prevented the drainage process. This phenomenon had already been reported in the literature by Zhou et al. (2015), who called it anode passivation. It was also observed that plastic anodes were little affected by electrolysis.

The intensity of the electric current induced by the voltage gradients is shown in Figure 8. It can be observed that plastic electrodes induce lower current when compared to copper electrodes despite the magnitude of the applied voltage gradient. This difference has a great influence on the dehydrating process because a higher electrical current intensity induces large changes in moisture content in the soil mass as can be seen in Figure 8. However, the use of copper electrodes increases energy consumption, and also reduces electro-osmotic efficiency as Figure 9 shows. The electro-osmotic efficiency relates the electrical current induced during the tests with the drained volume and length of the test (Jones et al., 2011), as follows:

$$k_i = \frac{I}{\dfrac{\Delta V}{\Delta t}} \tag{1}$$

where k_i is the electro-osmotic efficiency, I is the electrical current applied, ΔV is the drained volume, and Δt is the time interval in which the drained volume reading was recorded.

It was observed that electro-osmotic efficiency is higher in the initial stages of tests. As the electrokinetic process takes place hydraulic fracturing occurs, as shown in Figure 5 and Figure 6, and electro-osmotic efficiency is reduced (Zhang & Hu, 2019; Hu et al., 2016). Also, it should be noticed that electrolysis reactions in the vicinity of the anodes are very severe when copper electrodes are used impacting electro-osmotic efficiency (Lockhart, 1983; Turer & Genc, 2005).

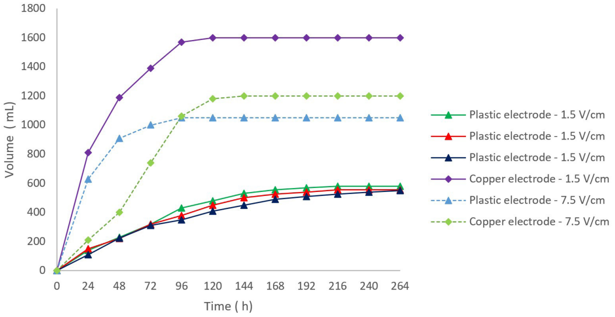

Figure 6. Drained volume as a function of time.

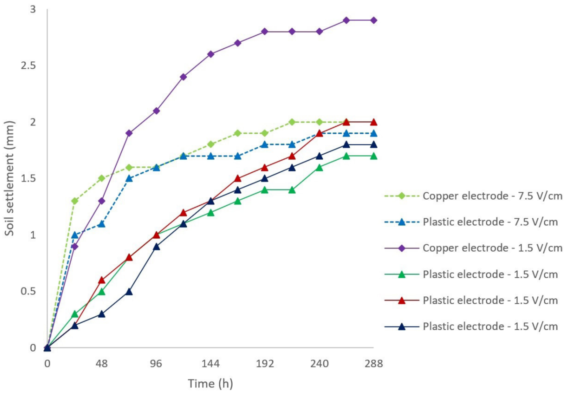

Figure 7. Soil settlement as a function of time.

It was also noticed a sudden increase in electro-osmotic efficiency at 96 hours concerning copper electrodes could be attributed to the corrosion of the anodes induced by electrolysis.

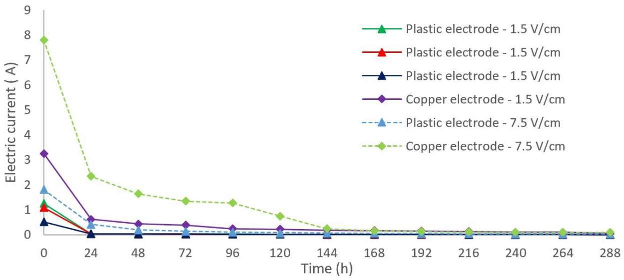

Figure 8. Intensity of electrical current induced during the electrokinetic process.

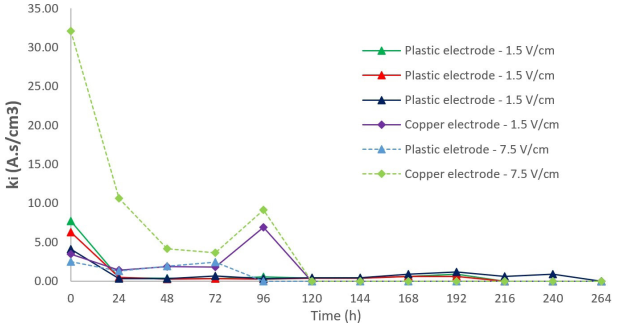

Figure 9. Electro-osmotic efficiency.

$$Cu + H_2O \rightarrow CuO + 2H^+ + 2e^- \tag{2}$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{3}$$

In these tests, the rise in electro-osmotic efficiency might be related to anode corrosion and the subsequent transport of metallic ions that increases the electrical conductivity of the media (Gregolec et al., 2005; Wu & Hu, 2014; Acar & Alshawabkeh, 1993). As process takes place, electro-osmotic efficiency sharply reduces as electrolysis induced corrosion occurs. This observation agrees with results from different authors (Mahmoud et al., 2010; Zhou et al., 2015; Karim, 2014). Corrosion was assessed by measuring changes in the mass of plastic and copper electrodes shown in Figure 10 before and after each test.

Figures 11 and 12 show the mass loss of plastic and copper anodes. It can be observed that plastic anodes have virtually no mass loss. On the other hand, it was also verified that the life of the copper anodes is greatly reduced since they are affected more severely by electrolysis-induced corrosion. The induced electric current during the electrokinetic process causes chemical oxidation and reduction reactions in the electrodes. The loss of electrons from the copper anodes generates their oxidation, which can lead to the loss of their mass. The mass loss is proportional to the oxidation process

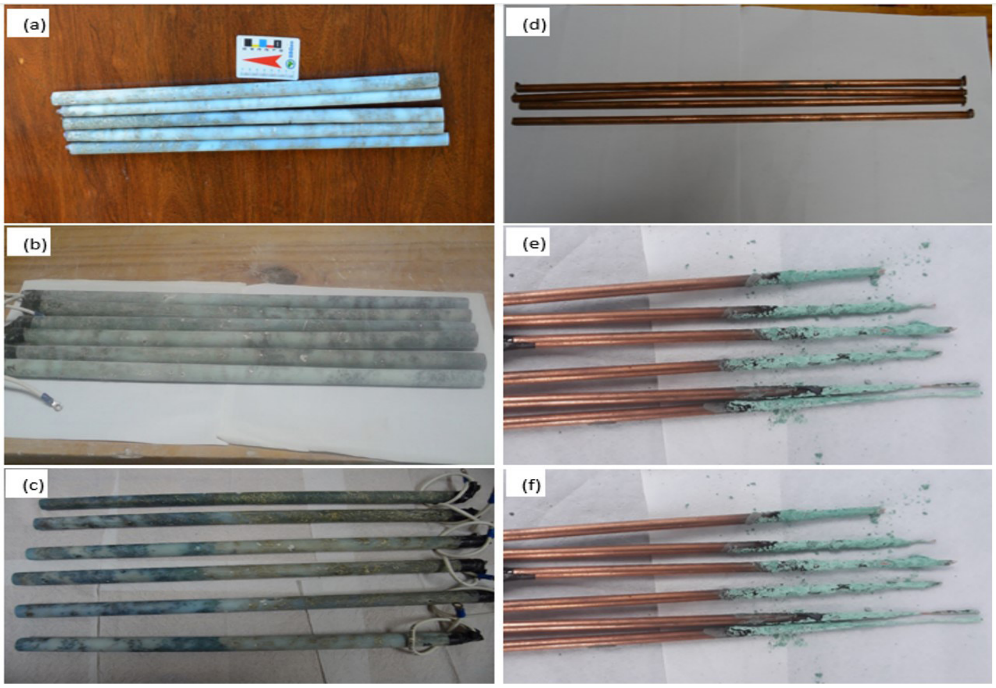

Figure 10. Electrodes: (a) original plastic anodes; (b) plastic anodes after tests with voltage gradient of 1.5 V/cm; (c) plastic anodes after tests with voltage gradient of 7.5 V/cm; (d) copper anodes; (e) copper anodes after tests with voltage gradient of 1.5 V/cm; (f) copper anodes after tests with voltage gradient of 7.5 V/cm.

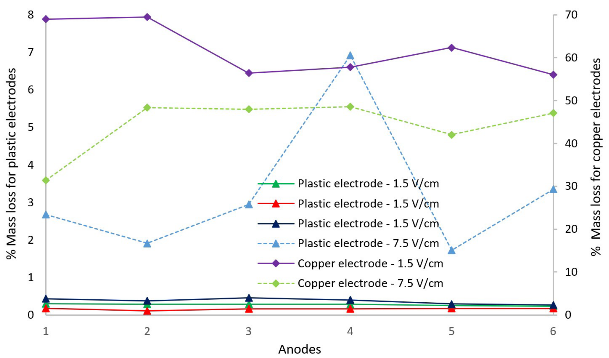

Figure 11. Anode mass loss. Plastic electrode on the main axis and a copper electrode on the secondary axis.

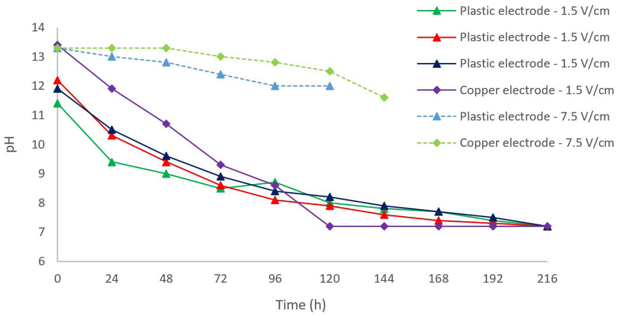

Figure 12. Changes in the pH values.

and since its magnitude could be related to the induced current intensity it is expected that tests performed with a greater electrical gradient cause a rise in percentage mass loss.

Electrolysis also induces changes in the pH of the soil mass. The oxidation of the water molecule in the anodes generates an acid front, and the reduction of water in the cathodes generates a basic front, as suggested by several authors (i.e., Estabragh et al., 2014; Azhar et al., 2017; Cameselle et al., 2013; Cameselle, 2015). Due to these processes, the pH of the porous medium in the vicinity of the anode usually decreases and the pH of the porous medium in the vicinity of the cathode generally increases. It is generally believed that changes in pH depend on the intensity of the current applied to the soil (Fardin et al., 2021; Chien et al., 2010; Hu et al., 2019; Cameselle & Reddy, 2012). The acid front generated in the anode will advance through the soil mass towards the cathodes due to the migration of ions and the phenomenon of electro-osmosis (Saichek & Reddy, 2003; Tuan et al., 2012). As the acid front advances through the soil mass towards the cathode, decreasing pH values of the effluent are observed, as shown in Figure 12.

It is verified, in the initial moments, that the pH values of the effluent present high values due to the generation of OH^- by the reaction of hydrolysis of water in the vicinity of the cathodes caused by electrolysis (Reddy & Saichek, 2004; Martin et al., 2019; Zhou et al., 2015). As the acid front advances from the regions close to the anode towards the cathode, there is a reduction in the pH values of the effluent, since H^+ is more mobile (Cameselle & Gouveia, 2018; Ghobadi et al., 2020; Wu et al., 2016). The results of the tests using a voltage gradient of 1.5 V/cm suggest that the reduction seems to be proportional to the intensity of the electrolysis reactions. The authors observed changes in pH values of the effluent depending on the intensity of the generated current. One can observe from the data displayed in Figure 8 that the magnitude of the generated electric current during the initial stages of the tests is directly proportional to the applied voltage gradient. As the process takes place, the authors observed similar values of either current magnitude and pH in tests with different voltage gradients.

The authors also point out that pH values did not undergo significant variation after 114 h of tests, indicating that the acid front arrived in the cathode generating a polarization of the medium preventing the development of the electro-osmotic flow that generates movement of fluid from one region to another (Virkutyte et al., 2002; Alaydi, 2016; Li & Li, 2000). It is also observed that there were no great changes in pH values of the effluent in tests where a voltage gradient of 7.5 V/cm was applied. The authors believe that the use of a gradient of such magnitude generated a rapid displacement of the acid front and induced a rapid polarization of the medium (Dukhin & Mishchuk, 1993; Mishchuk, 2010).

The electrokinetic process induces soil improvement (Hunter et al., 2021; Peng et al., 2015; Ammami et al., 2020; Babu et al., 2020). A fall cone apparatus was assembled in the plastic tank to assess the change in the undrained shear strength of the clayey soil. Hansbo (1957) proposed to determine the undrained shear strength, s_u, from the cone penetration amount d of soil by the fall cone, as follows:

$$s_u = K\frac{W}{d^2} \tag{4}$$

where W is the cone weight, m is the cone mass (g), g is the gravitational acceleration and K is the cone factor. According to the BS standard BS 1377-2 (BS, 1990), the conical tip has a standardized weight, size and angle (i.e., 80 g, 35 mm and 30°) and the sinking time is 5s. In these conditions, the cone factor (K) is equal to 1.0. Test results are presented in Figure 13.

Test results indicate that changes in undrained shear strength occur due to the free water dehydration process induced by electro-osmosis, and to the adsorbed water dehydration process induced by electromigration (Abdullah & Al-Abadi, 2010; Acar & Alshawabkeh, 1993; Gregolec et al., 2005). It was also observed that values of the undrained shear strength remained stable at the final stages of the electrokinetic process indicating a permanent soil improvement. This phenomenon had already been described in the literature by several authors, including (Casagrande, 1948, 1949, 1952, 1983; Bjerrum et al., 1967; Gray, 1970; Gray & Mitchell,

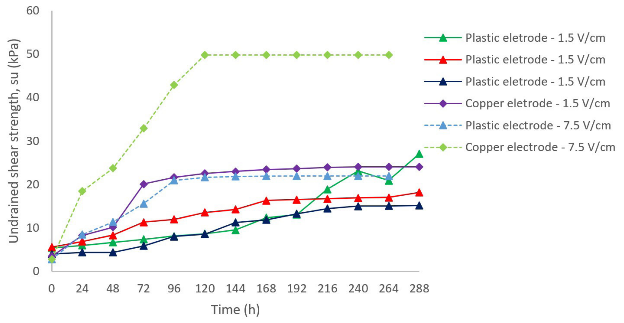

Figure 13. Changes in the undrained shear strength during tests.

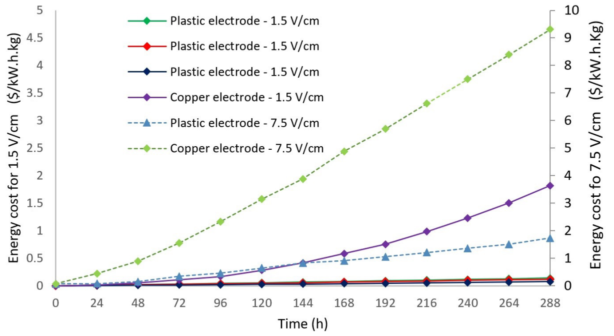

Figure 14. Costs associated to power consumption during tests.

1967, 1969; Lo & Ho, 1991; Lo et al., 1991; Micic et al., 2001). Unconsolidated undrained triaxial tests performed on samples collected just after the end of each test resulted in similar values, i.e., 50 KPa for 7.5 V/cm tests and 17 KPa for 1.5 V/cm tests, validating the results obtained from fall cone tests.

Figure 14 shows the costs associated with power consumption during tests. The primary vertical axis describes power consumption for tests where plastic electrodes were used and the secondary vertical axis describes power consumption for tests where copper electrodes were used. It should be noticed that dehydrating could be achieved at lower costs by employing plastic electrodes.

Plastic electrodes are also much cheaper. Plastic electrodes used in this study cost US$ 6.75 / each whereas copper electrodes with the same dimensions cost US$19.98/each.

4. Conclusions

A laboratory program was carried out aimed at assessing the efficacy of dehydrating subsurface clayey using plastic electrodes. A marine soil, classified according to the Unified Soil Classification System as MH-OH, composed of calcite, quartz, and kaolinite, and with a high concentration of Al, Fe, Mn and Ba, was used in the experimental program.

Tests were carried out on remolded soil samples using plastics and copper electrodes. Remolded samples were obtained using tap water instead of marine water, which significantly affects the electric conductivity of the medium. However, since the manuscript has focused on dehydrating efficacy using plastic and copper electrodes, a minor effect is expected in this regard. It was found that the dehydrating process is faster and more efficient when copper anodes were used since they possess a higher electrical conductivity despite the magnitude of the applied voltage gradient. However, the use of copper electrodes increases energy consumption, and also reduces electro-osmotic efficiency. It was observed that electro-osmotic efficiency is higher in the initial stages of tests, and as the electrokinetic process takes place hydraulic fracturing occurs and electro-osmotic efficiency is reduced. Also, it was noticed that electrolysis reactions in the vicinity of the anodes are very severe when copper alloys are used impacting electro-osmotic efficiency and reducing its life. On the other hand, it was observed that plastic anodes were less affected by electrolysis and have virtually no mass loss. Tests also indicate that pH changes in the soil mass seem to be proportional to the intensity of the electrolysis reactions. It was noticed that this effect is more severe at the early stages of the test.

The electrokinetic process induced positive changes in undrained shear strength due to the free water dehydration process induced by electro-osmosis and the adsorbed water dehydration process induced by electromigration. It was also observed that values of the undrained shear strength remained stable at the final stages of the electrokinetic process indicating a permanent soil improvement.

Finally, it was noticed that dehydrating could be achieved at lower costs by employing plastic electrodes. Hence, dehydrating subsurface clayey soils using plastic electrodes seems to be interesting to the earthwork portion on the construction of commercial, industrial and residential buildings, and transportation projects.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Ronald Beyner Mejia Sanchez: data curation, writing – original draft. José Tavares Araruna Júnior: supervision, funding acquisition, conceptualization, writing – review &

editing. Roberto Ribeiro de Avillez: writing – review & editing. Hongtao Wang: Writing – review & editing. Shuguang Liu: Writing – review & editing.

Data availability

All data, models, and code generated or used during the study appear in the submitted article.

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