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Research paper

SOME ASPECTS OF ELECTROKINETIC SOIL TREATMENT

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Abstract

One of the innovative and promising approaches to the stabilization of fine-grained soils with low bearing capacity is electrokinetic treatment which can be integrated with other techniques to enhance soil properties. This method could involve applying a low direct current through electrodes inserted into the soil while simultaneously introducing stabilizers through the electrokinetic process. The stabilization achieved in this way contributes to the improvement of the physical, chemical and mechanical characteristics of the soil. However, a significant challenge of this method is the corrosion of electrodes, which occurs due to electrochemical reactions at the interface between an electrode and the soil. When direct current is applied, oxidation and reduction reactions take place at the electrodes, leading to the dissolution of the electrode material. This can cause the reduction of the electrodes efficiency and longevity, impacting the overall effectiveness of the treatment. Consequently, it is important to examine the extent to which electrode corrosion can affect the flow of current and processes in the soil during the application of this innovative method. Therefore, the aim of this paper is to further elucidate the effects that occur when varying the parameters that affect the current flow.

Key words: *Electrokinetic Treatment of Soil, Direct Current, Electrode Corrosion*

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1. INTRODUCTION

Soil stabilization is a critical aspect of geotechnical engineering, particularly in areas where natural fine-grained soil conditions fail to meet the construction requirements. Furthermore climate change increases both the intensity and frequency of factors that influence the incidence of landslides, making them a more serious threat. The main reasons for the higher threat are increased precipitation, extreme weather conditions, prolonged droughts, permafrost melting and sea level rise. Namely, intense rains and longer periods of humidity saturate the soil with water, reducing its stability and increasing the risk of landslides. Also, more frequent storms, sudden downpours and longer periods of rain can cause erosion and destabilization of the terrain.Droughts can lead to drying out and cracking of the soil, which after heavy rains becomes unstable and prone to movement.In mountainous and cold areas, global warming causes permafrost to melt, which weakens the soil structure and contributes to landslides. Erosion of areas near coasts due to sea level rise can cause slope collapse and soil instability.

In addition to these global challenges the geotechnical properties of soils are of high importance in the performance and durability of infrastructure systems. In many cases, during the construction of large-scale infrastructure projects, the available locally fine-grained soil materials lack the necessary mechanical or physical properties required for safe and durable structural support. Consequently, the application of soil stabilization techniques becomes necessary to improve the engineering behavior of such materials and providerequired specifications.All this indicates the need to pay a special attention to methods that contribute to preventing the occurrence of landslides.

In response to these challenges, traditional methods, including chemical stabilization of soil, have been widely used. This chemical stabilization involves the addition of chemical agents (most commonly lime, cement, fly ash, or other pozzolanic materials) which react with the soil to enhance performance [1-7]. Regarding clayey soils, the chemical stabilization is especially effective and used, but there are limitations. Although this technique contributes to the permanent improvement of the physical, chemical, and mechanical characteristics of the soil, due to the method of application, it can only be used in surface, easily accessible soil layers.

On the other side, electrokinetic soil treatment has emerged as a novel and sustainable alternative [8-10]. This technique utilizes the principles of electrokinetics and involves applying a low-voltage direct current across electrodes embedded in the soil, generating electrical potential in the soil. The applied electric field induces the movement of pore water, dissolved ions, and fine particles through the soil. Given that the electrokinetic soil treatment can be performed at greater depths of the soil, and under existing structures, it seemed promising for drainage. Unfortunately, the effects of such treatment are not permanent. With new, more abundant rainfall, the water content in the soil increases again and the soil strength decreases.

Disadvantages of the previously mentioned soil stabilization procedures can be overcome with the innovative technique which might combine in some way the chemical soil stabilization and the electrokinetic soil treatment. In this way the improvement of the mentioned techniques could be achieved. During the possible procedure the, the introduction and movement of stabilizing agents through the soil could take place under the influence of the direct current, while the stabilization mechanism is based on the principles of chemical stabilization.In addition, the inclusion of chemical additives such as lime or other reagents helps to improve chemical bonding, reduce plasticity, and increase soil strength.

Moreover, this technique for soil stabilizationcould offer precise control over the treatment process, allowing engineers to modify the treatment parameters, such as voltage gradient, electrode spacing, treatment duration, and chemical dosage, to specific site conditions. This level of control not only enhances the treatment efficiency but also can reduce the risk of over-treatment or under-treatment, which can compromise soil performance and structural integrity.Despite these promising attributes, this technique faces practical challenges, notably the pronounced corrosion of electrodes due to electrochemical reactions at the electrode-soil interface. This degradation can reduce the effectiveness of the process over time and increase operational costs. Understanding the underlying mechanisms of electrokinetic soil treatment and variables influencing the electrode corrosion is therefore essential for optimizing this promising technique for the soil stabilization and ensuring its long-term viability as a soil stabilization method.

2. PRINCIPLES OF ELECTROKINETIC SOIL TREATMENT

One of the key advantages of the electrokinetic soil treatment is its effectiveness in low-permeability soils, such as clays which is typically difficult to treat using conventional methods. These fine-grained soils show that there are limitations in the infiltration of chemical stabilizers when applied in traditional ways. As mentioned, during the electrokinetic soil treatment, when the voltage is applied to the electrodes, due to difference of potentials, direct current flows. The fundamental mechanisms of the electrokinetic soil treatment are based on electrokinetic phenomena, including electroosmosis, electromigration, and electrophoresis. When a low direct current is applied across electrodes placed in the soil, the movement of water in the soil from the anode to the cathode is enabled.

The process of electroosmotic movement of water, leads to a decrease in pore pressure that begins in the anode zone, and then spreads to the surrounding soil. The result of this process is a decrease in soil moisture and an increase in effective stresses in the soil, which results in the consolidation of the treated soil. In laboratory conditions, the water that is collected in the cathode zone during this process is collected in a container, whereby the amount of collected water is a measure of the effect of the applied electrokinetic procedure in terms of soil drainage. There is also a movement of ions towards the electrodes, where appropriate electrochemical reactions and deposition occur around the electrodes. At the same time, electrolysis and the formation of H^+ and OH^- occur in the immediate vicinity of the electrodes. The processes which are mostly active in a part of clayey soil under an electrokinetic treatment and strengthening and repair of slopes have been examined in studies in the previous period [11-14]. The described processes that occur during the conduction of the direct current and are of importance for the electrokinetic soil treatment are illustrated in Figure 1.

It should be mentioned that the oxidation occurs at the anode, creating an acidic front, while the reduction occurs at the cathode, creating an alkaline front. These reactions cause a decrease in pH at the anode and an increase at the cathode [14]. This pH gradient (often referred to as an acid/base profile) and its influences on the transport of species through the porous soil medium have been extensively investigated and well documented by many researchers.

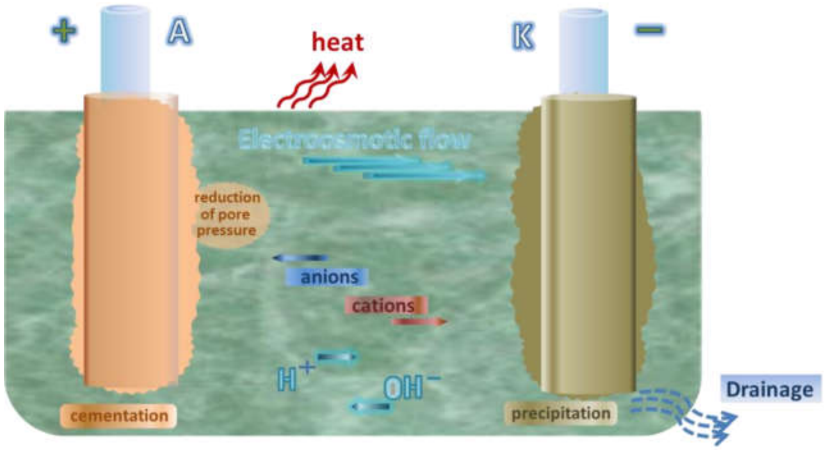

Figure 1. Mostly active processes that occur during electrokinetic soil treatment

In order to adequately predict which voltages and currents should be applied, the basic electrical characteristics of clay should be known. The specific resistance ρ of clay is usually taken to be from 10^2 up to 10^5 Ω•m for dry clay, and from 10 up to 100 Ω•m for wet clay. The specific resistance of clay depends on its mineral composition, water content, temperature and compactness. If precise values are needed for a particular type of clay, it is necessary to perform an experimental measurement under the conditions of interest, as was done during the experiment. Accordingly, a series of experiments is required under predefined laboratory conditions, during which specific parameters, expected to influence the electrokinetic stabilization process, should be systematically varied.

3. EXPERIMENTAL PROCEDURES AND RESULTS

Detailed research required experimental testing in controlled laboratory conditions, with validation through scientific methodologies.In order to conduct investigation, in laboratory conditions, on experimental models, the test was performed by applying predetermined voltages to the electrodes. In addition to the applied voltage levels, electrode spacing, numbers, and spatial configuration were adjusted and optimized throughout the testing process. Also, during the conducted experiment, the focus was on varying the water content of clay (*w*), as this can significantly affects its shear strength and compressibility.

Measurements were carried out under predefined voltage conditions using a direct current power supply DC Instek PSP-603, which is shown in Figure 2a. This used source provides the output voltage of 0 to 60 V and a direct current of up to 3.5 A. Since the applied voltages were varied up to 50 V, which is close to the limit value for safe work, measures were taken to secure the space where the experiment was conducted.

The electrodes were located in a test box, which contained clay with a predefined water content. The measurements were taken with electrodes inserted to a depth of 14 - 15 cm into the clay specimen, and on distance of 22.5 cm.The experiment was performed by applying five different voltages from 10 V to 50 V, and by measuring the intensity of the current flowing through the clay.

(a) (b)

Figure 2. Direct current power supply DC (a) and corroded electrodes (b)

In the first experimental phase, only new electrodes were used. Obtained results are presented in Figure 3. This figure presents the intensity of the electric current as a function of the applied voltage, for four different water contents (*w*) of 15%, 20%, 25% and 30%. It can be seen that the current increases in a continuous and uniform manner with increasing applied voltage and water content, which is consistent with theoretical expectations.The increase is more pronounced as the voltage and water content are higher, and with linear increase with different slope, what correspond to soil resistivity.

In general, during the electrokinetic soil treatment electrode the corrosion is a direct consequence of redox reactions at the soil-electrode interface. The anode typically undergoes oxidation and $M \rightarrow M^{n+} + n\ e^{-}$ occurs where M is the electrode material. On the other side, at the cathode, reduction reactions often produce hydroxide ions. The result is material loss at the anode and potential gas formation at the cathode, both of which compromise the electrode performance and the uniformity of soil treatment.The extent and rate of electrode corrosion is influenced by current density, electrode material, soil chemistry and when chemical additives are applied. Consequently, the electrode corrosion is a significant factor which can affect the electrokinetic treatment. Therefore, understanding the interaction between these factors is essential for optimizing the methods to be applied.

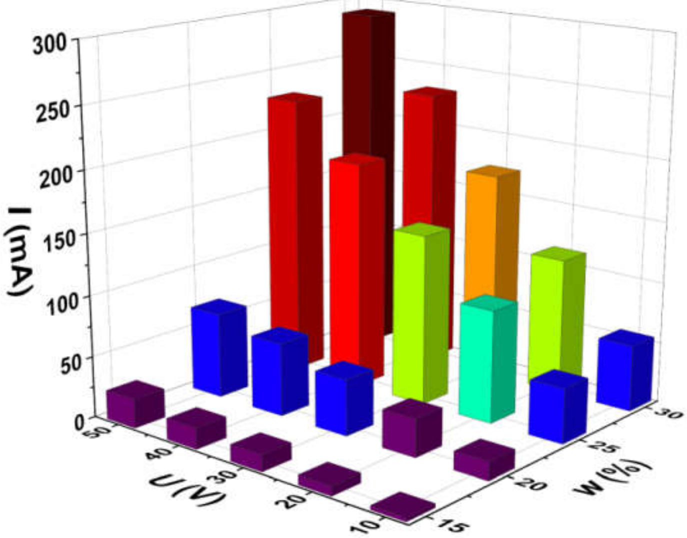

Figure 3. The intensity of the electric current as a function of the applied voltage, for four different water contents

That is why, during this part of the experiment, the influence of electrode corrosion that occurs over time was analyzed. For the samples in the test boxes, when there was clay with a water content of 20 and 25%, additional tests were performed. Under the same conditions of the experiment, as previously presented, measurements were performed when corroded electrodes were used (Figure 2b). The results obtained are shown in Figure 4, where the increase in electric current intensity as a function of applied voltage can be seen, for two different water contents, for both new and corroded electrodes. As expected, in case of application of corroded electrodes, current flow is significantly reduced. However, it is interesting that there is a greater difference in the current readings when using new or corroded electrodes at the same water content of 30%, than between new electrodes at water content of 30 and 25%. In Figure 5 are presented the differences between the increase in the electric current intensity (as a function of the applied voltage) for both new and corroded electrodes, which are shown in Figure 4. For all values of the applied voltage, this Figure 5 shows the differences in measured currents when using new and corroded electrodes, and in both cases, when the water content is 25% or 30%.

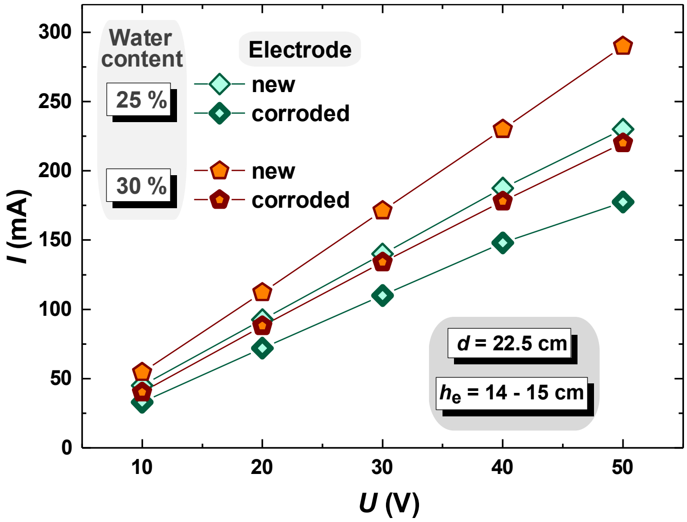

Figure 4. The increase in electric current intensity as a function of applied voltage for two different water contents, for both new and corroded electrodes

From Figure 5 it is clearly seen that the difference in the current flow between the cases when new and corroded electrodes are used is more significant when the water content is 30%, than when it is 25%. This difference becomes more pronounced with increasing voltage.It can be noticed that, for water content of 30%and an applied voltage of 50 V, the difference between the electric current intensity in the case when new and corroded electrodes are used is 70 mA. On the other hand, when only new electrodes are used at the applied voltage of 50 V,the electric current intensity is 60 mA higher in the case when the water content in the clay is 30% than when it is 25%.For all values of applied voltage, the trend is similar. Also, it can be seen that at all the applied voltages the smallest difference between the currents when the water content is 25% and when it is 30% is in the case when only corroded electrodes are used.This indicates that when the electrodes are corroded, the influence of the water content in the clay on the current flow is reduced. Obviously, in this case when only corroded electrodes are used, the specific resistivity of the clayey soil plays a relatively reduced role, i.e. the increased electrode resistance is more pronounced. These effectsare more noticeable at higher voltage values applied.

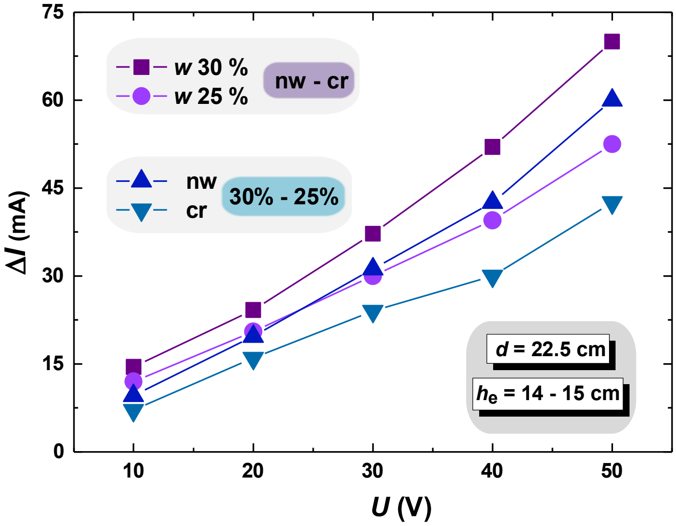

Figure 5. The difference between the increase in electric current intensity as a function of applied voltage for two different water contents, for both new and corroded electrodes

Obviously, the obtained results indicate a significant influence of electrode corrosion on the flow of electric current, and thus on electrokinetic soil treatment. Therefore additional research was performed in order to provide a more detailed analysis. The following sequence of experiments was carried out under the similar conditions. The test was carried out in the same test boxes, with a distance of 22.5 cm between the electrodes and a depth of clay to which the electrodes were inserted which was 14 - 15 cm, but with a successive increase of water content from 20% to 35% with an increase of 5%. The results of this sequence of experiments are presented in Figure 6.

For all cases of this additional experiment, which include samples of clayey soil with four different water contents, significant reduction in measured electric current intensity between electrodes embedded in clayey soil was observed. Table 1 shows the differences in the electric current intensity obtained during this part of the experiment, when new and corroded electrodes used for the highest and lowest values of water content percentage (20% and 35%). Based on the presented values can be seen that reduction of current was 21%-32% at applied 30 V, while at applied 50 V, it was 22%-38%.

As expected, the use of corroded electrodes leads to a significant reduction in electric current flow through the clay sample. This is due to the compromised conductivity at the electrode surface caused by electrochemical reactions that, over time, result in the formation of corrosion products (e.g., oxides, salts), a reduction in the effective electrode surface area, and an increase in contact resistance between the electrode and the clayey soil.Namely, the condition of the electrodes (new vs. corroded) has a more pronounced impact on the system's conductivity and the efficiency of the electrokinetic treatment than a percent change in clayey soilwater content. This is interesting, considering that the water content directly influences the ionic mobility and the overall electrical conductivity of the soil, and it is typically expected that even small changes in the water content would affect the current flow.However, the experimental results suggest that the electrode corrosion is an even more dominant factor.

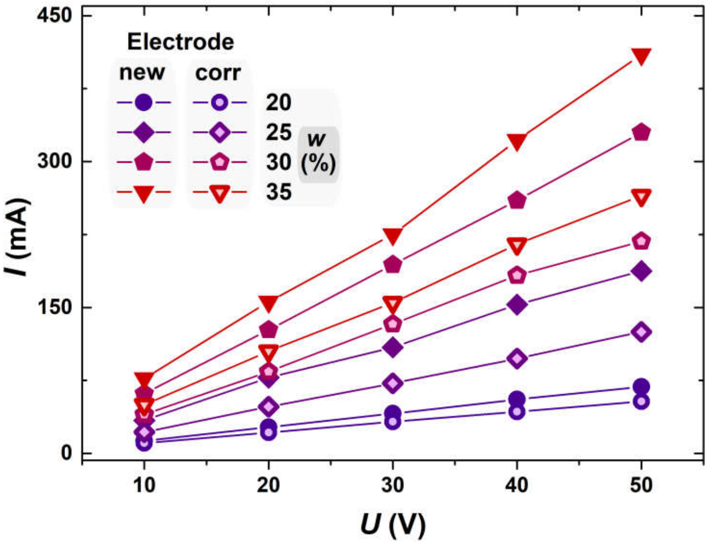

Figure 6. The increase in electric current intensity as a function of applied voltage for four common different water contents, for both new and corroded electrodes

Observed results imply that corroded electrodes not only reduce the efficiency of the current transmission but may also disrupt the uniform distribution of chemical stabilizers during a potential treatment. Since electrokinetic processes rely on the continuous and stable current flow to drive the electroosmosis and electromigration, any reduction in the current can negatively impact the overall effectiveness of the soil treatment.

Table 1. The difference in electrical current intensity obtained when new and corroded electrodes were used for the highest and lowest values of water content percentage

Voltage / *w* (%)	10 V	20 V	30 V	40 V	50 V
20	2.4	5.5	8.5	12.5	15
35	27	51	70	107	145

These findings clearly indicate that electrode corrosion is a critical parameter that can have a greater influence on the treatment success in addition to certain physical properties of the soil, such as water content. Therefore, a special attention must be given to the selection of electrode materials, maintenance practices, and potential strategies for corrosion protection in electrokinetic systems.By implementing these approaches, the operational lifespan of electrodes can be extended, making the electrokinetic soil treatment more viable for a large-scale or long-term application.

4. CONCLUDING REMARKS

This study highlights the potential of the electrokinetic soil treatment as a promising technique for stabilizing soils, especially where traditional methods are insufficient or environmentally unsuitable. The findings demonstrate that while parameters such as the soil water content are important for the effective current flow and treatment outcomes, the condition of the electrodes, particularly the extent of corrosion, plays a significantly more critical role in the overall performance of the system.

The observed reduction in the current flow when using corroded electrodes, even at an optimal water content, emphasizes the detrimental impact of electrode degradation on the electrokinetic process. The fact that the corrosion caused a more substantial decrease in the current than a 5% variation in soil moisture underlines the importance of electrode maintenance, material selection, and corrosion mitigation strategies in practical applications.

Given that electrokinetic stabilization relies heavily on the sustained and consistent current, the electrode corrosion emerges as a limiting factor that can compromise the treatment efficiency, duration, and cost-effectiveness. As such, future work should focus on the optimization of treatment parameters to reduce the electrochemical degradation, and the potential implementation of protective measures such as pulsed current techniques. Concerning that the electrokinetic soil treatment holds a great promise it can be further optimized for broader, more reliable use in geotechnical and environmental engineering.

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