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ARTICLE

Groundwater Drainage By Means Of Electrochemistry For Soil Improvement

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ABSTRACT

In the last decade, the construction of communication routes has intensified globally. As a result, many case studies have emerged related to the presence of saturated clayey soils in the foundation ground. In order to speed up the execution of highways and railways in a safely manner, the designers use different methods for improving soft clays in terms of compressibility. The present paper aims to evaluate the efficiency of an electrochemical method used for the dewatering of a soft montmorillonite clay subgrade. The effects on the consolidation process are analyzed for the final conclusions. The advantages of the method are briefly discussed, and some potential areas for scientific research are proposed.

1. Introduction

In applying the methods of soil improvement, it is necessary to understand the soil behavior and the natural phenomena that may affect it. A distinction must be made between the concept of soil consolidation as a natural phenomenon of compression under a certain load in time and the methods for consolidating the foundation ground through artificial improvements.

The electro-osmotic consolidation is a soil improvement method during which the pore water in the soil is drawn from an anode to a cathode under an induced electric field, thus creating a negative pore pressure. This phenomenon leads to the soil consolidation and the increase of the soil's strength parameters. This increase has proven to be permanent in clayey soils.

The electro-osmosis was first used by Casagrande [1] in geotechnical engineering and since then, it has been used in various applications, including stabilization of slopes, dams and embankments, soil improvement, dewatering of sludge and tailings, remediation works and groundwater displacement.

The combination of electro-osmosis and other techniques (preloading, chemical treatment, lime columns, vacuum) was also studied and numerous publications emerged over time.

The electro-osmosis can also be used as a tool in predicting the soil behavior during consolidation.

A laboratory experimental stand was developed for observing and evaluating the electro-osmotic consolidation process in a soft montmorillonite clay sample, as well as the variation of the mechanical properties of the clay be-

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fore and after the experiment.

2. Methodology and materials

2.1 Methodology

The total stress in any saturated soil, σ, is comprised of two parts, namely the effective stress, σ', and the pore water pressure, u, as follows:

$$\sigma = \sigma' + u\left[kPa\right] \quad (1)$$

The pore water pressure, u, is obtained by multiplying the unit weight of the water, γ_w, with the piezometric head, h_w:

$$u = \gamma_w \cdot h_w\left[kPa\right] \quad (2)$$

When an electrical current is applied across a saturated soil mass, the cations migrate toward the cathode and the anions toward the anode. The cations containing negatively charged particles from a clayey soil are in greater number, thus causing the water to migrate toward the cathode. This phenomenon is called electro-osmosis and its efficiency depends on a series of factors, such as the conductivity of soil, the voltage gradient, and the water properties.

During the electro-osmosis, a negative pore pressure is induced, leading to an increase of the effective stress, thus resulting the consolidation of the soil.

$$\sigma' = \sigma - \left(-u\right) = \sigma + u\left[kPa\right] \quad (3)$$

When the pore water is drawn from the anode towards the cathode, a hydraulic gradient is developed between the electrodes and there is free drainage at the cathode [2].

The relationship below is frequently used in geotechnical engineering for evaluating the electro-osmotic flow, being applicable when there is free access to water at both the anode and the cathode:

$$q = k_e \cdot i_e \cdot A\left[\frac{m^3}{s}\right] \quad (4)$$

, where:

k_e = coefficient of electro-osmotic permeability [m^2/sV or m/s per V/m]

i_e = electrical gradient [V/m]

A = cross-sectional area perpendicular to water flow [m^2]

This method acts on the weakly bound (film) water within the adsorption complex and especially on the free water.

Because cations of different valence (eg. Na^+, Ca^{2+}) may exist in the adsorption complex, the efficiency of the method also depends on the chemicals dissolved in the pore water of the soil. For example, marine clays (eg. Singaporean clays) are different from clays formed in freshwater.

2.2 Materials

The material used to carry out the experiment was a saturated montmorillonite clay, with the basic properties listed in Table 1.

Table 1. Basic properties of the clay used in the experiment

Parameter	Initial water content, w (%)	Degree of saturation, S (%)	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Specific gravity, ρ_s (g/cm^3)
Value	46.94	100	72.30	23.83	2.70

Before and after the experiment, the material was subjected to consolidation tests in the edometer to observe the effect of the electro-osmosis phenomenon on its mechanical properties (Figure 1).

Figure 1. Mounting of the sample in the edometer apparatus

After edometric consolidation on different loading steps (200, 300 and 500 kPa), the values presented in Table 2 were obtained.

The clay was placed in a plastic container of 27x18x12 cm in size.

The electrodes used (the anode and the cathode) consisted of two carbon iron bars (OB 37), which were inserted into the midline of the soil sample, at a distance of 17 cm, resulting a voltage gradient of 1.03 V/cm.

The power source consisted of a car rectifier, with a power supply at 220 V/50 Hz, the resulting voltage being

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12 V/DC. A multimeter was used to monitor the electrical current.

The total testing time was 72 hours.

The experimental stand is shown in Figure 2.

Table 2. Consolidation parameters of the clay

Stress, (kPa)	Deformation, e (%)	Compression modulus, M (kPa)	Coefficient of volume compressibility, m_v (kPa^{-1})	Coefficient of consolidation, c_v (cm^2/s)	Coefficient of permeability, k (cm/s)
100	1.45	2688	0.000372	4.978E-06	1.952E-06
200	5.17				
200	5.17	3125	0.00032	3.795E-06	1.325E-06
300	8.37				
300	8.37	3756	0.0002663	3.395E-06	1.047E-06
500	13.69				

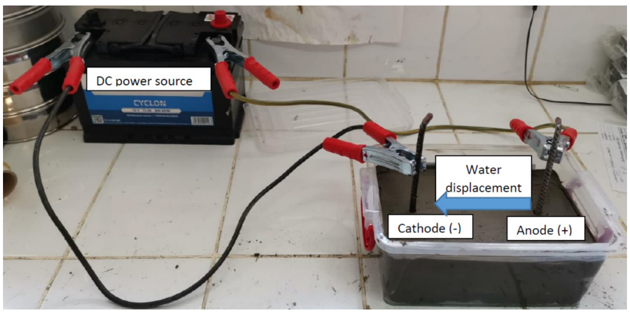


Figure 2. Experimental stand

3. Results and Discussion

After about 2 hours from the beginning of the experiment, the formation of a water film around the cathode was observed (Figure 3a), thus attesting the occurrence of the electro-osmosis phenomenon.

During the electro-osmotic consolidation, the water moved from the anode to the cathode inside the soil sample, causing the formation of some cracks near the anode (Figure 3b).

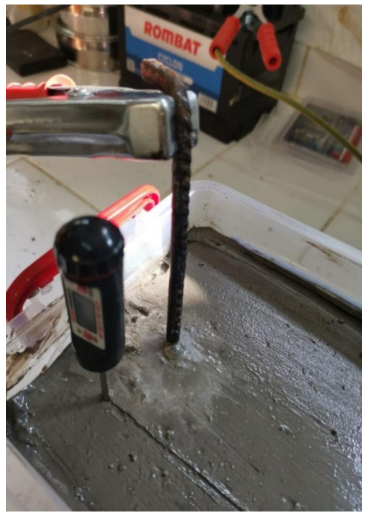
During the experiment, the following aspects were observed:

(1) the temperature measured near the cathode with the help of a thermometer recorded values with approx. 2 degrees higher than the one next to the anode throughout the experiment;

(2) the anode underwent oxidation during electro-osmosis, losing approx. 0.5% of the initial mass (Figure 4);

(3) the humidity of the soil sample near the cathode increased by approx. 14% compared to that determined near the anode;

(4) approx. 200 ml of water were discharged from the clay sample.



(a)

(b)

Figure 3. Experimental stand after the experiment: (a) formation of the water film around the cathode; (b) cracks appearance around the anode

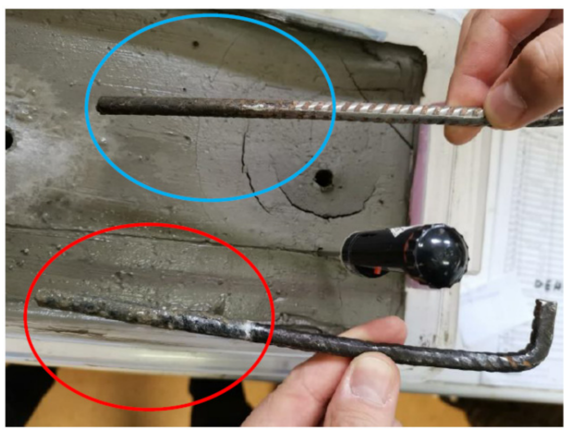


Figure 4. Oxidation effect of the anode (red circle) compared to the cathode (blue circle)

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Taking into account the scale of the model, we consider that the effect of applying the electro-osmosis method on the soft clay is more than satisfactory.

In order to directly point to this conclusion, mechanical compressibility tests were performed on the clay sample improved by electro-osmosis.

After edometric consolidation on different loading steps, the values presented in Table 3 were obtained.

Table 3. Consolidation parameters of the clay after electro-osmosis

Stress, (kPa)	Deformation, e (%)	Compression modulus, M (kPa)	Coefficient of volume compressibility, m_v (kPa^{-1})	Coefficient of consolidation, c_v (cm^2/s)	Coefficient of permeability, k (cm/s)
100	3.00	5952	0.000168	6.624E-06	1.246E-06
200	4.68				
200	4.68	5602	0.0001785	4.217E-06	8.574E-07
300	6.47				
300	6.47	5831	0.0001715	3.488E-06	7.084E-07
500	9.90				

The diagrams in Graphs 1-3 show the differences recorded before and after the application of electro-osmosis on the clay sample. From these graphs and from the values presented in Table 3, some very interesting engineering conclusions are drawn, namely:

(1) the compression-consolidation curves highlight the effect of "speeding up" the consolidation process and the increase of the specific deformations' values for the samples along with the variation of the consolidation pressure; if we consider the degree of vertical consolidation u_v=50% under the conditions of the double drainage specific to the edometric test it is observed that:

(A) for σ=200 kPa, $\Delta\varepsilon_{50}\approx1\%$;

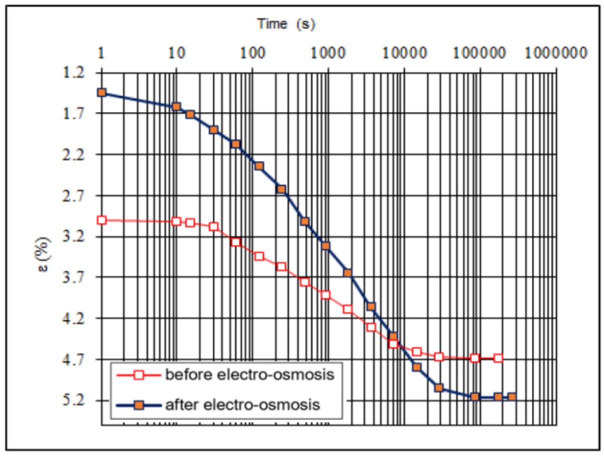
(B) for σ=300 kPa, $\Delta\varepsilon_{50}\approx1,5\%$;

(C) for σ=500 kPa, $\Delta\varepsilon_{50}\approx3\%$.

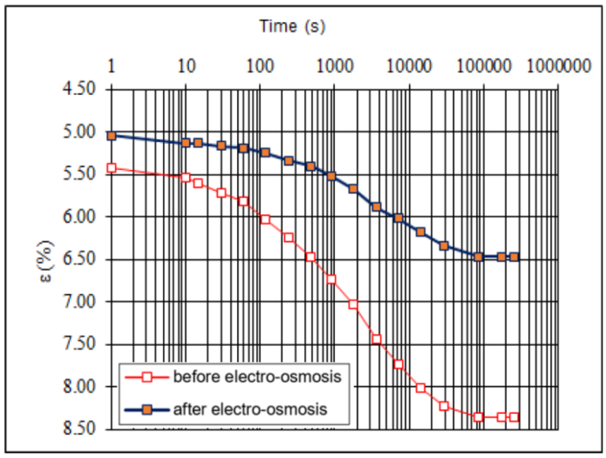
(2) the effects of the pressure, σ, on the consolidation coefficient's variation, c_v, is approx. 2.5 times higher for the clay improved by electro-osmosis in the range of (200÷300) kPa;

(3) the permeability coefficient, k, decreases to a range of values between ~ 0.75×10^{-6} cm/s and ~ 0.3×10^{-6} cm/s for loads within the range of (200÷500) kPa;

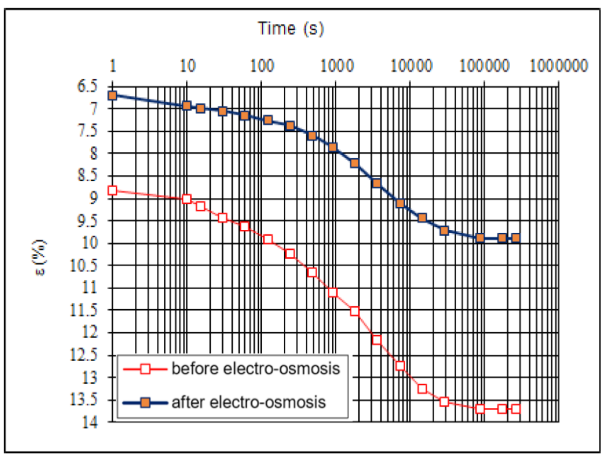
(4) it turns out that by applying the electro-osmosis process in soft clays deposits (very plastic and active in relation to water), the obvious improvement of the clay's mechanical properties (the compressibility decrease under increasing pressures) takes place.



(a)



(b)



(c)

Graph 1. Edometric consolidation curve under different loading stages: (a) σ=200 kPa; (b) σ=300 kPa; (c) σ=500 kPa

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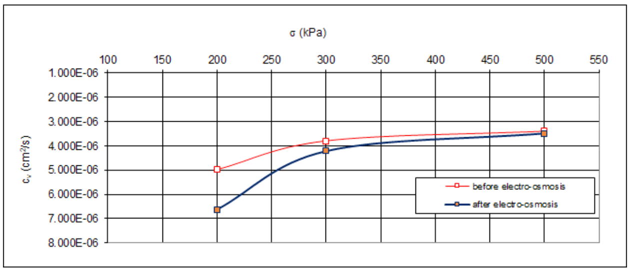
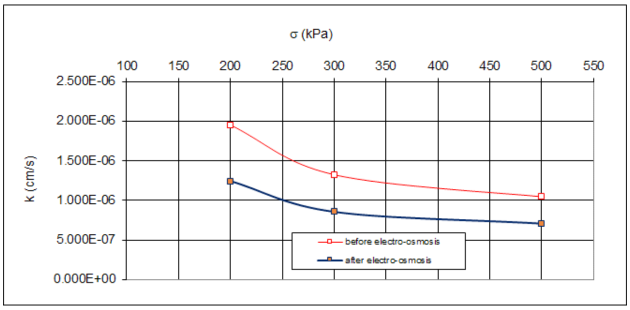


Graph 2. The variation of the consolidation coefficient with pressure



Graph 3. The variation of the permeability coefficient with pressure

4. Conclusion

The obtained results showed the electro-osmosis' influence on the soft clay's properties. The electrical current allowed the fast drainage of water from the clay sample.

An obvious increase of the clay's coefficient of consolidation was recorded, as well as a decrease of the permeability coefficient. All the measured values were within those provided by literature, confirming the efficiency of the electro-osmotic process.

Nevertheless, the results also showed the influence of electro-osmosis on the flow of water, a phenomenon that can successfully be used for remediation of contaminated soils and other similar applications.

The conductivity of the material plays an important role in controlling the efficiency of the electro-osmosis method. The increase in conductivity leads to a decrease in resistivity, thus improving the water flow through the sample.

Studies have shown that saline water added in the soil sample instead of tap water led to an increase in permeability by a factor of 1.2, without any electrical current connection [3].

Therefore, an interesting future research would regard the interaction between electro-osmosis and groundwater with a high salt content. This method could be very useful for coastline consolidation applications.

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