Note

Improvement of clay soil by electro-osmosis technique

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A B S T R A C T

The use of electro-osmosis for treatment of soft clay soils is a common ground improvement technique. A number of chemical, physical and mechanical interactions occur during the improvement of soil by this technique. This paper presents the results of an experimental study on the effects of treatment on the settlement and chemical and physical reactions of a clay soil. A series of experiments were conducted in a designed apparatus with electrical vertical drains (EVD) under different voltages. The experimental results showed that pH, electrical conductivity (EC) and Atterberg limits changed during the tests. In addition, electro-osmosis caused a significant increase in the settlement and undrained strength of the soil.

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1. Introduction

Water can have an important influence on stability of soils. The strength and stability of soil are dependent on the effective stress and hence, they are directly related to the change in pore water pressure. Dewatering is a technique of improving soil behavior by reducing pore water pressure and water content. Dewatering can be conducted by using vertical sand or gravel drains, surcharge or preloading and combination of preloading and prefabricated vertical drains (PVD) for improving the soft soil (e.g. Bergado et al., 2000; Hansbo et al., 1981; Indraratna et al., 1994; Terashi and Katagiri, 2005). When a direct current is applied to a porous medium saturated with water, the water moves towards the negative electrode (cathode) (Mohamedelhassan and Shang, 2001). This phenomenon is termed electro-osmosis. Electro-osmosis is used during dewatering to facilitate the movement of water. It accelerates the movement of water through the soil into an installed drain or well point. The water in the pores of the soil will flow out due to the ions with positive charge that are created by applying a direct current. The water content of the soil is decreased since the water can not enter in the anode (positively charged electrode) of the system. This results to the consolidation of the soil. The electro-osmosis has an advantage over other techniques as it accelerates the consolidation and strengthens the soft saturated clayey soil.

Electro-osmosis technology has been used since 1930s for removing water from clay and silt soils (Bruell et al., 1992). Since then, several successful applications have been reported by researchers such as Casagrande (1952), Bjerrum et al. (1967), Fetzer (1967), Wade (1976), Chappell and Burton (1975), Lo et al. (1991a, 1991b), Mohamedelhassan and Shang (2001), Chew et al. (2004), Burnotte et al. (2004), Rittirong et al. (2008), Jones et al. (2011) and Karunaratne (2011). Electro-osmotic technique has the potential to overcome limitations of very slow and in some cases effectively zero hydraulic flow in fine grained, low permeability materials such as silts and clays (Jones et al., 2011). Hydraulic permeability is related to grain size but the electro-osmotic permeability is independent of grain size (Shang, 1997). This means that electro-osmosis can result in flow rates 100 to 1000 times greater than hydraulic flow in fine grained materials because the value of electro-osmosis permeability (K_e) is greater than that of the hydraulic permeability (K_h) (Jones et al., 2011). Therefore, electro-osmosis can be considered for projects that require a rapid improvement in the properties of soft clayey soil.

The electrodes that are used in conventional electro-osmosis treatment are made of steel, aluminum and copper. These metallic electrodes corrode rapidly during the treatment, which reduces the treatment efficiency (Mohamedelhassan and Shang, 2001). Recently many researchers have tried to change the conventional electro-osmosis technique so that the corrosion is reduced and the advantages of PVD added to it. Chew et al. (2004) proposed the electrical vertical drains (EVD) as the electrode for electro-osmosis technique by assuming that the electric current is passed through conducting polymer. EVD are in the form of a sheet usually made of copper foil in the middle surrounded by conductive polymer.

Review of the literature shows that there have been limited studies on the electrochemical effects in treatment of soils by electro-osmosis (except the works of Chew et al., 2004 and Rittirong et al., 2008 that studied the electrochemical effects generated by the application of D.C. current in soil) and the majority of them are focussed only on the process of electro-osmosis consolidation. In this work the chemical, physical and mechanical aspects of a treated soil including variations in pH, EC (electric conductivity), Atterberg limits, strength and the rate of electro-osmosis flow are investigated through a series of experimental tests on samples of a clay soil. The tests were conducted in a designed apparatus under various applied voltages.

2. Experimental study

2.1. Apparatus

Based on the considerations followed by previous researchers, an apparatus was designed and fabricated for this work, similar to the one used by Rittirong et al. (2008) and Mohamedelhassan and Shang (2001). The apparatus consists of main cell, loading frame and D.C. power supply as shown in Fig. 1. The main section of the apparatus is the cell that consists of a rectangular tank that holds the soil sample. It was made of plexiglass plates with 1 cm thickness. Two reservoirs, namely anode and cathode, were added on the two sides of the main cell and were connected to the cell through perforated plexiglass sheets as shown in Fig. 1. The reservoirs are filled with water and the total hydraulic head in them can be controlled by adjusting two identical standing tubes through valves. Two EVD made of copper foil covered with conductive polymer were vertically placed adjacent to the anode and cathode reservoirs and in contact with soil in the cell. A number of voltage probes were installed at the bottom of the cell at distances of 2, 5, 8 and 11 cm from the anode. The diameter of the probes was 1 mm and they were made from iridium oxide (as used by Rittirong et al., 2008). These probes were used to measure the voltage in certain time intervals during the progress of the test. A loading system was designed for applying the desired load to the soil sample (see Fig. 1). The load was applied through the bottom plate to the sample. A dial

gauge was mounted on the top plate for measuring the vertical deformation due to the consolidation. The power supplier of D.C. current consists of a generator that produces various ranges of voltage and is connected to the EVD through the connections.

2.2. Soil and water

The soil used in the testing program was kaolin. Tables 1 and 2 summarize the various indices, and physical, mechanical and chemical properties of the soil. The soil can be classified as the clay with low plasticity (CL) according to the Unified Classification System (USCS).

Drinking water was used for conducting the tests and it had a pH of 7.76, Cl content of 1.7 meq/L and Ca–Mg content of 9.1 meq/L.

2.3. Sample preparation and experimental procedure

A specific amount of air-dried soil was mixed with water to achieve a water content of 5% above the liquid limit. The soil was mixed by hand steer for about 1 h until a smooth condition was achieved. This mixture was kept in a plastic bowl with closed lid for about 10 days for uniform distribution of water content. The strength of the prepared soil was measured by using shear vane apparatus (ASTM D4648-00, 2000) in random points of the soil. The prepared soil sample was placed in the main cell and a saturated geomembrane was placed on top of the soil to create a horizontal flow condition. The level of water was kept the same in the anode and cathode reservoirs at two sides of soil in the main cell. Then a surcharge pressure of 22 kPa was applied to the soil via the loading plate. The settlement of the sample was monitored using a dial gauge. The consolidation settlement stopped after about five days. This stage of test will be referred to as preloading consolidation. When this stage was completed a number of samples were taken along the soil for determining the water content. The osmosis consolidation was carried out after the preloading consolidation stage by setting the hydraulic gradient between two reservoirs to zero. The osmotic consolidation was enforced by applying a D.C. current through the soil. The vertical deformation was measured by monitoring the readings of the dial gauge and the volume of the sample was calculated by measuring
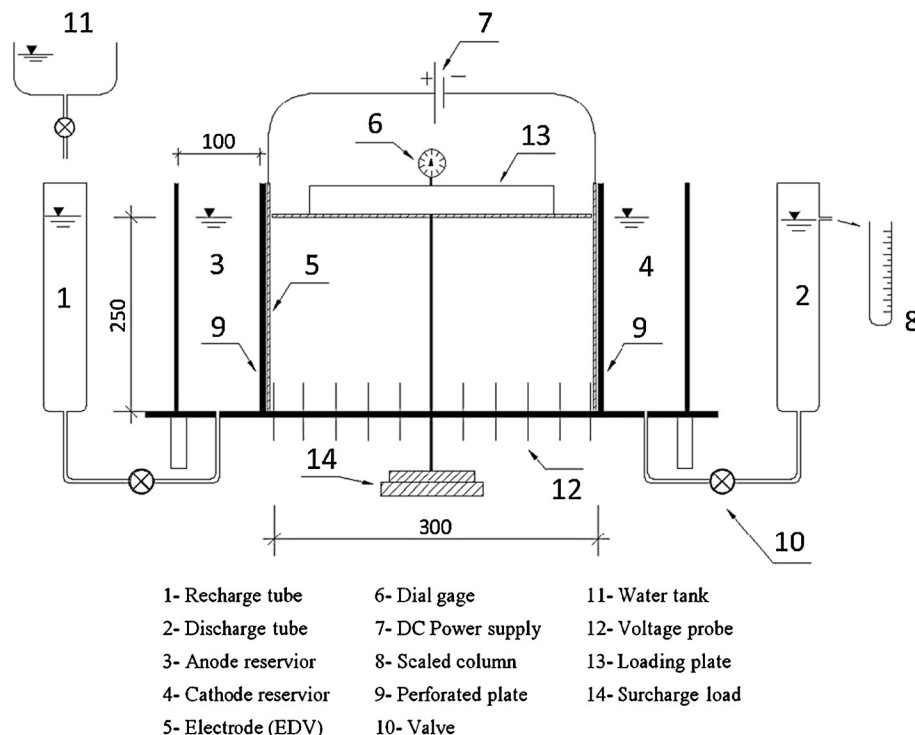

1- Recharge tube	6- Dial gage	11- Water tank
2- Discharge tube	7- DC Power supply	12- Voltage probe
3- Anode reservior	8- Scaled column	13- Loading plate
4- Cathode reservior	9- Perforated plate	14- Surcharge load
5- Electrode (EDV)	10- Valve	

Fig. 1. Schematic plan of test set-up (dimension in mm).

Table 1
Physical and mechanical properties of the soil.

Properties	Standard designation	Values
Specific gravity (G_S)	ASTM D854-10, 2010a	2.7
Consistency limits		
Liquid limit (LL)	ASTM D 4318-10, 2010b	49 (%)
Plastic limit (PL)	ASTM D 4318-10, 2010b	25 (%)
Plastic index (PI)	ASTM D 4318-10, 2010b	24 (%)
Shrinkage limit (SL)	ASTM427-01, 2001	12 (%)
Swelling potential	ASTM D4546-08, 2008	20 (%)
USCS classification	ASTM D 2487-10, 2010c	CL
Compaction characteristics		
Optimum water content (*w*)	ASTM D698-07, 2007	17 (%)
Maximum dry unit weight ($\gamma_{d_{max}}$)		17.2 kN/m³

the volume of outflow water from the cathode reservoir during the test. The total time for consolidation stage was about 10 days for different voltages. After the test, the undrained shear strength was measured using shear vane at the anode, middle and cathode and a number of samples were taken for determination of water content and Atterberg limits.

3. Results

The voltage profiles at 15, 25, 35 and 45 V for soil at different times (1 to 10 days) were measured through the probes located at the bottom of the sample. Fig. 2 shows the results of voltage drop for various voltages along the samples at the end of each test. It can be deduced that the higher the voltage, the higher is the drop in voltage. The settlement of the soil was determined based on measurement of the volume of discharge water from the cathode. The variations of settlement with treatment time (Fig. 3) show that after 10 days the total settlements are 11 and 13 mm for 15 and 45 V respectively. It can be observed from this figure that the majority of settlement occurred during the first three days of treatment and after that the settlement attained a constant value. The settlement resulting from preloading (Fig. 3) is negligible in comparison with those of electro-osmotic settlements with 15 and 45 V.

The changes in the values of pH for water in the electrode reservoir with time show that the initial value of pH (7.6) is increased in cathode and decreased in anode. The results of pH show that the rate of changes in the variations of pH depends on the value of applied voltage; higher applied voltages resulted in higher rates of pH variations in both electrode reservoirs. Reduction in the applied voltage resulted in fewer ions being produced by electrolysis. This led to migration of cations creating the acid front continuously moving towards the cathode resulting in the decrease of pH in the water in the cathode reservoir after 20 h of the electrokinetic process. The results of variations of electric conductivity with time for water in anode and cathode reservoirs for different applied voltages show that the value of EC was greater in the cathode reservoir than anode and it increased with time. It reached a constant value after 120 h for 45 V and about 200 h for 25 V. After 240 h, the values of EC for 25 V were 32 and 88.1 ds/m in anode and cathode respectively. The increase in the value of EC was

Table 2
Chemical composition of the soil.

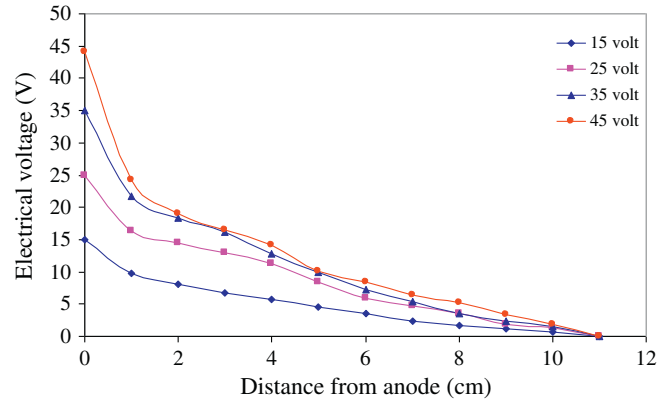| Chemical component	Amount	Chemical component	Amount
SO_4^{2-} (meq/L)	19.3	Na^+ (meq/L)	43.0
HCO_3^- (meq/L)	3.7	Ca^{2+} (meq/L)	4.6
CO_3^{2-} (meq/L)	0.3	K^+ (meq/L)	0.4
CL^- (meq/L)	26.6	Mg^{2+} (meq/L)	2.1
pH	8.5	EC (ds/m)	5.05

Fig. 2. Profile of voltage drop at the end of each test for various voltages.

dependent on the applied voltage; the values of EC in the cathode reservoir were 88 and 95 ds/m for 25 and 45 V respectively.

The liquid limit (LL) and plastic limit (PL) of the soil (Atterberg limits) were obtained on the samples that were extracted from the soil in the apparatus after the test. The changes in the values of Atterberg limits in the cathode for different voltages show that they are changed from their initial values and these variations are dependent on the applied voltage and distance from the anode.

After the test, the undrained shear strengths were measured at three points in the soil (anode, middle and cathode) using a shear vane (ASTM D4648-00, 2000). The results show the strength increased in comparison with the original value (2 kPa) and it had different values along the length of the sample. Therefore, the values of strength are dependent on the applied voltage and distance from anode.

4. Discussion

In this work different voltages (15, 25, 30 and 45 V) were applied across the length of soil sample in the main cell. The results showed that the drop in a specific voltage increased with time. The magnitude of the voltage drop depends on the soil properties, applied voltage and electrode material (Mohamedelhassan and Shang, 2001). An efficiency factor, β is defined to quantify the voltage drop at the soil/EVD interfaces (Rittirong et al., 2008):

$$\beta = \left(\frac{v_e}{v_0}\right)*100 \tag{1}$$

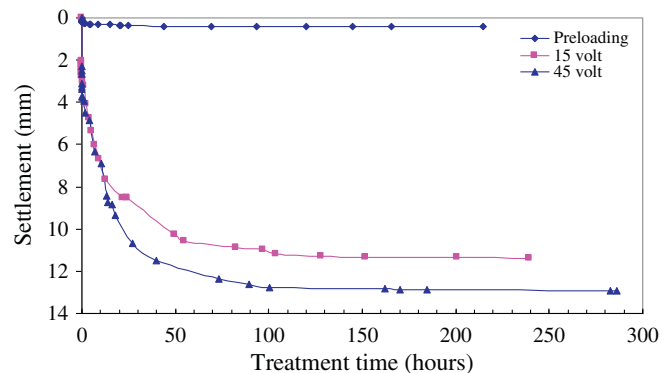$$v_e = v_0 - (\Delta v_a + \Delta v_c) \tag{2}$$

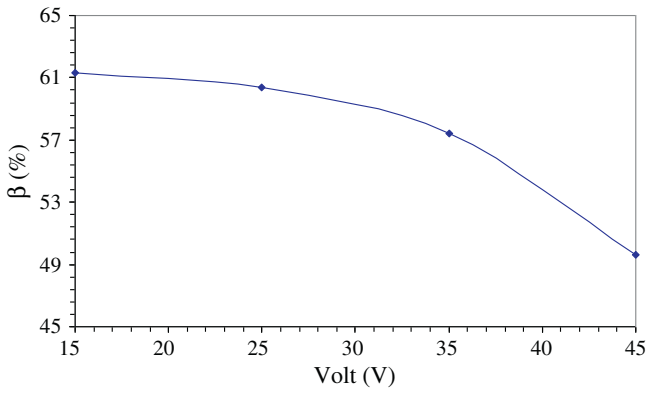**Fig. 3.** Electro-osmotic and preloading settlement.

Fig. 4. Variations of β at the end of tests for different volts.

where v_e and v_0 are effective and applied voltages to the soil respectively and Δv_a and Δv_c are the voltage drops at anode and cathode. The values of β were calculated for different voltages at various time intervals according to the above equations. The values obtained for parameter β at the end of the tests for different voltages (Fig. 4) show that its value is decreased with increasing voltage. It can be said that higher applied voltages cause higher drop in the value of β. The amount of outflow of water from the soil during electro-osmosis can be defined by the following relationship (Mitchell, 1993):

$$Q = K_e*E*A \tag{3}$$

where Q is the electro-osmotic flow rate, A is the cross sectional area normal to the direction of flow, E is the electric field intensity and K_e is the electro-osmotic permeability. As seen from Eq. (3) the rate of outflow of water from the soil is controlled by K_e and E so, this rate under a specific electric field is dependent on the value of K_e. The values of K_e were calculated based on Eq. (3) and the data. The results (Fig. 5) show that the (initial) values of K_e are $3.83 * 10^{-9}$ and $3.79 * 10^{-9}$ m²/sV for 15 and 45 V and they decrease rapidly from the initial value to a more or less constant value with increasing the treatment time. These results are consistent with the results reported by Mohamedelhassan and Shang (2001) and Rittirong et al. (2008). The changes of K_e are dependent on the variations of pH and reduction of water content. Shang (1997) indicated that the value of K_e is dependent on the zeta potential. The variation of zeta potential is function of pH changes. Since the values of pH are not the same along the sample therefore, the zeta potential is not constant and this leads to the reduction of K_e. The outflow of water from the cathode is decreased by reduction of K_e. The consolidation settlement is also caused by the outflow of water from the cathode. It can be assumed that the settlement continues until the hydraulic force that
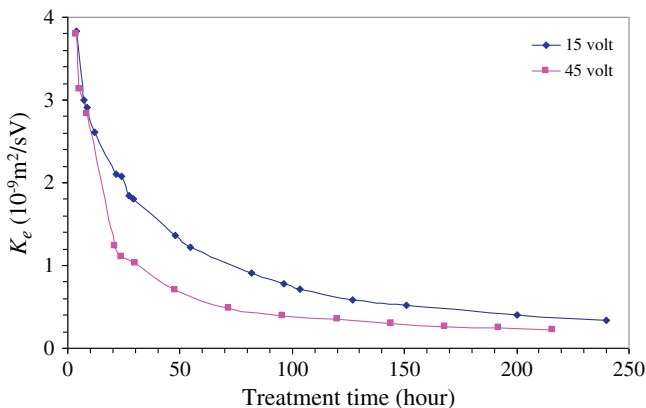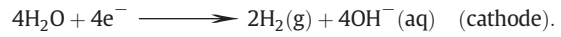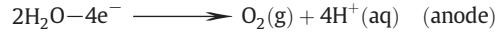

Fig. 5. Variations of electro-osmotic permeability during treatment.

drives water back towards the anode balances the electro-osmotic force driving water towards the cathode (Jones et al., 2011). The amount of settlement that will take place depends on the soil compressibility as well as the change in effective stress.

Based on the results of variation of pH in the anode and cathode during the application of the electrical current the following chemical reactions occur in the anode and cathode:

$$2H_2O - 4e^- \longrightarrow O_2(g) + 4H^+(aq) \quad \text{(anode)}$$

$$4H_2O + 4e^- \longrightarrow 2H_2(g) + 4OH^-(aq) \quad \text{(cathode)}.$$

These reactions in the cathode and anode cause the creation of oxygen and hydrogen gasses and H^+ and OH^- as an aqueous. Therefore the existence of H^+ in anode causes the value of pH to decrease and the liquid adjacent to the anode gets acidic but in the cathode it changes to alkaline. By increasing the applied voltage the amount of H^+ and OH^- is increased and it results in pH attaining a constant value in a relatively short time. The changes in the electrical conductivity of water in the electrode reservoirs show the increasing of EC with applied voltage. The increase of EC can be the result of accumulation of dissolved ions particularly in the cathode reservoir. As it was discussed earlier, the decrease of pH in anode creates an acid front which moves from the anode to the cathode. As the acid front moves from the anode to the cathode, the H^+ ions exchange with the adsorbed cations in the diffuse ion layer around clay particles. The Atterberg limits are changed along the soil during the tests and the values of them after the tests are dependent on the applied voltage. The change in the values of the Atterberg limits is dependent on the change in the quality of pore water, change in the grain size distribution and change in the minerals of clay (Chew et al., 2004). Application of a current with specified voltage results in an increase in the strength of the soil. These results are consistent with the results that were reported by Micic et al. (2002), Alshawabkeh and Sheahan (2003), Burnotte et al. (2004) and Rittirong et al. (2008). The increase in the strength of soil can be related to the Atterberg limits through liquid index. Wood (1990) presented a relationship between the strength and liquid index as:

$$C_u = 2*100^{1-I_L} \tag{4}$$

where C_u and I_L are undrained strength and liquid index of soil respectively. The experimental results and the results from the above equation are consistent with each other for this soil in the range of applied voltages in this program. The increase in strength may occur by reduction of water content during the test, pasting the particles of soil to each other by the cementation process and forming meniscus in the pore of soil (Casagrande, 1949). The high value of pH changes the soil to alkaline condition. The cementation can occur in the alkaline conditions. Therefore, the increase in pH can result in an increase in the strength of the soil. The cementation may be formed by the free ions that are produced from the cathode. For example Al^{+3} has the ability to paste and produce rigid bonds between particles.

In practice, for the safety and economic design of electro-osmotic projects in the field, some information about design parameters is needed. Therefore, it is necessary to conduct a set of laboratory tests on soil samples to find the required design information such as K_e, K_h, E (electric field intensity) and ρ (energy consumptions). However, this work shows that, although electro-osmosis induces settlement of soil, the improvement in the mechanical behavior of soil such as strength is not dependent on electro-osmotic consolidation alone. It relies on the chemical and physical reactions that occur during the electro-osmotic process.

5. Conclusion

The effect of electro-osmosis on the chemical, physical and mechanical behavior of a clay soil was investigated through laboratory tests. An electro-osmotic apparatus was designed and fabricated with electrical vertical drains (EVD) to measure the desired parameters. The results showed that:The value of K_e decreases with treatment time and with increasing the applied voltage. The efficiency factor (β) is dependent on the applied voltage and it decreases with increasing the applied voltage. The values of pH and EC of anode and cathode reservoirs are changed during the treatment time and their variations are increased with increasing the applied voltage. Increasing the liquid and plastic limits decreases the liquid index leading to an increase in shear strength of the soil.

Acknowledgment

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