

Effect of electrochemical treatment on consolidation of soft clay

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Abstract. In this study, a method of electrochemical consolidation is applied. This method utilizes electro-osmosis, which is an effective ground improvement technique for soft clays, and soil treatment using lime, which is the oldest traditional soil stabilizer. The mechanism of lime treatment for soil involves cation exchange, which leads to the flocculation and agglomeration. Five representative laboratory tests—an electro-osmotic test and four electrochemical tests with various proportions of lime—were performed on dredged marine clay. The objectives of this study are to investigate the effect of electrochemical treatment and to determine the optimum dose for optimal consolidation performance of dredged marine clay. The results show that a better consolidation effect was achieved in terms of current, temperature, and vane shear strength by using electrochemical treatment. The best results were observed for the electrochemical test using 4% lime content.

Keywords: electro-osmosis, electrochemical treatment, lime, dredged marine clay, vane shear strength

1. Introduction

Recently, with the rapidly developing economies and booming populations of coastal cities in China, existing land resources have been unable to meet demand for the sustainable development of cities. Land reclamation has been widely adopted in the coastal cities of China. Dredged slurry from the nearby seabed serves as the main fill material for land reclamation. However, this fill material is typically characterized by high water content, high compressibility, low shear strength, and low permeability (Chu *et al.* 2000). Therefore, it is essential to consolidate the soft clayey soil before any construction work is conducted.

The popular approach for consolidating the extremely soft foundation is the vacuum preloading method (Wang *et al.* 2016, Cai *et al.* 2017, Wang *et al.* 2017, Wang *et al.* 2018a). Unfortunately, the vacuum preloading method for soft clay has the big challenge of sludge cliquing around prefabricated vertical drains. Meanwhile, the hydraulic conductivity of dredged marine clay can be as low as 10–9 m/s (far less than 10–7 m/s), which means that it is difficult to dewater using the above method. However, electro-osmotic technology has the potential to overcome these shortcomings (Jones *et al.* 2011). Hydraulic permeability is relative to particle size, but the electro-osmotic permeability is independent of grain size (Mitchell and Soga 1993, Shang 1997). Therefore, electro-osmotic technology serves as a potential method for projects containing low-

permeability materials such as dredged slurry.

Electro-osmosis (EO), which was first discovered by Reuss in 1809, describes the process of water moving from anodes to cathodes when a direct current (DC) is applied across electrodes inserted into a saturated porous medium. The ions in the diffusion layer (Mitchell and Soga 1993) migrate toward the cathode under the imposed DC and drag water with them, which results in the strengthening of the soil (Burnotte *et al.* 2004, Mohamedelhassan and Shang 2001). Ever since Casagrande in 1939 reported its successful application for stabilizing a long railroad cutting, EO has been extensively applied to numerous field and laboratory tests such as slope stabilization (Casagrande 1952), embankment stabilization (Bjerrum *et al.* 1967, Chappell and Burton 1975, Fetzner 1967), and foundation reinforcement (Chew *et al.* 2004, Estabragh *et al.* 2014, Lee and Shang 2011, Rittirong *et al.* 2008, Wang *et al.* 2016, Wang *et al.* 2018b, Liu *et al.* 2017, Fu *et al.* 2018). However, corrosion of anodes during the tests causes severe loss in electric potential, reducing the consolidation effect (Mohamedelhassan and Shang 2001, Zhou *et al.* 2015).

Electrochemical stabilization improves the engineering properties of soft soils by injecting chemical agents into soil during the EO process. Gray and Schlocker (1969) and Gray (1970) introduced the addition of aluminum ions to harden the soft soil. Shang (2004) demonstrated the use of electro-kinetics assisted by inorganic additives, such as CaCl₂ and KCl, as a remedial measure for in situ stabilization of coastal marine deposits. Ozkan *et al.* (1999) investigated the injection of aluminum and phosphate ions to stabilize kaolinite. Their results show a 500% to 600% increase in the strength of the treated samples. Lefebvre and Burnotte (2002) investigated the injection of a saline solution to minimize power loss between electrodes and soil

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and thereby improve the performance of electro-osmotic consolidation. Mohamedelhassan and Shang (2003) used solutions of 15% CaCl_2 and 10% $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ to improve soft soil; their results showed the significant effect of electro-migration in transporting the cations in the permeating solutions from the anode to the cathode. Furthermore, the use of calcium chloride, calcium ions, and electrolyte solutions to increase the consolidation effect were introduced in numerous laboratory and field tests (Alshawabkeh *et al.* 2004, Asavadorndeja and Glawe 2005, Chien *et al.* 2014, Otsuki *et al.* 2007, Ou *et al.* 2009a).

In the case of EO treatment without electrochemical stabilization, the primary goals are reduction of water content and improvement of shear strength. Meanwhile, cementation is mainly generated by electrochemical reactions at the electrodes during the treatment period, which leads to precipitation of iron hydroxides and carbonates to form cementation bonding between the soil particles (Shang *et al.*, 2004). However, two basic reactions occur when lime is employed and added to the soil. First, the ion exchanges between calcium ions and other cations absorbed into the soil minerals surface lead to the flocculation and agglomeration of soil particles. Second, the pozzolanic reaction—resulting from the dissolution of silicon and aluminum from soil minerals under alkaline conditions—permits the formation of the cementitious gels (Chai *et al.* 2016, Ou *et al.* 2015, Wang *et al.* 2010), i.e., calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). Noting that more additive would convert the free water into bound water via electrochemical reaction, more additive would result in larger void ratios and post-construction settlement. Thus, an electrochemical stabilization technique that utilizes lime as a chemical additive is proposed. The predominant mechanism of electrochemical stabilization is the combination of EO dewatering and cementation generated by electrochemical reactions.

Lime has been used as an additive in soil because of noticeable advantages such as non-toxicity and low cost. This research investigates the beneficial changes in the engineering properties of a marine clay using the electro-kinetics technique with lime as the chemical additive. Five specimens were prepared by adding various proportions of lime. The goal of the present research is to explore the feasibility of applying electro-kinetic and electrochemical techniques in the improvement of marine clays. The specific objective of the study is to determine the optimal dose of chemical stabilization agent to be used in the electrochemical treatment. This will pave the way for the application of electrochemical stabilization to field treatment.

2. Materials and Methods

2.1 Experimental Soil

The soil samples were obtained from the Dongtuo reclamation site in Wenzhou, China. The main components of the dredged marine clay were mud and muddy clay. The soil was extremely soft, having water content above the

Table 1 Properties of tested soil

Water content, ω (%)	Liquid limit, ω_L (%)	Plastic limit, ω_P (%)	Specific gravity, G_s	Void ratio, e	Electrical conductivity (S/m)	pH	Degree of saturation, S_r (%)
78	58.6	25.4	2.72	2.34	3.39	8.5	90.7

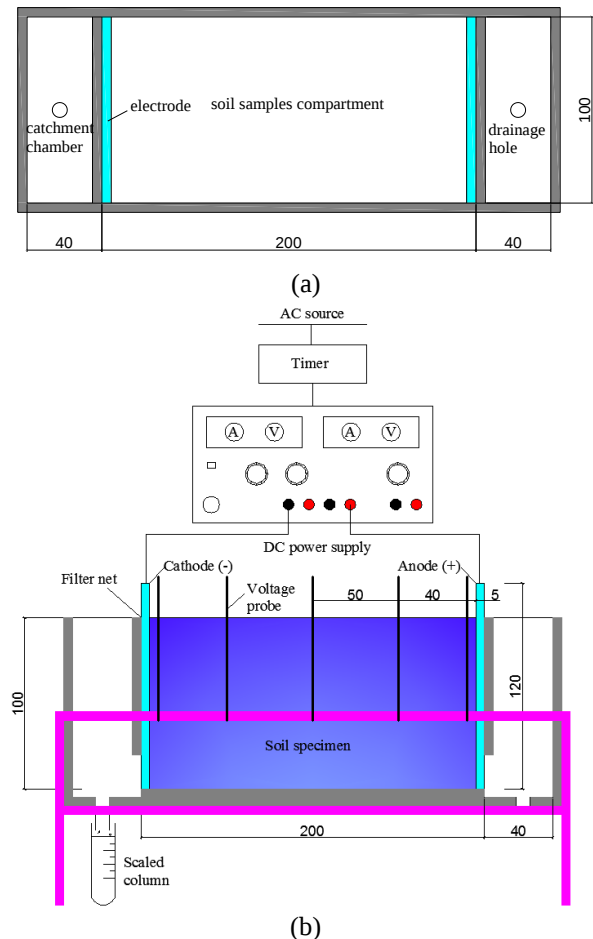


Fig. 1 Schematic of the experimental apparatus (units: mm): (a) plan view and (b) elevation view

liquid limit and virtually no shear strength. The physical properties of the soils are listed in Table 1.

2.2 Experimental Apparatus

A schematic of the apparatus of the experimental used for the EO test is shown in Fig. 1. It consists of an experimental cell, an EO system and a braced steel frame. The details of the three main components are described as follows.

2.2.1 Experimental cell

The model cell used in the experiment is shown in Fig. 1(a). The cell was made of 5-mm-thick acrylic plates. This model cell consisted of a soil sample compartment and two catchment chambers. The soil sample compartment—with an inner length of 200 mm, a height of 100 mm, and a width of 100 mm—was used to contain the soil samples, while the catchment chambers were used to collect water. There was a drainage hole at the bottom of each catchment chamber. The

Table 2 Test program

Test	Lime content (by weight)	Applied voltage [V]	Active time [hours]
T0	0%	20	24
T1	2%	20	24
T2	4%	20	24
T3	6%	20	24
T4	8%	20	24

water accumulated in the vicinity of the cathode and flowed through the hole to the measuring cylinder.

2.2.2 EO system

The EO system consisted of an anode plate, a cathode plate, electric wires, and a DC power supply, as shown in Fig. 1(b). The electrodes used in this study were 5-mm-thick iron plates, 120 mm in height and 100 mm in width. The cathodes were arranged with some holes, 5 mm in diameter, to discharge the water. Filters net were placed behind the cathode plate to filter the drainage. Electric wires connected the electrodes to the DC power supply, with a maximum output power of 30 V and 6 A. It is adjustable for a specific application when fixed allowable ranges of power are required in experimental tests. When DC was applied to the soil through the electrodes, the pore water moved towards the negative electrode.

2.3 Experimental program

Five EO experiments (tests T0, T1, T2, T3, and T4) were conducted in five identical experimental cells with dredged marine clay, wherein the raw clay was mixed with lime in various proportions of 0%, 2%, 4%, 6%, and 8% (dry basis), respectively. A constant voltage of 20 V was applied to the clay samples for a duration of 24 hours. This test program is summarized in Table 2. During the treatment, the electric current, water temperature, and discharge of water were monitored. After the experiments, soil samples from different locations of the rectangular cell were extracted for the measurement of vane shear strength and water content. The main objectives of this research were to study the effect of lime on EO consolidation of the clay and obtain the optimum dose.

2.4 Experimental procedure

To prepare each test, the original soil was sequentially oven-dried, smashed, and ground into powder (Estabragh *et al.*, 2014). Five soil specimens were prepared by mixing the dry clay soil, seawater, and lime at proportions of 0%, 2%, 4%, 6%, and 8% (i.e., mass of dry lime divided by mass of clay soil). The lime was first mixed with seawater to obtain a lime slurry. Then, the soil powder was mixed with the lime slurry using a planetary mixer to obtain remolded samples with a certain water content of 78% (i.e., ratio of water to dry soil, mass/mass). The mixing process was repeated until the required quantity of slurry was obtained. The mixed soil slurry was thoroughly mixed again to make the water content uniform throughout the slurry. This

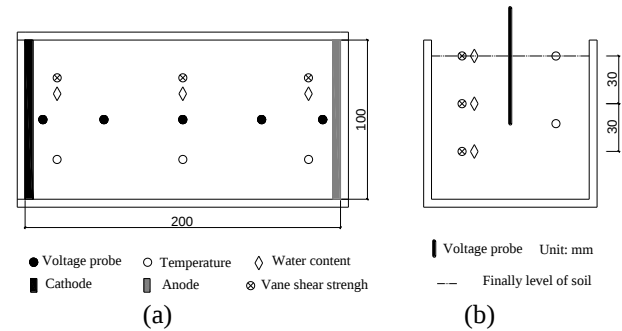


Fig. 2 Monitoring and measurement positions: (a) plan view and (b) elevated view

remolded sample was left stationary for 24 hours to obtain a uniform water content.

Petroleum jelly was smeared on the inner walls of the experimental cell to allow for easy recovery of the soil specimen with minimum disturbance for subsequent parametric studies. After that, two parallel-plate electrodes were placed vertically in the cell in direct contact with the soil specimen to be tested, in accordance with Fig. 1. The soil sample compartment was filled with soil in 20-mm thick layers until a height of approximately 100 mm was achieved. Care was taken to remove air voids through slight tamping of the soil. Five voltage probes were installed at the top of the test cell (as shown in Fig. 2) to monitor the voltage distribution across the specimen during testing.

After installing the soil samples, a constant potential of 20 V was sustained between the electrodes during the entire period of the treatment. The electro-kinetic processes effectively ceased after approximately 24 hours. Prolonged treatment increased energy consumption without a concomitant strength improvement. Therefore, the tests were stopped after 24 hours.

During the tests, the amount of drained water collected in the measuring cylinder, the voltage distribution, and the current were recorded. The temperatures were monitored using thermometers at six different locations, as shown in Fig. 2. After the electro-osmotic consolidation tests, the water content and vane shear strength were measured at distances 20 mm, 100 mm, and 180 mm away from the cathode rows.

The additional tests that were performed distinguish whether the effect of lime was flocculation or stiffness. The container used in these tests was 100 mm in diameter and 150 mm in height. All other experimental conditions were identical to those described in mentioned above. The remolded samples installed in the container were left stationary for 24 hours. No electric current was applied in the additional tests. Vane shear strength tests were carried out at different locations after 24 hours. The shear strengths were 1 kPa, 2 kPa, 2.5 kPa, 3 kPa, and 3.5 kPa for lime proportions of 0%, 2%, 4%, 6%, and 8%, respectively. The average strengths obtained after a 24-hour treatment were 15.8 kPa, 23.3 kPa, 38.3 kPa, 32 kPa, and 27 kPa for tests T0-T4 respectively. In the electrochemical treatment experiment, strengths increased by 143.9%, 241.9%, 195.9%, and 158.8% for lime proportions of 2%, 4%, 6%, and 8%, respectively, compared with EO alone. However,

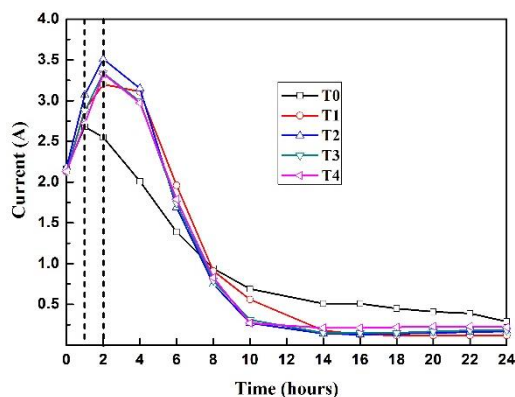


Fig. 3 Current time history for various proportions of lime

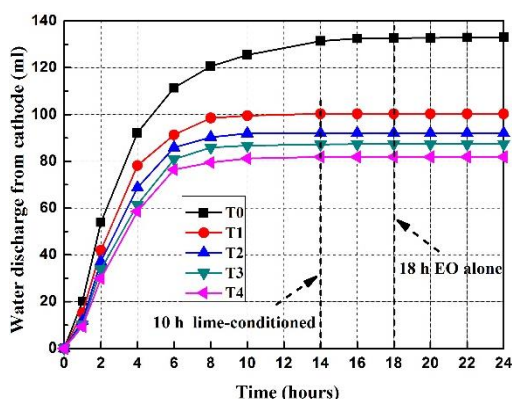


Fig. 4 Drainage time history in tests

the strength increase ratios owing to lime flocculation are only 4.6%, 4.2%, 6.8%, 10.6%, respectively. This low strength means that the effect of lime is flocculation. Thus, the main strength increase is derived from the interaction of EO with lime.

3. Results and discussion

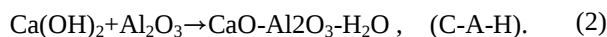
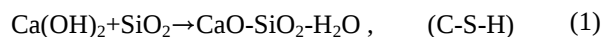
3.1 Current

The currents of these samples were recorded to establish the trend shown in Fig. 3, which plots the electric current history. For all tests, the electric currents first increased and then decreased, in agreement with previous studies (Ou *et al.* 2009b, Peng *et al.* 2015). In the first 2 hours of testing, the most noticeable difference between the electro-kinetic test (T0) and the electrochemical tests (T1-T4) is the increase in current with time. This resulted from the formation of a drainage channel and low interface resistance between the soil and electrodes (Fu *et al.* 2016). After 2 hours, with decreasing water content and salinity, the pathways of conductance in the soil deteriorated (Corwin and Lesch 2005). In addition, anode corrosion occurred during the process of electrolysis, which also increased the interface resistance between the soil and electrodes, eventually reducing the current. Thus, the current decreased sharply after 4 hours of testing. Comparing the currents over all tests, the maximum current, which was obtained during test T2, with 4% lime (dry basis), was approximately

3.51 A—1.31 times the maximum current of test T0. This is attributed to the increase in electrical conductivity of the soil pore fluid resulting from the replacement of the seawater solutes by the chemical additive of lime.

3.2 Discharge of water

The drainage time histories in all tests are shown in Fig. 4. Overall, the electrochemical drainage was much lower than the electro-kinetic drainage. Over 70% of the total discharge volumes occurred in the first 4 hours for all tests. At the end of testing, the total volumes of the discharged water were 133 ml, 101 ml, 92 ml, 78 ml, and 81 ml for tests T0, T1, T2, T3, and T4, respectively. This indicates that the electrochemical additives do not improve drainage capability. These results can be explained by a series of chemical reactions between the soil and lime. The reactions between the calcium ions from lime hydration and the released soluble silica and alumina create cementitious materials such as C-S-H and C-A-H, respectively, which consist of solid products of hydration and water (Le Runigo *et al.* 2009). These reactions can be clarified using the following chemical equations (Mallela *et al.* 2004, Yong and Ouhadi 2007)



The cementing agents containing water explain why test T0 exhibited the greatest water drainage. Furthermore, test T0 required 18 hours for water drainage from the cathode to cease, whereas tests T2-T4 only needed 14 hours to achieve this condition. Hence, the treatment time can be shortened by approximately 22.2% by adding 4% lime to the soil.

3.3 Temperature

The temperature data are presented in Fig. 5. The thermometers recorded the temperatures at electrode rows and different soil depths. The temperature in the soil was initially recorded as being between 27°C and 28°C. Fig. 5(a) shows the temperature distributions (at time $t = 4$ hours, depth of 0 mm and 50 mm) between the cathode and anode. With increasing distance from the cathode, the temperature rose. The increase in temperature at the anode was much higher than that at the cathode. The temperature at a depth of 50 mm was much higher than that at a depth of 0 mm. In test T2 at a depth of 0 mm, compared to the highest temperature of 57.6°C at the anode, there was a temperature difference of approximately 10°C between the cathode and anode. Meanwhile, the maximum temperature approximately 92°C was obtained at distances 100 mm away from the cathode in the same specimen for the test T2. The electric resistance of the soil near the anode was higher than that near the cathode owing to the water move from the anode to the cathode, which led to a higher temperature according to the Joule heating. Moreover, as the proportion of lime increased in the range of 0% to 4%, the temperature showed a corresponding increment, and the maximum temperature was achieved in the sample containing 4%

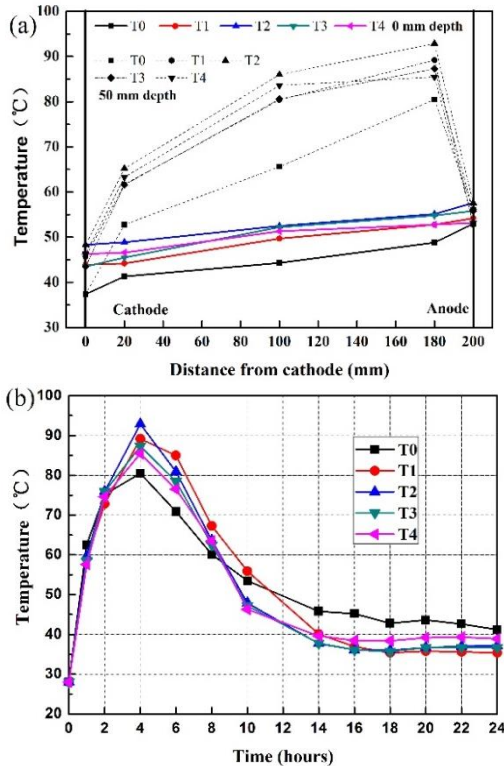


Fig. 5 (a) Temperature distributions between anode and cathode at time $t = 4$ h with a depth of 0 cm and 50 mm and (b) temperature time history near the anode at a depth of 5 cm

lime. Heat generation is proportional to the level of electrical power applied (Joule heating), which is influenced by the applied voltage (Burnotte *et al.* 2004). The Joule heat can be calculated from the measurement of voltage, electrical current and time, i.e., $Q=VIt$, where the voltage, V , and time, t , are homogeneous. Thus, the temperature is determined by the electrical current. From the electric current curves (Fig. 3) the maximum current occurs in test T2, which may explain the temperature phenomenon.

The temperature histories near the anode at a depth of 5 cm are plotted in Fig. 5(b). The results show that in the first 2 hours, the temperature is nearly identical in all tests. The temperatures of all samples increase sharply at the beginning of the test and achieve their maximum values at 4 hours, for which the highest temperature was 92°C, in test T2. After reaching the maximum temperature, the temperatures of the electrochemical tests decreased more quickly than that of the EO test. Comparing Fig. 5(a) with Fig. 5(b) at 4 hours, the temperatures inside the treated zone were higher than those recorded at the surface. This occurs because heat cannot be emitted from within the soil. The water content of the soil varies predominantly due to electroosmotic advection, whereas natural drying and evaporation could also decrease water content to some extent, depending on the time and environmental conditions such as temperature (Jayasekera 2015). However, higher temperatures in the soil could make soft clay foundation reinforcement more efficient.

3.4 Water content

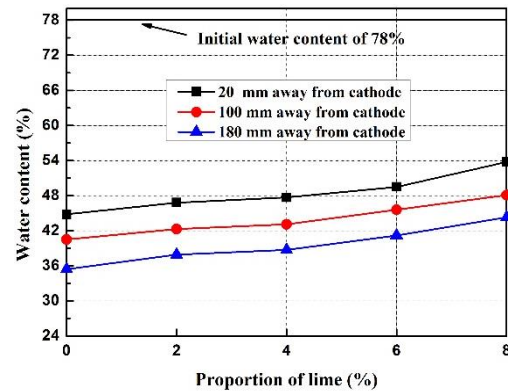
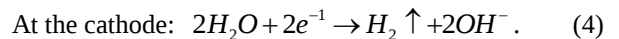
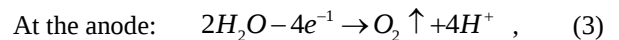


Fig. 6 Distribution of water content versus proportion of lime

The distributions of water content between the cathode and anode for the various proportions of lime are plotted in Fig. 6. The water content of the consolidated soil decreased from the initial 78% to between 35% and 53%. It can be noted from Fig. 6 that the water content near the anode decreased more than that near the cathode owing to the drainage water direction from the anode to the cathode. Moreover, the measured water content increased with the proportion of lime at a given location. As shown in Fig. 6, the water contents near the anode were 35.4%, 37.9%, 38.7%, 41.2%, and 44.3% for soil conditioned with 0%, 2%, 4%, 6%, and 8% lime, respectively. It can be reasoned that the lime addition to the soil cannot promote electro-osmotic dewatering during the EO processes. As shown in Eqs. (1) and (2), the C-S-H and C-A-H cementing agents contain water for electrochemical tests T1-T4, resulting in increased water content compared with the EO test, T0. The temperature is another non-negligible factor for water content variation. Especially for test T2, with 4% lime, the maximum temperature—approximately 92°C—promoted water evaporation, thereby decreasing the water content.

In addition to the C-S-H and C-A-H chemical reactions that bind water in hydrates, the electrodes cause electrolysis of the water. Applying an electrical potential via the electrodes embedded in soil generates oxidation at the anode and reduction at the cathode through the following reactions



From what has been discussed above, when a soil is subjected to EO processing, the variations of water content of the experimental soil are affected by three factors, (a) electro-kinetic induced dewatering associated with EO, (b) natural evaporation and drying process (Jayasekera 2015), and (c) various chemical reactions.

3.5 Vane shear strength C_u

Vane shear tests were conducted using a miniature vane shear apparatus after soil treatment in all tests, and the test

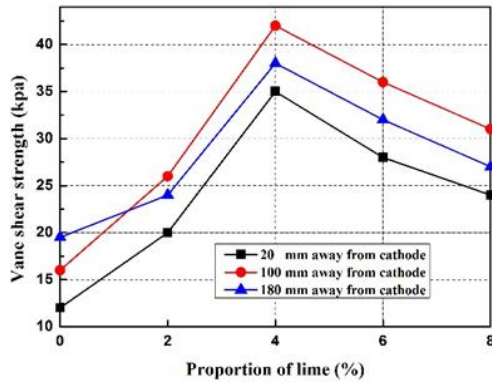


Fig. 7 Vane shear strength variation relative to proportion of lime

Table 3 Summary of strength results

Tests	C_u (kPa)		Increase in C_u due to	
	Additional test	Average C_u after EO test	Flocculation	Electrochemical treatment
T0	1	15.8	0	0
T1	2	23.3	4.6	57.4
T2	2.5	38.3	4.2	158.8
T3	3	32	6.8	116.2
T4	3.5	27	10.6	82.4

* Increase in C_u due to Flocculation (%) = $(C_{u \text{ additional}} - 1)/(C_{u \text{ Average}} - C_{u \text{ additional}}) \times 100\%$

Increase in C_u due to Electrochemical (%) = $(C_{u \text{ Average}} - C_{u \text{ EO alone}})/C_{u \text{ EO alone}} \times 100\%$, where $C_{u \text{ EO alone}} = 15.8$ is shear strength in test T0

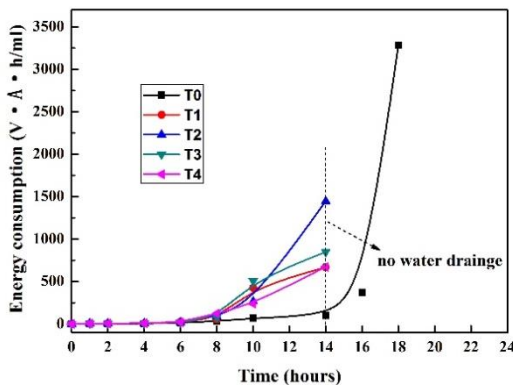


Fig. 8 Energy consumption time history

results are shown in Fig. 7. It is evident that all electrochemical-treated specimens exhibited higher shear strengths that lie well above the EO-treated specimens, demonstrating the effect of the treatment. Fig. 7 shows that the most significant increases in the vane shear strengths occurred with specimens at distances 100 mm away from the cathode in the experiment cells. The highest strength was measured at this distance in test T2 (4% lime). Therefore, it can be concluded that the optimum dose of lime is 4% for electrochemical treatment.

The vane shear strengths of the soil after electrochemical treatment range from 20 kPa to 42 kPa, depending on the locations relative to cathode, compared with 12 kPa to 19.5 kPa for the electro-osmotic treatment

soil specimens from the same locations. The soil specimens adjacent to the anode had higher strength than those adjacent to the cathode, which was attributed to the EO-generated water transport; however, the highest strength was obtained at distances 100 mm away from the cathode in the same specimen, attributed to the combination of EO and electrophoresis processes cause particles to converge in the middle. Lime-slurry reactions produce cementing agents called calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), in which soil particles cement filling the voids of flocculated fabric in the soil with cementitious compounds marginally reduces compressibility but significantly increases strength (Zhang *et al.* 2015). Among all soil specimens after electrochemical treatment, the soil of test T2 (4% lime) had the highest shear strengths at all locations. Its strength increases relative to the EO test, T0, are 23 kPa, 26 kPa, and 18.5 kPa for locations at distances 20 mm, 100 mm, and 180 mm away from the cathode. These increases are attributed to cementation by electro-osmotic and electrochemical effects.

The cementation is limited by the available amount of silica and alumina that exist in the soil. Therefore, the shear strength decreased for proportions of lime more than 4%. Furthermore, the strength increment near the cathode was much higher than that near the anode and in the middle of sample. Thus, the non-uniform effect of electro-osmotic consolidation was improved by this method. The average strength results in all tests were as follows:

In the electrochemical treatment experiment, vane shear strengths increased by 57.4%, 158.8%, 116.2%, and 82.4% for lime proportions of 2%, 4%, 6%, and 8%, respectively, as compared with EO alone. However, vane shear strengths increase from lime flocculation is only 4.6%, 4.2%, 6.8%, and 10.6% respectively. These low strengths are resulted from the effect of lime flocculation.

The vane shear strengths of the electrochemical treatments were improved owing to the following factors. (1) The water content decrease resulted from EO dewatering and the evaporation generated by the high temperatures. (2) Flocculation results from ions exchanges permitted by the reduction in water layer thickness, causing the soil particles to agglomerate, thereby changing the soil texture. (3) The formation of cementation products, such as C-S-H and C-A-H, which bind the clay particles together, causes significant increases in strength.

3.6 Energy consumption

The coefficient of energy consumption, E_c , is introduced to study the efficiency of the EO process. It reflects the amount of electricity required to discharge the unit volume of water

$$E_c = \frac{U \int_{t_1}^{t_2} I dt}{V_{t_2} - V_{t_1}} \quad (5)$$

where E_c is the energy consumption per unit volume of water, U is the applied electrical potential, I is the current, t is time, and V_{t_2} and V_{t_1} are the volumes of water at the times t_2 and t_1 , respectively. Fig. 8 shows the energy consumption histories for each test. The results show that in the first 6

hours, the coefficients of energy consumption are practically the same for each test. Then, with the application of electrochemical treatment, the energy consumption increased compared with electro-osmotic treatment, which was attributed to the reduction in the thickness of the diffused water layer due to ion exchange. After 14 hours, the energy consumption in the electrochemical tests reached their maximum values of 669 V·A·h/ml, 1446 V·A·h/ml, 848 V·A·h/ml, and 672 V·A·h/ml for tests T1, T2, T3, and T4, respectively. For test T0, the energy consumption increased significantly for the last 10 hours, mainly because more energy consumption was consumed in the discharge of free water than in the discharge of weakly bound water. Based on the data mentioned above, the coefficients of energy consumption in the electrochemical treatments were much high than that of the electro-osmotic test in the stage of discharge water.

4. Conclusions

In this study, an electrochemical treatment method was proposed to improve dredged marine clay slurry. An electro-osmotic test and four electrochemical tests with various proportions of lime (2%, 4%, 6%, and 8%) were conducted on dredged marine clay. The test results demonstrated that electrochemical treatment is an effective method. Based on the measurements and analyses, the following conclusions can be drawn.

- Employing electrochemical treatment increases shear strength by 57% to 158.8% compared to electro-osmotic treatment. The best treatment result was observed for the electrochemical tests using 4% lime. The highest strength was obtained in the middle of the cathode and anode.
- Low doses of lime were used as a flocculation agent in this study.
- It is evident that an increase of current and heat generation were observed owing to the addition of lime, leading to an increase of electro-osmotic efficiency.
- The water content of the electrochemical tests was higher than that of the electro-osmotic test owing to the generation of cementation agents containing water. The volume of drainage water was not increased, but the necessary treatment time was shortened by approximately 22.2% by adding 4% lime test. Furthermore, the energy consumption of the electrochemical tests was much higher than that of the electro-osmotic test.

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References

- Alshawabkeh, A.N., Sheahan, T.C. and Wu, X. (2004), "Coupling of electrochemical and mechanical processes in soils under DC fields", *Mech. Mater.*, **36**(5-6), 453-465.
- Asavadorndej, P. and Glawe, U. (2005), "Electrokinetic strengthening of soft clay using the anode depolarization method", *Bull. Eng. Geol. Environ.*, **64**(3), 237-245.
- Bjerrum, L., Moum, J. and Eide, O. (1967), "Application of electro-osmosis to a foundation problem in a Norwegian quick clay", *Géotechnique*, **17**(3), 214-235.
- Burnotte, F., Lefebvre, G. and Grondin, G. (2004), "A case record of electroosmotic consolidation of soft clay with improved soil-electrode contact", *Can. Geotech. J.*, **41**(6), 1038-1053.
- Cai, Y., Qiao, H., Wang, J., Geng, X., Wang, P. and Cai, Y. (2017), "Experimental tests on effect of deformed prefabricated vertical drains in dredged soil on consolidation via vacuum preloading", *Eng. Geol.*, **222**, 10-19.
- Casagrande, L. (1952), "Electro-osmotic stabilization of soils", *J. Boston Soc. Civ. Eng.*, **39**(1), 51-83.
- Chai, Z., Zhang, Y. and Scheuermann, A., (2016), "Study of physical simulation of electrochemical modification of clayey rock", *Geomech. Eng.*, **11**(2), 197-209.
- Chappell, B.A. and Burton, P.L. (1975), "Electro-osmosis applied to unstable embankment", *J. Geotech. Eng.*, **101**(8), 733-740.
- Chew, S.H., Karunaratne, G.P., Kuma, V.M., Lim, L.H., Toh, M.L. and Hee, A.M. (2004), "A field trial for soft clay consolidation using electric vertical drains", *Geotext. Geomembr.*, **22**(1-2), 17-35.
- Chien, S.C., Teng, F.C. and Ou, C.Y. (2015), "Soil improvement of electroosmosis with the chemical treatment using the suitable operation process", *Acta Geotech.*, **10**(6), 813-820.
- Chu, J., Yan, S.W. and Yang, H. (2000), "Soil improvement by the vacuum preloading method for an oil storage station", *Géotechnique*, **50**(6), 625-632.
- Corwin, D.L. and Lesch, S.M. (2005), "Apparent soil electrical conductivity measurements in agriculture", *Comput. Electron. Agric.*, **46**(1-3), 11-43.
- Estabragh, A.R., Naseh, M. and Javadi, A.A. (2014), "Improvement of clay soil by electro-osmosis technique", *Appl. Clay Sci.*, **95**, 32-36.
- Fetzer, C.A. (1967), "Electro-osmotic stabilization of West Branch Dam", *J. Soil Mech. Found. Div.*, **93**(4), 85-106.
- Fu, H., Cai, Y., Wang, J. and Wang, P. (2017), "Experimental study on the combined application of vacuum preloading-variable-spacing electro-osmosis to soft ground improvement", *Geosynth.*, **24**(1), 72-81.
- Fu, H., Fang, Z., Wang, J., Chai, J., Cai, Y., Geng, X., Jin, J. and Jin, F. (2018), "Experimental comparison of electro-osmotic consolidation of wenzhou dredged clay sediment using intermittent current and polarity reversal", *Mar. Georesour. Geotechnol.*, **36**(1), 131-138.
- Gray, D.H. (1970), "Electrochemical hardening of clay soils", *Géotechnique*, **20**(1), 81-93.
- Gray, D.H. and Schlocker, J. (1969), "Electrochemical alteration of clay soils", *Clay. Clay Miner.*, **17**(5), 309-322.
- Jayasekera, S. (2015), "Electrokinetics to modify strength characteristics of soft clayey soils: A laboratory based investigation", *Electrochimica Acta*, **181**, 39-47.
- Jones, C.J.F.P., Lamont-Black, J. and Glendinning, S. (2011), "Electrokinetic geosynthetics in hydraulic applications", *Geotext. Geomembr.*, **29**(4), 381-390.
- Le Runigo, B., Cuisinier, O., Cui, Y.J., Ferber, V. and Deneele, D.

- (2009), "Impact of initial state on the fabric and permeability of a lime-treated silt under long-term leaching", *Can. Geotech. J.*, **46**(11), 1243-1257.
- Lee, J.K. and Shang, J.Q. (2011), "Influencing factors on electrical conductivity of compacted kaolin clay", *Geomech. Eng.*, **3**(2), 131-151.
- Lefebvre, G. and Burnotte, F. (2002), "Improvements of electroosmotic consolidation of soft clays by minimizing power loss at electrodes", *Can. Geotech. J.*, **39**(2), 399-408.
- Liu, F., Fu, H., Wang, J., Mi, W., Cai, Y. and Geng, X. (2017), "Influence of soluble salt on electro-osmotic consolidation of soft clay", *Soil Mech. Found. Eng.*, **54**(1), 49-55.
- Mallela, J., Von Quintus, P.E.H. and Smith, K.L. (2004), *Consideration of Lime-Stabilized Layers in Mechanistic-Empirical Pavement Design*, The National Lime Association, Arlington, Virginia, U.S.A.
- Mitchell, J.K. and Soga, K. (1993), *Fundamentals of Soil Behaviour*, John Wiley & Sons, Hoboken, New Jersey, U.S.A.
- Mohamedelhasan, E. and Shang, J.Q. (2001), "Effects of electrode materials and current intermittence in electro-osmosis", *Proc. Inst. Civ. Eng. Ground Improv.*, **5**(1), 3-11.
- Mohamedelhasan, E. and Shang, J.Q. (2003), "Electrokinetics-generated pore fluid and ionic transport in an offshore calcareous soil", *Can. Geotech. J.*, **40**(6), 1185-1199.
- Otsuki, N., Yodsudjai, W. and Nishida, T. (2007), "Feasibility study on soil improvement using electrochemical technique", *Construct. Build. Mater.*, **21**(5), 1046-1051.
- Ou, C.Y., Chien, S.C. and Chang, H.H. (2009a), "Soil improvement using electroosmosis with the injection of chemical solutions: field tests", *Can. Geotech. J.*, **46**(6), 727-733.
- Ou, C.Y., Chien, S.C. and Wang, Y.G. (2009b), "On the enhancement of electroosmotic soil improvement by the injection of saline solutions", *Appl. Clay Sci.*, **44**(1-2), 130-136.
- Ou, C.Y., Chien, S.C., Yang, C.C. and Chen, C.T. (2015), "Mechanism of soil cementation by electroosmotic chemical treatment", *Appl. Clay Sci.*, **104**, 135-142.
- Ozkan, S., Gale, R.J. and Seals, R.K. (1999), "Electrokinetic stabilization of kaolinite by injection of Al and PO_4^{3-} ions", *Proc. Inst. Civ. Eng. Ground Improv.*, **3**(4), 135-144.
- Peng, J., Ye, H. and Alshawabkeh, A.N. (2015), "Soil improvement by electroosmotic grouting of saline solutions with vacuum drainage at the cathode", *Appl. Clay Sci.*, **114**, 53-60.
- Rittirong, A., Douglas, R.S., Shang, J.Q. and Lee, E.C. (2008), "Electrokinetic improvement of soft clay using electrical vertical drains", *Geosynth.*, **15**(5), 369-381.
- Shang, J.Q. (1997), "Zeta potential and electroosmotic permeability of clay soils", *Can. Geotech. J.*, **34**(4), 627-631.
- Shang, J.Q., Mohamedelhasan, E. and Ismail, M. (2004), "Electrochemical cementation of offshore calcareous soil", *Can. Geotech. J.*, **41**(5), 877-893.
- Wang, D., Kang, T., Han, W., Liu, Z. and Chai, Z. (2010), "Electrochemical modification of the porosity and zeta potential of montmorillonitic soft rock", *Geomech. Eng.*, **2**(3), 191-202.
- Wang, J., Cai, Y., Ma, J., Chu, J., Fu, H., Wang, P. and Jin, Y. (2016), "Improved vacuum preloading method for consolidation of dredged clay-slurry fill", *J. Geotech. Geoenviron. Eng.*, **142**(11), 06016012.
- Wang, J., Cai, Y., Ni, J., Geng, X. and Xu, F. (2018a), "Effect of sand on the vacuum consolidation of dredged slurry", *Mar. Georesour. Geotechnol.*, **36**(2), 238-244.
- Wang, J., Fu, H., Liu, F., Cai, Y. and Zhou, J. (2018b), "Influence of the electro-osmosis activation time on vacuum electro-osmosis consolidation of a dredged slurry", *Can. Geotech. J.*, **55**(1), 147-153.
- Wang, J., Ma, J., Liu, F., Mi, W., Cai, Y., Fu, H. and Wang, P. (2016), "Experimental study on the improvement of marine clay slurry by electroosmosis-vacuum preloading", *Geotext. Geomembr.*, **44**(4), 615-622.
- Wang, J., Ni, J., Cai, Y., Fu, H. and Wang, P. (2017), "Combination of vacuum preloading and lime treatment for improvement of dredged fill", *Eng. Geol.*, **227**, 149-158.
- Yong, R.N. and Ouhadi, V.R. (2007), "Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils", *Appl. Clay Sci.*, **35**(3-4), 238-249.
- Zhou, J., Tao, Y.L., Xu, C.J., Gong, X.N. and Hu, P.C. (2015), "Electro-osmotic strengthening of silts based on selected electrode materials", *Soil. Found.*, **55**(5), 1171-1180.

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