The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Ground improvement on Clay with Interbedded Sand Using Electroosmotic Chemical Treatment

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ABSTRACT

Electroosmotic chemical treatment (ECT) is a ground improvement method for soft clayey soil that injects chemical solutions into the soil during electroosmosis to increase soil shear strength. However, previous studies have shown the ECT method was inadequate when applied to soft clay with interbedded sand seams. An appropriate process of ECT for soft clay with interbedded sand seams was developed to avoid loss of chemical solutions from the interbedded sand seams during electroosmosis and to improve the soft clay. Seven tests of ECT were performed in order to assess an appropriate process of ECT for soft clay with interbedded sand seams. The results show the permeability coefficient of the interbedded sand seams could be effectively reduced to 10^{-5}-10^{-6} m/s by first injecting the sodium silicate solution into the sand seam by pressure, followed by injecting the calcium chloride solution by electroosmosis. Therefore, the injection of chemical solutions could be effectively flowed in the soft clay during electroosmosis, resulting in strength improvement of the soft clay after decreasing the permeability coefficient of the interbedded sand seams.

1. INTRODUCTION

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Since 1930 electroosmosis has been used as a tool in geotechnical engineering to improve the mechanical strength of soft clay. Casagrande and Casagrande (1986) attempted to improve the strength of sensitive silty clay by electroosmosis. Fundamental aspects of electroosmosis in soil were reported by Gray and Mitchell (1967). The main mechanism of improving soft clay for electroosmosis is dewatering, which leads to consolidation and a consequent increase in strength of the soil until intergranular stresses are in equilibrium with the tension that develops in the pore water during electroosmosis.

To enhance the effect of electroosmotic improvement, injection of chemical solutions into soil from the anode or cathode during electroosmosis has been adopted in recent years (Lefebvre 2002, Alshawabkeh 2004, Asavadorndeja 2005, Paczkowska 2005, Otsuki 2007, Ou 2009a, Ou 2009b, Chien 2009; Abdullah 2010; Chien 2010). The technique sometimes is termed as the electroosmotic chemical treatment (ECT). It has been found, in the literature, that the effect of electroosmosis can be enhanced by injecting chemical solutions during electroosmosis, such as NaCl, KCl, $CaCl_2$, aluminum ions, phosphoric ions, methacrylate poly cations, $Al_2(SO_4)_3$, Mg $(CH_3COO)_2$, $MgSO_4$, $Mg(NO_3)_2$, $ZnSO_4$, $AgNO_3$, NaOH, and Na_2CO_3. With the ECT soil improvement, a substantial strength increase can be gained by chemical reactions in the soil matrix including cation exchange, cementation, and precipitation other than consolidation. However, most of the ECT soil improvement only occurs in the region near the anode or cathode. Asavadorndeja (2005) applied the electrockinetic strengthening of soft clay using the anode depolarization method for increase in improvement region. Increases in strength up to 170% immediately after treatment and up to 570% after a 7 days curing were measured. The depolarization method can enhance the improvement area nearly covered the entire specimen from the anode to the cathode. Chien (2010) made good progress in an electroosmotic application by installing a relay pipe between the anode and the cathode. The results showed that the cementation area nearly covered the entire specimen and its average cone resistance could be raised to nine times more than that of the untreated soil.

Despite many studies in the past, ECT has not yet received a wide application, because some uncertainties remain. For example, long-term performance of improved soil is not fully understood. The ECT still needs a quite long treatment time, for instance, Alshawabkeh (2003) spent over 14 days to treat the soil in the laboratory and Burnotte (2004) 48 days in the field. The strength increase may not be uniform across the cross section of the sample and with depth (Ozkan 1999). Caron (1971) also found from some unsuccessful applications that continuous sand and silt layers in the subsoil are not favorable for ECT because the relatively high conductivity of such layers causes loss of chemical solutions during electroosmosis. The loss of chemical solutions might affect the efficiency of ECT. However, a clay strata with interbedded permeable soils such as sand or silt are often encountered in the field and few studies on the ECT soil improvement on such a soil stratum were conducted in the past.

In this study, a small scale of test cell with a pair of electrodes was design to develop an appropriate ECT process for clay strata with sand layers. A clay stratum overlying a sand layer was used to make the relatively high conductivity of sand layer that may cause the loss of chemical solutions during ECT. As a matter of fact, many pairs of electrodes, anode and cathode, are normally used for tens of meters wide in the field and a quite complicate subsoil condition may exist in the field. The test cell and a layered (clay/sand) soil are certainly different from what is normally found in the field. Therefore, the objective of this study is to develop an appropriate ECT process for soft clay with interbedded sand during ECT through the laboratory ECT tests. It is expected that the developed process would be applicable for the field condition with more complicated subsoil conditions.

2. Experimental details

2.1. Experimental cell

A schematic diagram of the test set-up is shown in Fig. 1. The test container for the electroosmotic tests was made of plexiglas plate and was 0.23 m wide, 0.44 m long, and 0.32 m deep. Two platinum (Pt) coated titanium (Ti) meshed plates to make only a pair of electrodes during electroosmosis, 350 mm in span, connected to a power supply device, served as the anode and cathode, respectively. A chamber connected to the anode, 20 mm wide and 150 mm long, was used to store a very small amount of injected chemical solutions, allowing the chemical solutions uniformly injected into the soil under the electric field. The same dimension of another chamber connected to the cathode was used to store drained water, which would be discharged through a drained tube. The top plate also served as a bearing plate, on which air pressure acted to provide the designated consolidation pressure. Several O-rings were fastened on both ends of the cell to prevent leakage.

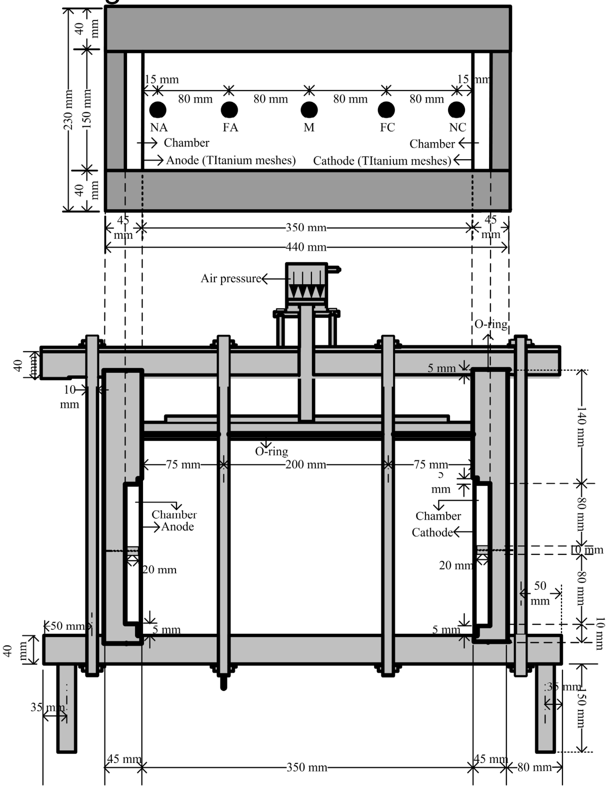

Fig. 1 Schematic configuration of the electroosmotic cell (top view and side view).

2.2. Description of soil specimen

Kaolinite and very clean sand, of which the basic properties are listed in Table 1, were used in this study. The particle size distribution of the sand was 0.3-3 mm. The objective of selected sand was to make the relatively high conductivity of sand layer that causes loss of chemical solution during electroosmosis. Kaolinite powder was thoroughly mixed with a sufficient amount of distilled deionized water by a mechanical mixer so its water content was 60%. The sand was first placed and then layers of kaolinite slime were placed in the test container. The purpose of adding water was to ensure more than 100% saturation and high workability. At each layer, air bubbles were eliminated by a vibrator. After putting sand and slime of kaolinite in the experimental cell, it was covered with a filter paper, and then the electrode (platinum coated titanium mesh) was attached. The samples for the electroosmotic test were then made by applying 30 kPa of the vertical pressure to the soil by increments to reproduce the normally consolidated condition and the state of stress at a depth of about 3 m below the ground surface. Thus, the water content of the sample (kaolinite) following consolidation equaled 51%. Table 1 lists the physical properties of the sample. Table 1 shows the liquid limit and plastic limit are 46% and 25%, respectively.

Table 1. Summary of soil properties.

Kaolin		Sand	
Liquid limit (%)	46	particle size (mm)	0.3-3
Plastic limit (%)	25	Specific gravity, Gs	2.62
Plastic index (%)	21	SiO_2 (%)	99.5
Particle size (μm)	1.0-2.0	Al_2O_3 (%)	0.7
Specific gravity, G_s	2.61	Fe_2O_3 (%)	0.02
SiO_2 (%)	44.5	Silt (%)	0.25
Al_2O_3 (%)	39.5	Loss On Ignition (%)	0.25
TiO_2 (%)	1.0		
MgO (%)	0.07		
Na_2O (%)	0.52		
Fe_2O_3 (%)	0.5		
CaO (%)	0.05		
K_2O (%)	0.04		
Loss On Ignition (%)	13.5		

2.3. Test procedure

The sand was first placed and then layers of kaolinite slime were placed in the test container. Sodium silicate solution was injected into the sand seam by pressure before ECT. The sample (sand and kaolinite) was consolidated at 30 kPa pressure in increments. After setting up the specimen, the sample was treated by injecting chemical solutions during electroosmosis under the consolidation pressure of 30 kPa. ECT was carried out by injecting calcium chloride over different treatment times (24, 48, 72, and 168 hours). For description, the symbol TC denotes electroosmosis with injection of calcium chloride through the anode. Two chemical solutions, i.e., calcium chloride and sodium silicate, were used as the injection material. The calcium chloride solution was first injected over different treatment times (24, 48, and 72 hours) through the anode, followed by injection of the sodium silicate solution over different treatment times (144, 120, and 96 hours) during electroosmosis. For description, the symbol TCS denotes electroosmosis with injection of calcium chloride and sodium silicate through the anode. The electroosmosis was continued until a total of 7 days (168 hours) of treatment time was reached for type TCS. Treatment time was 7 days according to experience (Ou et al., 2009a).

A voltage gradient is very important and major parameter in relation the length of the experimental cell and applied voltage for electroosmosis. A voltage gradient of 50 V/m was applied for field application, as suggested by Mitchell (1993). The distance (length) between the anode and cathode was 350 mm in the experimental cell. The voltage gradient of 50 V/m was applied to simulate field application for all tests. Hence, a voltage of 17.5 V (0.35 m×50 V/m) was applied between the anode and cathode in all tests. The thickness of the strata (clay/sand) was equal to electrode length. The improvement region increased in strength of the clay and changes in permeability of the sand was expected. Hence, the experiment can provide the effective applicability of the appropriate process of ECT in the field for soft clay with interbedded sand.

The permeability coefficient of the interbedded sand before and after ECT was measured in experimental cell under 30 kPa pressure by falling head test. The soil's cone resistance before and after ECT was also measured by a specially designed laboratory cone penetration apparatus. It was attached to an adjustable rod of 0.0092 m in diameter that could measure the cone resistance at different locations and depths. The cone resistance values were measured at various locations throughout the specimen before and after treatment, as shown in Fig. 1.

3. Results and discussion

Seven tests of ECT were performed. The calcium chloride was injected over different treatment times (24, 48, 72, and 168 hours) during electroosmosis for samples of TC1, TC2, TC3, and TC4. The calcium chloride solution was first injected over different treatment times (24, 48, and 72 hours), followed by injection of the sodium silicate solution over different treatment times (144, 120, and 96 hours) during electroosmosis for samples of TCS1, TCS2, and TCS3. The initial cone resistance in soft clay obtained from the laboratory cone penetration apparatus was about 40 kPa. The initial permeability coefficient of the interbedded sand was 1.58×10^{-4} m/s.

3.1. Permeability coefficient of sand

The permeability coefficients of interbedded sand after ECT for samples of 24 (TC1), 48 (TC2), 72 (TC3), and 168 (TC4) hours are shown in Fig. 2. When different treatment times of calcium chloride were injected, in conjunction with 24, 48, 72 and 168 hour treatment times, significant decrease in the permeability coefficient of the interbedded sand were observed. The permeability coefficient of interbedded sand was

5.1×10^{-5} m/s, 1.3×10^{-6}m/s, 9.9×10^{-7} m/s, and 4.2×10^{-7} m/s when 24, 48, 72, and 168 hour treatment times were used, respectively. The initial permeability coefficient of the interbedded sand was 1.58×10^{-4} m/s. Therefore, the permeability coefficient of interbedded sand could be effectively reduced to 10^{-5}-10^{-6} m/s by first injecting the sodium silicate solution into the sand seam by pressure before ECT, followed by injecting the calcium chloride solution during electroosmosis.

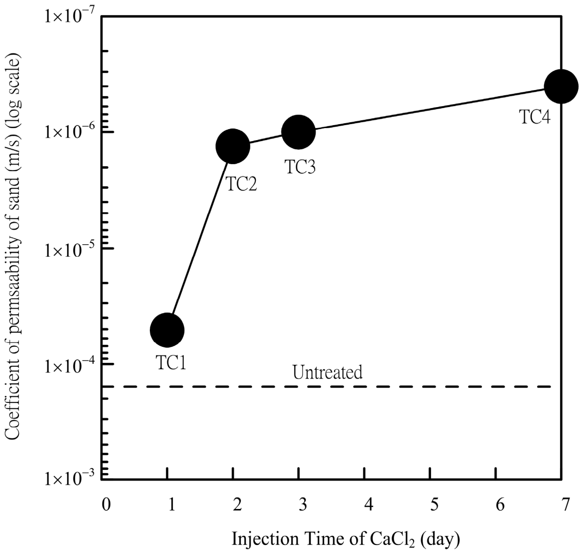

Fig. 2 Effect of different treatment times with injection of calcium chloride on the permeability coefficient of sand.

The permeability coefficients of interbedded sand after ECT for the samples of TCS1, TCS2, and TCS3 are shown in Fig. 3. When calcium chloride (24, 48, and 72 hour) followed by sodium silicate (144, 120, and 96 hour) were injected, a significant change in the permeability coefficient of interbedded sand was observed. The permeability coefficient of the interbedded sand was 2.7×10^{-7} m/s, 8.3×10^{-8} m/s, and 6.6×10^{-8} m/s when 24, 48, and 72 hour treatment times with calcium chloride and 144, 120, and 96 hour treatment times with sodium silicate were used, respectively. Hence, the permeability coefficient of the interbedded sand could be more effectively reduced to 10^{-7}-10^{-8} m/s by first injecting the sodium silicate solution into the sand seam by pressure before ECT, followed by injecting the calcium chloride solution and sodium silicate solution during electroosmosis.

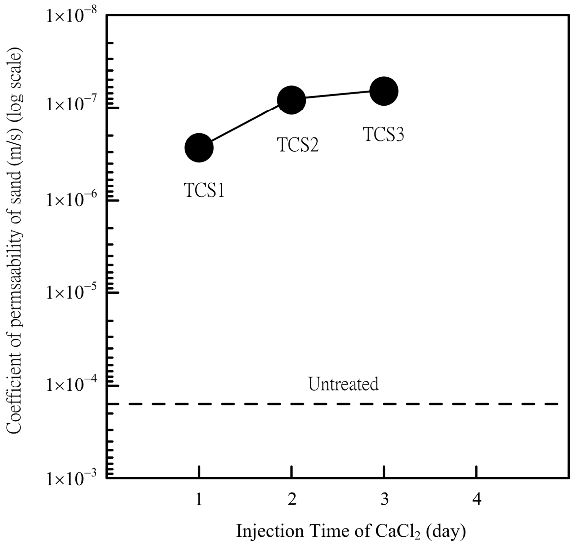

Fig. 3 Effect of different treatment times with injection of calcium chloride, followed by injection of the sodium silicate solution, on the permeability coefficient of sand.

3.2. Cone resistance

Figure 4 illustrates the cone resistance after ECT for samples of TC1, TC2, TC3, and TC4. When the specimen was treated for 24 (TC1), 48 (TC2), 72 (TC3), and 168 (TC4) hours with calcium chloride, significantly increased cone resistance in the sand was observed from the anode to the cathode. At the NA, FA, and M positions, the cone resistance in soft clay was increased slightly due to cation exchange and decreased water content (effect of electroosmosis) for samples of TC1, TC2, TC3, and TC4. The entire samples' cone resistance in soft clay decreased and became zero at the M position and remained at zero up to the FC and NC positions. A remarkable increase in cone resistance at the cathode for the soft clay with the 168 hour treatment time was observed, compared with the samples receiving 24, 48, and 72 hours of treatment time. The average cone resistances in the FC and NC regions for soft clay that underwent a 168 hour treatment time reached 746 kPa and 1,230 kPa, respectively. When the treatment time was 168 hours, the cone resistance in soft clay increased at the FC and NC positions.

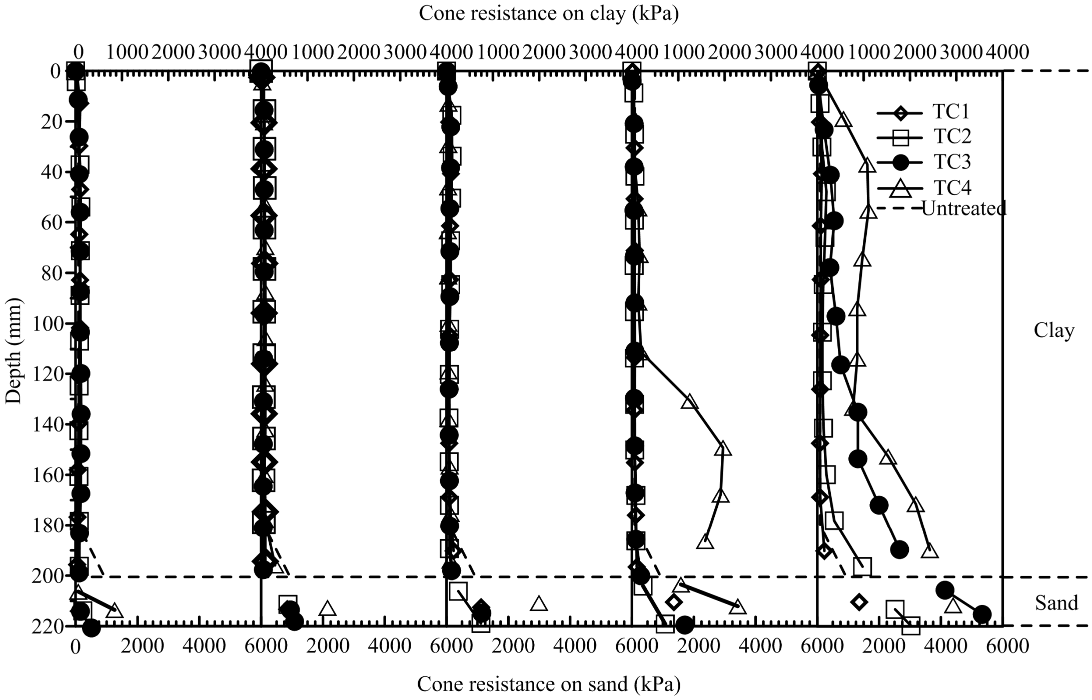

Fig. 4 Profiles of cone resistance for different treatment times with injection of calcium chloride.

Figure 5 illustrates the cone resistance after ECT for samples of TCS1, TCS2, and TCS3. When calcium chloride (24, 48, and 72 hour) followed by sodium silicate (144, 120, and 96 hour) were injected, a more significant increase of cone resistance in sand was observed from the anode to the cathode. At the NA, FA, and M positions, the cone resistance in soft clay was increased slightly due to cation exchange and decreased water content (effect of electroosmosis) for samples of TCS1, TCS2, and TCS3. A remarkable increase in the cone resistance for the soft clay was observed when the specimen was treated for 72 hours with calcium chloride followed by 96 hours with sodium silicate (TCS3), compared with the samples of TCS1 and TCS2. The average cone resistances in the FC and NC regions for soft clay that underwent a 72 hours with calcium chloride followed by 96 hours with sodium silicate (TCS3) reaching 654 kPa and 1,284 kPa, respectively.

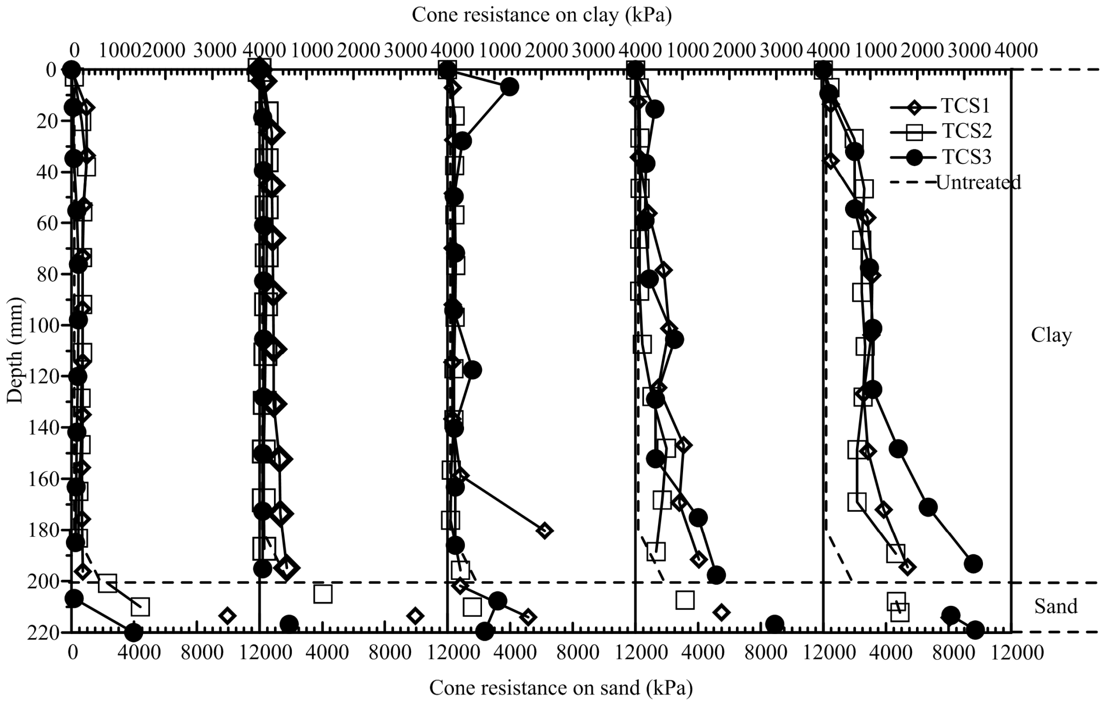

Fig. 5 Profiles of cone resistance for different treatment times with injection of calcium chloride, followed by injection of the sodium silicate solution.

3.5. Discussion

In this study, the sand was first placed and then the slime of kaolinite was placed in the test container in layers. The interbedded sand seam was injected with sodium silicate solution by pressure before ECT. The sample (sand and kaolinite) was treated by injecting chemical solutions during electroosmosis (ECT) under the consolidation pressure of 30 kPa. The effect of ECT can be divided into two phases. These are decreased permeability coefficient of the interbedded sand and improved strength of the soft clay. When the sample was injected with calcium chloride during electroosmosis (TC), the injected chemical solutions may first leak from the interbedded sand due to the relatively high conductivity. The main reaction mechanism between calcium chloride and sodium silicate solution in sand, pozzolanic reaction, is responsible for the increased strength and decreased permeability coefficient of the interbedded sand. The pozzolanic reaction chiefly occurs between siliceous materials and slaked lime (calcium hydroxide) under alkaline conditions, forming calcium silicate hydrates (CSH), a cementing agent that binds the sand particles together. The pozzolanic reaction is as follows:

Ca2+ + 2(OH)- +SiO2 ---------> CSH (Calcium Silicate Hydrate)

The permeability coefficient of the interbedded sand could be effectively reduced to 10^{-5} -10^{-6} m/s (Fig. 2) by first injecting the sodium silicate solution into the interbedded sand seam by pressure before ECT, followed by injecting the calcium chloride solution by electroosmosis (TC). The increased cone resistance on the sand near the cathode (Fig. 4) also confirms the decreased permeability coefficient of the interbedded sand and pozzolanic reaction. When the sample was injected with calcium chloride followed by sodium silicate during electroosmosis (TCS), the permeability coefficient of the interbedded sand could be more effectively reduced to 10^{-7}-10^{-8} m/s (Fig. 3). The increased cone resistance on the sand from the anode to the cathode (Fig. 5) also confirm the above decrease in the permeability coefficient of the interbedded sand and pozzolanic reaction.

Therefore, the injection of chemical solutions (calcium chloride) could be effectively flowed in the soft clay (kaolinite) during electroosmosis due to the decreased permeability coefficient of the interbedded sand.

4. Conclusion

From the unsuccessful application, it is deduced continuous sand and silt layers in the subsoil are unfavorable for ECT. Because of the relatively high conductivity of such layers, it would cause loss of chemical solution from the relatively high permeability coefficient of such layers during electroosmosis. The purpose of this study was to avoid loss of chemical solutions from the interbedded sand during electroosmosis and to improve the soft clay. An appropriate ECT process for soft clay with interbedded sand was developed. A series of laboratory ECT tests were performed to verify the developed ECT process. Though the laboratory ECT tests were with limited scale and a specific type of soil stratum, which may be different from what is actually found in the field, the developed process should be applicable to real field condtions with complicate subsoil deposits.

The calcium chloride and sodium silicate were used as chemical solutions. Variables like permeability coefficient and cone resistance of samples were measured after ECT. The results show the permeability coefficient of the interbedded sand could be effectively reduced to 10^{-5}-10^{-6} m/s by first injecting the sodium silicate solution into the sand layerby pressure before ECT, followed by injecting the calcium chloride solution by electroosmosis. Therefore, the injection of chemical solutions could effectively flow in the soft clay during electroosmosis, resulting in strength improvement of the soft clay after decreases in the permeability coefficient of the interbedded sand. The strength of soft clay was increased by up to 20 times the original strength near the cathode region. These results confirm the improved soil strength was mainly due to the precipitation reaction of Ca^{2+} ions and pozzolanic reaction near the NC position during ECT. Moreover, the permeability coefficient of the interbedded sand could be more effectively reduced to 10^{-7}-10^{-8} m/s by first injecting the sodium silicate solution into the sand seam by pressure before ECT, followed by injecting the calcium chloride solution and sodium silicate solution during electroosmosis.

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