

Fine-grained soil improvement by electrokinetic injection

Amélioration de sols fins par injection électrolytique

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ABSTRACT

The objective of this paper is to investigate the improvement of fine-grained soils by electrokinetic injection of silicate grouts. The sodium silicate solution with 5, 10 and 20% concentrations are injected from the anode compartment by electrical gradient equal to 1 V/cm across silty specimens for a week while 10% acid phosphoric solution is used as the catholyte to control pH. It is shown that silicate precipitate into the soil pores and increases the cementation of the soil. For all silicate concentrations, the injection of Na-silicate solution increases the strength adjacent to the anode significantly (between 400 to 700%) and more concentration generated more strength. Furthermore, decreasing the silicate concentration increases the penetration length of the grout. Injection of Na-silicate solution from anode chamber also decreases the electroosmosis flow significantly, i.e., the soil is treated with relatively low volume change by this technology.

RÉSUMÉ

Cet article vise à étudier l'amélioration de sols fins par injection électrolytique de coulis de silicate. La solution de silicate de sodium concentrée à 5, 10 ou 20% est injectée du côté anode avec un gradient électrique de 1 V/cm à travers un échantillon silteux, avec une solution à 10% d'acide phosphorique à la cathode pour contrôler le pH. On montre que le silicate précipite dans les pores du sol et augmente sa cimentation. Pour toutes les concentrations du silicate, l'injection de silicate de sodium accroît significativement la résistance à proximité de l'anode (entre 400 et 700%), qui augmente avec la concentration. Réduire la concentration en silicate augmente la longueur de pénétration du coulis. L'injection d'une solution de silicate de sodium à l'anode réduit aussi substantiellement l'écoulement d'électro-osmose, c'est-à-dire que par cette technologie le sol est traité avec une variation de volume relativement faible.

Keywords : electrokinetics, electroosmosis, injection, grouting, silicates

1 INTRODUCTION

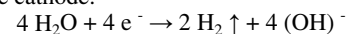
Electrokinetic (EK) injection is relatively a new concept in which grouts move in a controlled direction at an accelerated velocity through a fine grained soil. In this technique, the inserted anode and cathode electrodes form an electric field in ground. Ion migration, electro-osmotic flow, advection, and diffusion of chemical gradient under electric field cause the ions to transport through the soil (Acar et al., 1989). In this process, pore water flows through fine-grained soils from anode to cathode named electroosmosis (EO) in the electrical field. Therefore stabilizing chemicals or suspension grouts may be injected at anode to improve soil properties. The idea of soft soil stabilization with low volume change by ionic injection under electric fields has been studied by Alshawabkeh and Sheahan (2004).

Many researchers have accomplished electrokinetic injection in the last 50 years to improve soil properties as a solution to different geotechnical problems (Gray, 1970; O'Bannon et al., 1976; Feldkamp and Belhomme, 1990; Srinivasaraghavan and Rajasekaran, 1994; Azzam et al., 1997; Ozkan et al., 1999; Mohamadelhassan and Shang, 2003; Shang et al., 2004; Alshawabkeh and Sheahan, 2004). Few of these studies related to silty/sandy soils. Thevanayagam and Jia (2003) used the EK grouting for silty sand to mitigate liquefaction potential. The results indicate that it is feasible to inject silicate grouts into silty sand soils by EK technique and significant increase in strength has been achieved. However, the results are not very clear and further researches are required. The objective of the present work is to investigate electrokinetic transport of sodium silicate in the silt formations while an acidic catholyte is also

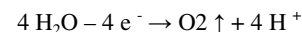
used in the cathode side of the sample. Therefore, a series of laboratory tests on a pure silt are performed. It is shown that injection of only a few amount of sodium silicate in the anolyte, improves the soil strength. In addition, sodium silicate solution decreases the electroosmosis flow, i.e. the soil is treated with relatively low volume change by this technology.

2 BACKGROUND

In the EK process, the reaction took place at the cathode producing an excess of hydroxyl ions and a basic solution is generated at the cathode:



At the anode, the oxidation takes place, hence the solution becomes acidic:



The soil pH changes along the sample as the pH of the solution varies at the anode and cathode. Therefore, the generated H^+ and OH^- as well as the existing anions and cations in the pore fluid of the specimen under the electrical field, migrate toward the opposite electrical side which has a significant influence on the local conductance. Acar and Alshawabkeh (1993) compared the role of electroosmosis and ionic migration for different conditions. The results indicated that in the most cases ionic migration is more significant than electroosmosis.

Sodium silicate is one of the primary chemical grouts to be used in grout injection today. According to Karol (1990), sodium silicates are generally considered to be non-hazardous to health and environmentally safe. Dilute sodium silicate solutions can be made to gel by adding a catalyst. The acid

generated from a catalysts reaction with the silicate-water mixture causes precipitation of the silica. Consequently, if a solution of sodium silicate grout injects through the anode into the soil by EK process, the generated acid at the anode may cause the grout forming gel and strengthen the soil. It seems that sodium silicate is compatible with pH variation due to EK process in the soil.

3 EXPERIMENTAL PROGRAM

To achieve the objectives of this research an experimental program is scheduled as given in Table 1.

Table 1. Summary of the EK tests

| Test | No EK | T1 | T3 | T5 | T7 |
|---|-------|-------|-----------------|-----------------|-----------------|
| Anode solution | - | water | 5% Na – Si | 10% Na – Si | 20% Na – Si |
| Cathode solution | - | water | 10% ph. acid | 10% ph. acid | 10% ph. acid |
| Total Energy Exp. (W-H) | - | 28.99 | 36.21 | 39.1 | 50.96 |
| Unit weight (kN/m ³) | 19.92 | 20.03 | 19.92 | 20.04 | 19.86 |
| Dry unit weight (kN/m ³) | 16.82 | 16.95 | 16.79 | 16.88 | 16.49 |
| Void ratio | 0.54 | 0.53 | 0.55 | 0.54 | 0.58 |
| Average Degree of Saturation (%) | 89.8 | 90.2 | 90.3 | 91.9 | 94 |

In this program, a non-plastic silt was grouted by sodium silicate in an electrokinetic cell. The silicate solution with different concentrations is injected through the reservoir next to the anode electrode. The tests were conducted with phosphoric acid solution as the catholyte. According to Table 1, four electrokinetic tests were conducted. The first test (T1) is carried out under EK process without additives to evaluate the effect of electrical gradient on the base soil. The other tests namely, T2, T3 and T4 in which 5, 10 and 20% sodium silicate solution injected to the soil through the anode chamber, respectively, while 10% phosphoric acid solutions are mixed in the cathode chamber. Summary of the soil properties; e.g. density, void ratio, degree of saturation at the end of each test are presented in Table 1. Electrical gradient equal to 1 V/cm has been applied across all the specimens for a week. The EO flow through the anode and cathode, variation of pH in the anode and cathode chambers and the current across the specimens during the EK process have been monitored. pH and water content profile of the specimens at the end of each test are also determined.

3.1 Electrokinetic equipments and materials

Figure 1 illustrates a schematic diagram of the EK apparatus which is designed for this study. The apparatus consists of a box with three sections of plexiglass. The two 40×90×120 mm end boxes each are assigned to place the anode and the cathode solutions, respectively. The soil sample is set in the 160×90×120 mm middle box. Stainless steel perforated plates are selected as the anode and cathode electrodes. The anode and cathode chambers are separated from the sample by filter paper. The electrodes are placed in the intermediate caps that are drilled with 2 mm holes at 5 mm spacing in order to achieve uniform flow across the cell. Nitrogen is used to circulate the fluid in the electrode reservoirs to provide a homogenous solution at anode and cathode compartments. A plexiglass box is connected to the anode chamber by a tube and a micro tube of 160 mm diameter is connected to the box by a floating valve. As the water level in the anode chamber drops, it is compensated by the solution of the adjacent box. The floating valve allows the solution of microtube flowing to the box. Utilizing this system provides the measurement of the input EO flow through the anode chamber into the soil. In addition, a

micro tube is connected to the cathode chamber by a fitting. If the water level in the cathode chamber rises due to the EO flow from the anode, it overflows into the microtube and makes it possible to measure the output EO flow into the cathode chamber. A power supply with 3 A and 60 V ultimate capacity provides the continuous constant voltage.

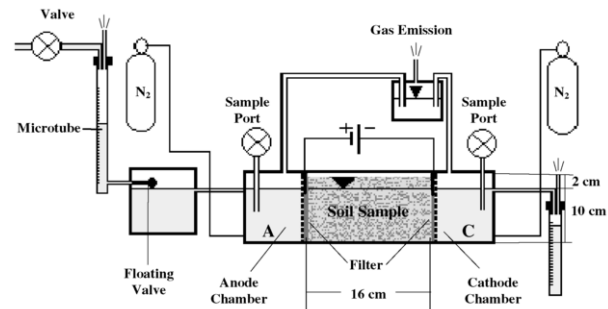


Figure 1. Experimental setup

A silty soil located in Firoozkuh city, north of Iran is used in the present research. The soil is brown, in the form of a dry powder. Laboratory tests are performed to find out the various physical and chemical properties of this soil. The results indicate that the soil is non-plastic silt (ML) with maximum grain size equal to 0.036 mm. The major mineral compositions of the soil are quartz and feldspar. The compositions of the soil based on X-ray diffraction as well as other properties are summarized in Table 2.

Table 2. Properties of the soil

| Soil type | ML |
|----------------------|-------------|
| Max. grain size | 0.036 mm |
| Less than 0.002 mm | 10% |
| Plasticity index | Non-plastic |
| Specific gravity | 2.65 |
| Initial pH | 8.1 |
| w _{opt} (%) | 14.6 |
| Main cations (%): | |
| Fe | 1.62 |
| Ca | 0.96 |
| Ti | 0.62 |
| K | 0.49 |

The soil specimens are prepared by adding 300 ml tap water to 2000 g of dried soil to bring the soil to 15% water content. The specimens are prepared in 5 layers and each layer is compacted by 50 blows of a light hammer to produce the same energy per volume of the soil as proctor test. Then, the anode chamber is filled with water for three days to saturate the soil. To evaluate the strength of the specimen (control test), three samples are prepared from a cell by a thin wall sampler with 35 mm diameter and 70 mm height. The unconfined compressive strength (UCS); q_u , as well as the water content of the samples are determined as shown in Figure 2. According to this figure, the UCS of the samples are measured equal to 85.45, 86.32 and 88.53 kN/m² with 16.7, 16.0 and 16.4% water content, respectively.

Shang et al. (2004) used a steel plate to evaluate the cementation of the soil adjacent to the anode. They used Tani and Craig (1995) failure load which is defined as the point of intersection of the load–displacement curve and the bisector line of the angle made by two tangents on both sides of the sharp bend of the load–displacement curve. In this study, five steel pipes with 8 mm outside diameter and 50 mm length are installed through the cell in all tests as it is given in Figure 3 to have a better view of the penetration length of the grout under electrical field. These micropiles are installed after saturating the soil and are axially loaded (1 mm/min).

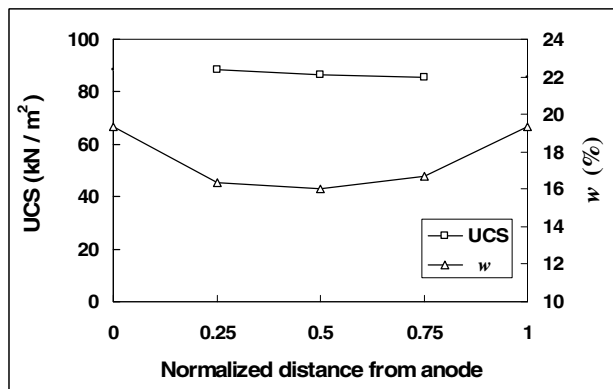


Figure 2. Unconfined compressive strength (UCS) and the water content variation

The cells are cured for a month after the finishing of the EK process and then the micropiles were loaded. The EO flow through the anode and cathode, variation of pH in the anode and cathode chambers and the current across the specimens during the EK process have been monitored. pH and water content profile of the specimens at the end of each test are also determined.

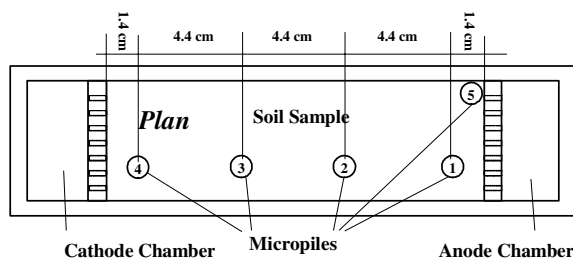


Figure 3. Location of installed steel pipes (micropiles) through the cell

Figure 4 shows the shear stress on the lateral surface of the micropile while neglecting tip resistance (load divided by lateral surface) versus the displacement. The coincidence of failure points of micropiles 1 and 4 and micropiles 2 and 3 have been observed in Figure 4. Micropile 5 presents the maximum resistance mainly seems due to the wall stiffness. A comparison between the results of the skin resistance of micro piles and the UCS of the soil demonstrates the obtained results confirm that the specimen may be relatively uniform.

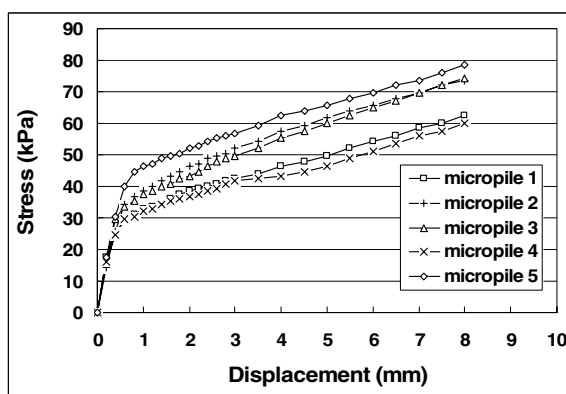


Figure 4. Penetration resistance of micropiles for non-treated soil

In the case of EK grouting tests, all chambers and reservoirs are filled with the required solutions after saturating the specimens subjecting to electrical gradient equal to 1 V/cm for a week. Micropile 5 was not considered and installed for the EK tests (T2 to T4).

4 RESULTS AND DISCUSSIONS

4.1 Profile of the strength

Two major concerns in the EK injection of sodium silicate solution are: 1) the precipitation of grout adjacent to the anode that may prevent the EO flow as well as ionic migration of silicate toward the cathode and 2) the reduction taken place at the cathode that may prevent the silicate precipitation. Na-silicate requires acid generated from a catalyst or anode electrode in EK process to precipitate and improve the soil mechanically.

To change the results of skin shear stress-displacement of micropiles 1 through 4 in each test into more interpretable results, Figure 5 was provided in which the failure stress of micropiles are presented.

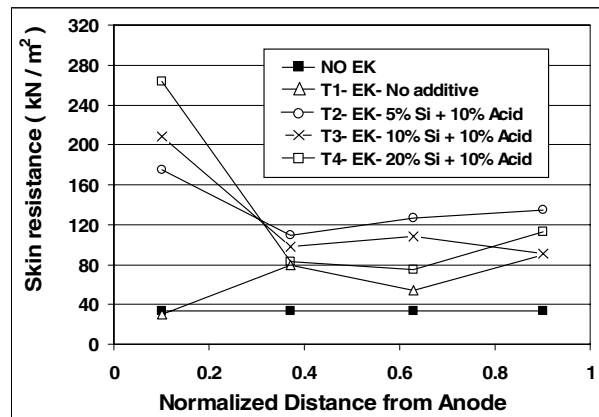


Figure 5. Comparing the effect of Na-silicate concentration with phosphoric acid as catholyte solution

The EK process without additive (Test T1) increases the strength of the soil except around the anode electrode. For Test T1, the highest increase in strength is observed for section close to the cathode (micropile 4), while the smallest increase is next to the anode. Although EK process is very complicated, the strength increase may be due to the dewatering of the specimen; oxidation of transported corroded iron from the anode (Segall et al., 1980) and precipitation of cations in pores where pH is high. Comparing the results of all tests in Figure 6 leads to this result that increasing 5, 10 and 20% Na-silicate and acid in the anode and cathode chambers, respectively, increases the strength adjacent to the anode electrode significantly (between 400 to 700%). The amount of increase depends on the concentration of Na-silicate as more concentration yields more strength. However, increasing silicate concentration does not warrant strengthening the rest of the specimen length. Increasing silicate concentration generates lower increase in strength across the specimen (except adjacent to the anode). This means that decreasing the silicate concentration increases the penetration length of the grout.

4.2 Electroosmosis flow and water content profile

Figures 6 shows the EO flow changes with time for all tests. The EK flow in Test T1 has increased while the electric gradient is applied to the specimen; however, the rate of the flow has decreased after the two first days of the test. As a general conclusion, in Tests T2 through T4 where Na-silicate solution has added to the anode chamber the flow has decreased dramatically and terminated in few hours after beginning of the tests. The maximum total flow is measured in Test T1 where no additive has added to the soil. The minimum total flow is measured in Test T3 and T4 (less than 20 cc) where only 5% Na-silicate has added to the anolyte. Alshawabkeh et al. (2004)

demonstrate the idea of improving the soil strength without either significant soil disturbance or volume change. Based on these results, it is concluded that Na- silicate injection may improve the soil properties without significant volume change or disturbance.

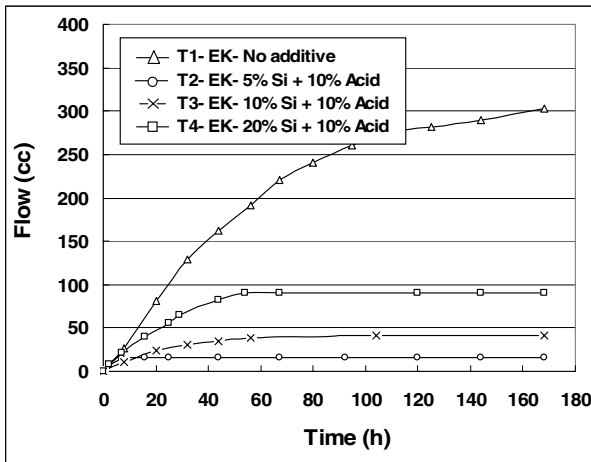


Figure 6. EO flow versus time

4.3 pH profile

pH of the Na- silicate solutions used in this study is measured 10.8-11.0, depending on the concentration of the solution. Figure 7 shows the pH variation for Tests T1 through T4 over the length of the specimens at the end of EK process. pH of the soil before the EK process is measured to be 8.1. The results of Test T1 show that conducting electrical gradient on specimen causes a decrease in pH of the soil to lower than 6.2 near the anode while it is increased to more than 10.5 around the cathode. The pH profile of Tests T2 and T3 is less than the natural pH of the soil (8.1) and pH profile of the Test T4 is greater than T1. These results indicate that more precipitation of silicate is expected for Tests T2 and T3, therefore, more penetration length as depicted in Figure 6. Therefore, the precipitation of silicate into the soil pores and cementation of the soil is dependent on the pH of the soil. Specimens with minimum pH profile or with locations where pH decreases locally at the end of electrokinetic process (like adjacent to the anode), shows the maximum cementation and strength.

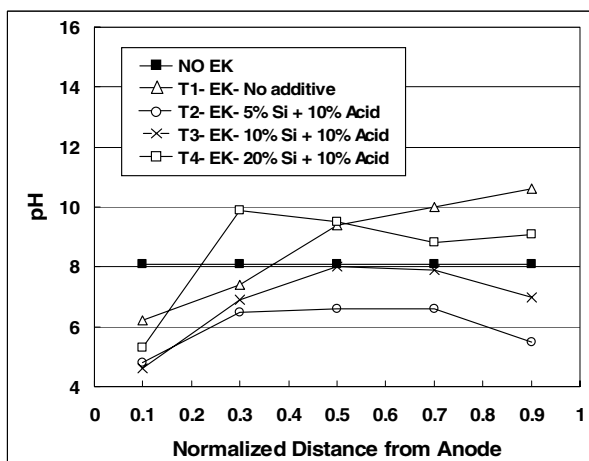


Figure 7. pH variation of the specimens after the test

5 CONCLUSIONS

An experimental study has been conducted on a non plastic silt to understand the electrokinetic stabilization processes involved

in sodium silicate treated silt. The silicate solution with 5, 10 and 20% concentrations is injected through the reservoir next to the anode electrode. The tests has been performed with 10% phosphoric acid solution as the catholyte. The results demonstrate that the precipitation of silicate into the soil pores and cementation of the soil is dependent on the pH of the soil and Na- silicate concentration. Specimens with minimum pH profile or with locations that pH decreases locally (near the anode electrode) at the end of electrokinetic process, show the maximum cementation and strength. In all concentrations, the injection of Na- silicate solution increases the strength adjacent to the anode electrode significantly (between 400 to 700%). The amount of increase depends on the concentration of Na- silicate, more concentration leads more strength. However, increasing silicate concentration does not warrant strengthening the rest of the specimen length. Increasing silicate concentration generates lower increase in strength across the specimen. In other words, decreasing the silicate concentration increases the penetration length of the grout.

ACKNOWLEDGMENT

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