Electrokinetic injection of grout into silty soils

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ABSTRACT
The aim of this work is to present the effect of sodium silicate into the silt formations by electrokinetic transport process. A non-plastic silt is grouted by sodium silicate in an electrokinetic cell. The silicate solution with 5 and 10 % concentrations are injected by electrical gradient equal to 1 V/cm across the specimens for a week. It is shown 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 locations where pH decreases locally (near the anode electrode), demonstrates the maximum cementation and strength. The injection of Na- silicate solution increases the strength adjacent to the anode significantly (between 400 to 600%) and more concentration generated more strength. Increasing silicate generates lower increase in strength across the rest of the specimen i.e., decreasing the silicate concentration increases the penetration length of the grout.

RÉSUMÉ
L'objectif de ce travail est de présenter l'effet du silicate de sodium dans les formations de silt par le processus de transport électrocinétique. Un silt non-plastique est injecté par du silicate de sodium dans une cellule d'électrocinétique. La solution de silicate de 5 et 10 % en concentration est injectée par gradient électrique de 1 V/cm à travers les échantillons pendant une semaine. Il est démontré que la précipitation de silicate dans les pores du sol et la cimentation du sol sont influencées par le pH du sol et la concentration en Na-silicate. Les échantillons avec emplacements où le pH diminue localement (près de l'électrode anodique) démontrent une cimentation et une résistance maximales. L'injection de la solution de Na-silicate augmente la résistance de façon significative (de 400 à 600%) et une concentration plus élevée résulte en une résistance accrue. Une concentration croissante en silicate produit une augmentation plus réduite de la résistance à travers le reste de l'échantillon, i.e., une réduction de la concentration de silicate augmente la longueur de pénétration du coulis.

1 INTRODUCTION

Use of electrokinetic (EK) injection instead of pressure to cause grout moving in a controlled direction at an accelerated velocity through a fine grained soil, is relatively a new concept. In this technique, the anode and cathode electrodes are inserted in ground, and forming an electric field. Injected ions are transported through ion migration, electro-osmotic flow, advection, and diffusion of chemical gradient under electric field (Acar et al., 1989). Electroosmosis (EO) can made water to flow through fine-grained soils from anode to cathode in a direct current of electrical field. If grout materials like stabilizing chemical or suspension grouts are injected at the anode soil improvement may be achieved by electrokinetic injection. Most of the studies were carried out to inject grouts into clays and few of them were achieved on sand/silt soils (Azzam et al.; 1997 and Thevanayagam and Jia; 2003). Thevanayagam and Jia (2003) mitigated liquefaction potential in silty sand soils by EK grouting. They conducted EK injection laboratory tests and used 50/50 sand silt and N-silicate as grout. Results showed that it is feasible to inject silicate into silty sand soils by E-K technique and significant increase in strength was achieved. They concluded EO is effective in silty soils; however, the results were not very clear and further work is required. The aim of this work is to present the effect of sodium silicate into the silt formations by electrokinetic transport process.

Among the different chemicals that are used in grout injection, Sodium silicate is one of the primary chemical grouts in use today. According to Karol (1990), sodium silicates are generally considered to be non-hazardous to health and environmentally safe. Sodium silicate grout solutions typically range in viscosity from 3 to 10 cP. Dilute sodium silicate solutions can be made to gel by the addition of a catalyst (like bicarbonate). The acid generated from a catalysts reaction with the silicate-water mixture, causes precipitation of the silica. The rate of acid formation controls the setting time. 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.

This paper focuses on understanding the electrokinetic stabilization processes involved in sodium silicate treated silt, on cementation between the silty soil and steel foundation elements (like piles and existing foundations).

2 EXPERIMENTAL PROGRAM

An experimental program has been designed to evaluate the foregoing objectives of this study and carried out. In this program, a non-plastic silt is grouted by sodium silicate in an electrokinetic cell (Figure 1). The apparatus consists of a box with three sections of Plexiglas. The two 40×90×120 mm end boxes each house the anode and the cathode solutions respectively, and the 160×90×120 mm middle box houses the soil sample. Stainless steel perforated plates have been selected as the anode and cathode electrodes.

The anode and cathode chambers were separated from the sample by filter paper. The electrodes are placed in the intermediate caps that are drilled with 2 mm holes at 0.5 mm spacing in order to achieve uniform flow across the cell.

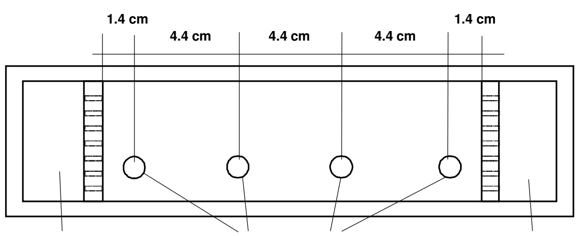

Figure 1. electrokinetic cell

According to Table 1, three electrokinetic tests are conducted. The first one is a control test (T1) conducted under EK process without additives to evaluate the electrical gradient on the base soil. In Tests T2 and T3, 5% and 10% sodium silicate solution are injected to the soil through the anode, respectively. Summery of the specimens properties; e.g. density, void ratio, degree of saturation and consumed energy at the end of each test were presented in Table 1. In addition, a test without electrokinetic process is performed to investigate the properties of the base soil.

Table 1. Experimental program

Test	NO EK	T1	T2	T3
Anode solution	-	water	5% Na-silicate	10% Na-silicate
Cathode solution	-	water	water	water
Total Energy Exp.(W-H)	-	28.99	45.12	73.22
Unit weight(kN/m3)	19.92	20.03	19.91	19.88
Dry unit weight(kN/m3)	16.82	16.95	16.59	16.63
Void ratio	0.54	0.53	0.57	0.56
Average Degree of Saturation (%)	89.8	90.2	93.7	92.1

Electrical gradient equal to 1 V/cm are 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 are monitored. pH and water content profile of the specimens at the end of each test were also determined. A silty soil located in Firoozkuh City, north of Iran, is used in this study. The soil was brown, in the form of a dry powder and all the grains passed through sieve No. 200. Laboratory tests were performed to find out the various physical and chemical properties of this soil. The Atterberg limits could not be measured on the soil solids. The results showed that the soil is non-plastic silt (ML) with maximum grain size equal to 0.036 mm. Figure 2 shows the grain size distribution curve of the soil. The major mineral compositions of the soil are quartz and feldspar.

The soil specimens prepared by adding 300 ml tap water to 2000 g of dried soil to bring the soil to 15% water content. Since the hammer of the standard proctor test was not applicable in the EK cell, a lighter hammer was used to provide compacted specimens. Instead, the number of blows was set to provide the same energy per volume of the soil as proctor test. The specimens were prepared in 5 layers and each layer was compacted by 50 blow of hammer to provide the same energy as the proctor test per volume of the soil. Then, the anode chamber was filled with water for three days to saturate the soil.

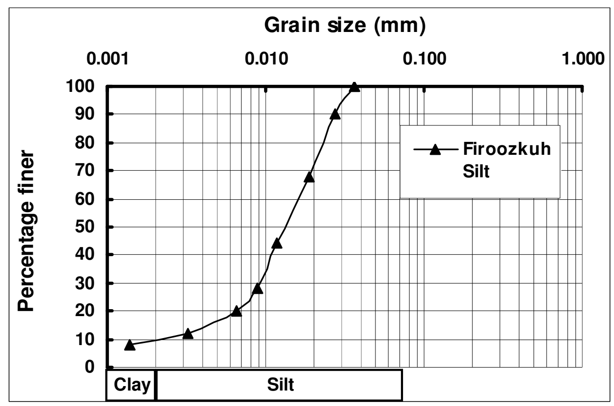

Figure 2. The grain size distribution curve of non-plastic silt

To have a better understanding of the penetration length of the grout under electrical filed four steel pipes with 8 mm outside diameter and 50 mm length were installed through the cell according to Figure 1. These micropiles were axially loaded to compare the penetration resistance of the non-treated and treated soil by EK process. A control test is conducted to determine the skin resistance (penetration resistance) of the micropiles before the injection of sodium silicate by the EK process. After saturating of the cell, 4 micropiles loaded axially after 1 week (the remaining time for all EK tests). Figure 3 shows the shear stress on the lateral surface of the micropile neglecting tip resistance (load divided by lateral surface) versus the displacement. 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 description which was 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. The coincidence of failure points of Micropiles 1 and 4 and Micropiles 2 and 3 are depicted in Figure 3. The failure stress of Micropiles 1 to 4 were measured equal to 29.6, 33.6, 34.4 and 30.4 kN/m^2, respectively and the higher resistance of Micropiles 2 and 3 before EK process relative to 1 and 4 may be due to higher water content of the soil next to the anode and cathode chamber. The results of the Figures 3 confirm that the specimen may be relatively considered uniform.

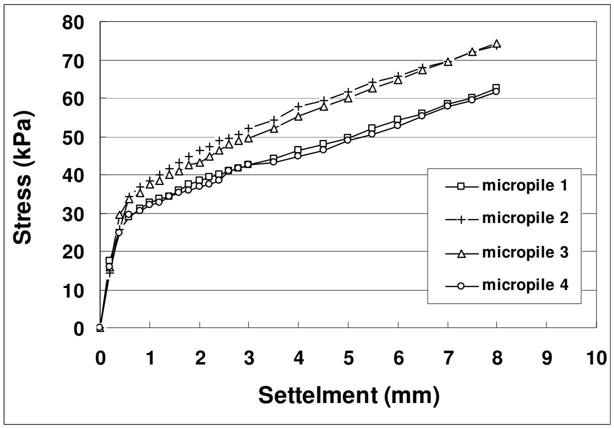

Figure 3. Penetration resistance of micropiles for non-treated soil, control test

3 RESULTS AND DISCUSSION

3.1 Profile of the strength

The curves of skin shear stress versus displacement of micropile 1 in all tests are shown in Figure 4. The results illustrate that the EK process with no additive (Test T1) does not alter the strength of the soil and the stress-displacement curve of micropile 1 for both control tests coincides. However, injection of Na- silicate solution by EK process increases the skin shear resistance of micropile 1 in Tests T2 and T3 significantly.

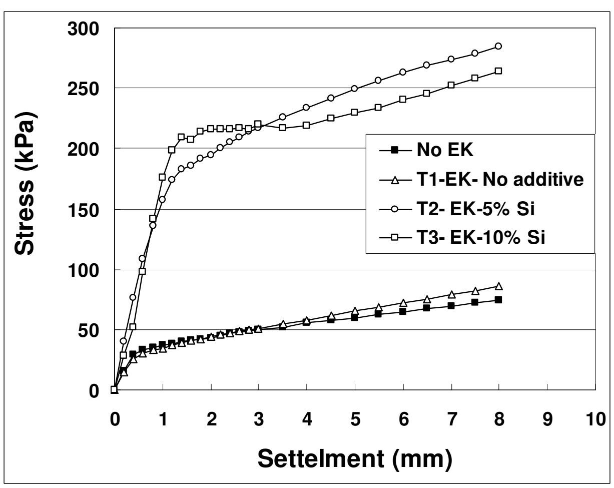

Figure 4. Skin shear stress versus displacement of micropile No. 1

To change the results of skin shear stress-displacement of micropiles 1 through 4 in each test into a more interpretable results, Figure 5 is provided in which the failure stress of micropiles are presented. The EK process without additives (Test T1) increases the strength of the soil except around the anode electrode. 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 along the sample 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. The results also display that injection of 5 and 10% Na silicate solution increases the strength of the soil. The injection of Na- silicate solution increases the strength adjacent to the anode electrode significantly (between 500 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.

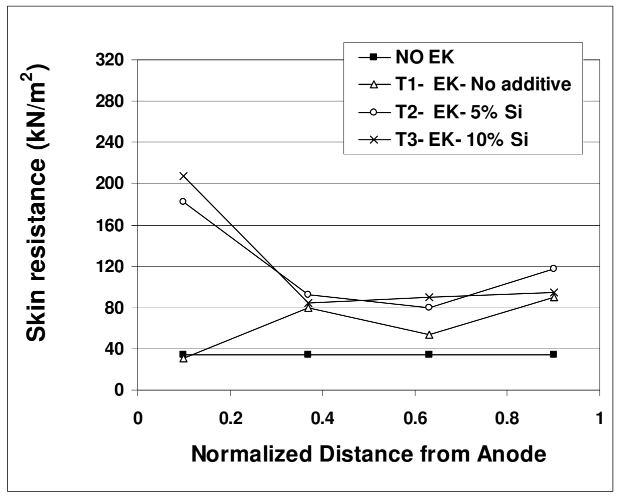

Figure 5. Comparison of the strength profiles after injecting 5 and 10% Na-silicate

3.2 Electroosmosis flow and water content profile

Application a constant dc voltage on the EK-cell tests under different boundary conditions causes the generation of electroosmotic flow and ionic migration. The hydraulic gradient is set to zero during the process; hence the measured water flow is entirely attributed to electroosmosis. Figures 5(a) and 5(b) show the input and output EO flow change with time for all tests through the anode and cathode, respectively.

The EK flow from the anode and cathode compartment 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 and T3 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 total volume of the EK flow after a week is measured in Test T1 (303 and 356 through the anode and cathode, respectively) where no additive has been added to the soil. The minimum total flow is measured in Test T2 (less than 20 cc) where only 5% Na- silicate has added to the anolyte. The results also show that increasing Na- silicate concentration may increase the

EO flow. It is worthy to mention the maximum difference between input and output is observed in Test T1. 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.

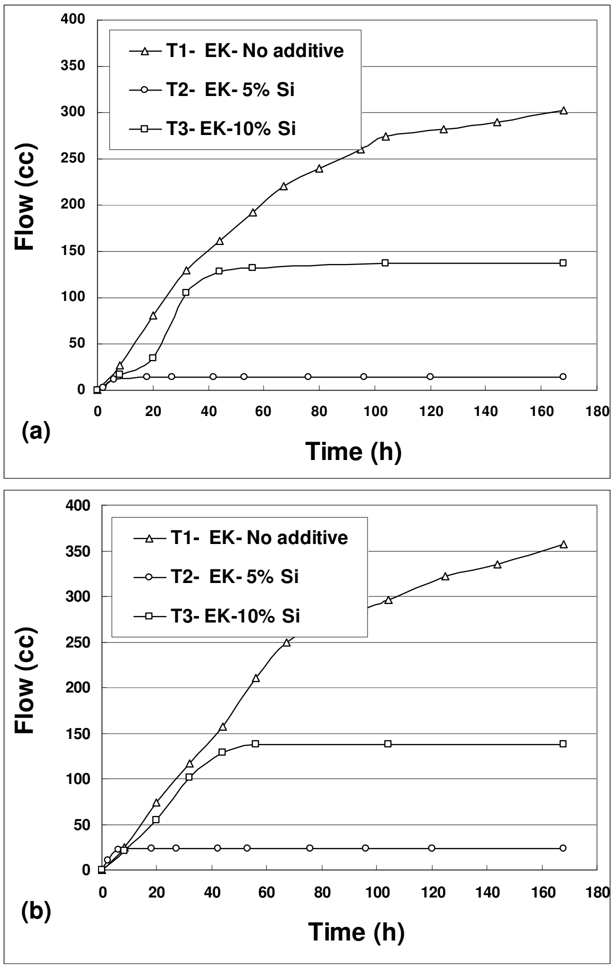

Figure 6. The EO flow verses time through (a) anode (b) cathode

To have a better view, the profile of the water content over the specimen length after the termination of the EK process is shown in Figure 7. All the Specimens are prepared with an initial water content equal to 15%, however, the water content has increased after saturating the specimens. In this figure the minimum water content profile relative to the other tests belongs to Test T1 (EK improvement without additive). These results confirm that Na- silicate injection by EK process provides less disturbance and volume change in comparison to the EK process without additives. Alshawabkeh et al. (2004) declared that even though electro-osmosis carries the pore fluid and consequently soluble grouts toward the cathode, ionic migration effectively transports negative anions to the positive anode and positive cations to the negative cathode while this mode of chemical transport can potentially occur without any fluid flow, compared to the use of electro-osmosis to induce chemical transport.

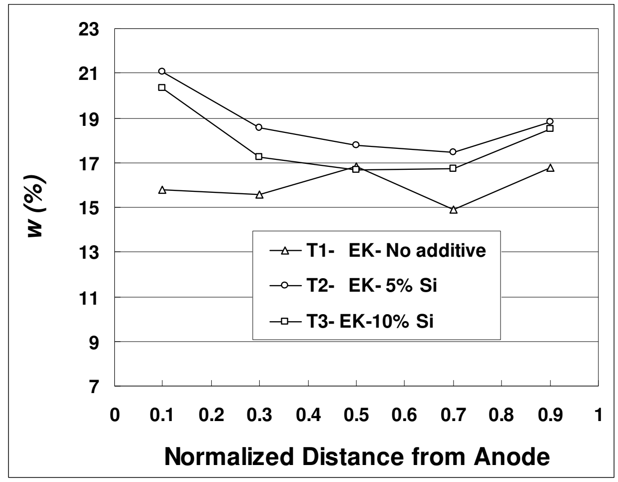

Figure 7. Profile of the water content over the specimen length

3.3 pH profile

In the present research pH variation of the specimens is considered as a critical parameter since the aim of the process is to improve the soil strength by Na- silicate injection. Precipitation of the silicate through the soil requires an acid generated from a catalysts reaction with the silicate-water mixture. pH of the Na- silicate solutions used in this study is measured 10.8 and 11.0 for 5 and 10% silicate concentrations, respectively. To provide the acidic environment for the precipitation of silicate through the soil specimen, the generated acid from electrolyze of water adjacent to the anode in EK process has been used. The generated acid migrates from the anode toward the cathode. The rate of acid formation controls the setting time of the sodium silicate. For low concentration injection of Na- silicate by the EK process, the acid generated at the early hours of the process may cause silicate to precipitate, fill the pores of the soil near the anode and prevent the EO flow toward the cathode. As mentioned, the EO flow is terminated in Tests T2 and T3 in the first and second days of conducting electrical gradient. In the case of 5% Na-silicate solution injection tests, the termination time of EO flow is less than 10 hours after beginning of the tests. However, more concentrations of silicate require more acid generation, i.e. more time duration is needed to cause precipitation and filling the pores of the soil.

Figure 8 shows the pH variation of the soil for all tests 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. In 60% of the length of the specimen, the pH seems to be more than 8.1 (natural pH of the soil). For Tests T2 and T3 where Na- silicate is injected to the specimens without any additive to the cathode compartment, pH of the soil in 70-80% of the length has increased. pH of the soil around the anode decreases even if higher concentration of Na- silicate is added to the anode chamber, resulting silicate precipitation near the anode electrode, filling the pores of the soil and causing the EO flow terminating.

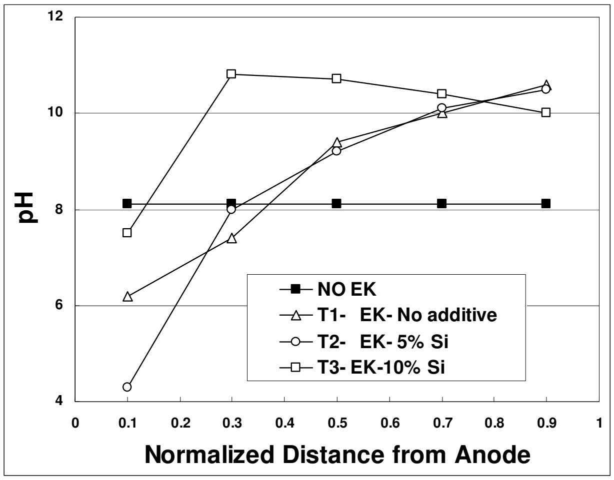

Figure 8. pH variation over the length of the specimens at the end of EK process

4 CONCLUSION

An experimental study has been conducted to understand the electrokinetic stabilization processes involved in sodium silicate treated silt. In this regard, a non-plastic silt is grouted by sodium silicate in an electrokinetic cell. The silicate solution with 5 and 10% concentrations is injected through the reservoir next to the anode electrode. Electrical gradient equal to 1 V/cm has been applied across all the specimens for a week.

The results indicate that injection of 5 and 10% Na silicate solution increases the strength of the soil. The results also demonstrate that the precipitation of silicate into the soil pores and cementation of the soil is dependent on the pH of the soil. Specimens with locations where pH decreases locally (near the anode electrode) at the end of electrokinetic process, show the maximum cementation and strength.

The minimum water content profile at the end of the tests and the maximum difference between input and output flow both belong to Test T1 (EK improvement without additive). Injecting of Na-silicate not only terminates the flow but also decreases input/output flow difference. The results confirm that Na-silicate injection by EK process provide less disturbance and volume change in comparison to the EK dewatering soil improvement. Injection of Na-silicate solution from anode chamber decreases the EO flow dramatically and the flow terminates in few hours after the start of the tests.

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