

Stabilizing fine-grained soil by electrically injecting Ca^{2+} , CO_3^{2-} , and HPO_4^{2-} ions

R. M. Rustamaji^{a,*}, Eka Priadi^b

^aDepartment of professional engineer (profession of civil engineer), Universitas Tanjungpura, Pontianak 78124, Indonesia

^bDepartment of civil engineering, Universitas Tanjungpura, Pontianak 78124, Indonesia

Article history:

Received: 31 May 2024 / Received in revised form: 19 June 2024 / Accepted: 22 June 2024

Abstract

This paper presents a new technique that can electrically inject stabilizing ions, which can be used to stabilize soil. Other processes also occur simultaneously during treatment such as electrolysis, dissociation, sorption, and exchange mechanisms, etc. The aim of the research is to evaluate the effectiveness of the injection of stabilizing ions (Ca^{2+} , CO_3^{2-} , and HPO_4^{2-}) in enhancing the shear strength of fine-grained soils. The shear strength of the soil increased up to 127% after treatment when measured near the anode and up to 495% when measured near the cathode. The results show that the proposed method can significantly increase soil strength; hence, it overcomes bearing capacity problems in soft fine-grained soils with low hydraulic conductivity.

Keywords: Chemical stabilization; electrokinetic; electroosmosis; electro-chemical stabilization; soil stabilization

1. Introduction

Low bearing capacity usually becomes a problem for constructions over ground with poor geotechnical properties such as soft-saturated or fine-grained soils. Geotechnical engineers have increasingly designed more complex geotechnical structures over sites with such poor ground. In such cases, ground improvement has become a preferred option and is used widely to stabilize the soil. An innovative soil improvement technique was carried out by electrically injecting stabilizing substances. A bench scale experiment was conducted to assess changes in soil strength after treatment processing. This technique was developed using the principles of electrokinetic phenomena in soil (i.e. electroosmosis, electromigration, electrophoresis, and streaming potential). The phenomenon of main electromigration enables stabilizing agents to be electrically introduced into the fine-grained soil. Since stabilizing agents (or ions) are placed into both the anode and cathode compartments, cross-transport of ions will occur under the electric field induced by DC current passing through the electrode-soil system [8][20]. This paper presents the bench-scale experiments of fine-grained soil electrically injected with the combinations of $\text{Ca}^{2+} + \text{CO}_3^{2-}$ and $\text{Ca}^{2+} +$

$(\text{HPO}_4)^{2-}$ ions. The formation of cemented compounds such as CaCO_3 and $\text{Ca}(\text{HPO}_4)$ is expected to be formed within the soil, binding the particles strongly in order to increase the soil strength. Experiments were performed to assess the strength of the improved soil and the distribution of strengthening along the soil specimen.

Chemical stabilization is commonly used for ground improvement. Lime and cement stabilization have been used widely for surface and deep treatment. In the case of deep treatment, cement mixtures can be employed for deep stabilization under hydraulic injection. However, for certain conditions of fine-grained soil, the utility of the hydraulic injection technique might be inappropriate. In the case where the ground water table is near the ground surface, a cement mixture cannot be used effectively. Moreover, most of soft soils are mainly composed of clay and fine-grained silt. The permeability coefficient k (m/s) of soft fine-grained soils is generally low. In such conditions, the grouting technique cannot be used properly since the grout material of hydraulic injection is difficult to introduce into the soil with a low permeability coefficient. However, the electrical injection of species is employable for in-situ treatment and does not require excavation or other disturbances. In the five decades since Casagrande (1933-1934) demonstrated the first applications of the electrokinetic technique for short and long term

* Corresponding author.

Email: rustamaji@civil.untan.ac.id

<https://doi.org/10.21924/cst.9.1.2024.1448>



stabilization of submarine pens excavated in Trondheim harbor, the utility of electrokinetics has been used widely for several applications in geotechnical and environmental engineering [11]. However, a good understanding of the relation between mechanical and chemical mechanisms in multi-species transport under an electric field has only been unveiled in recent years [11,18].

The electric field induced by a DC current passing through the adjacent electrode-soil system results in the crossing movement of ions (Fig. 1). Cations will move from the anode to the cathode, and anions will move from the cathode to the anode. These ion movements are mainly due to the electromigration mechanism. The inducement of an electric field in a soil medium also results in electroosmotic water transport, which certainly causes soil pore water flow to the cathode. When the rate of electroosmotic transport is less than the rate of electromigration transport, the transport of anions is hindered, and anions mostly remain in the anolyte. Anions can be efficiently transported from the cathode to the anode because the rate of electroosmotic transport is lower than the rate of electromigration transport [11]. When cations and anions meet each other, this results in chemical precipitation reactions and the formation of new chemical compounds within the soil [17].

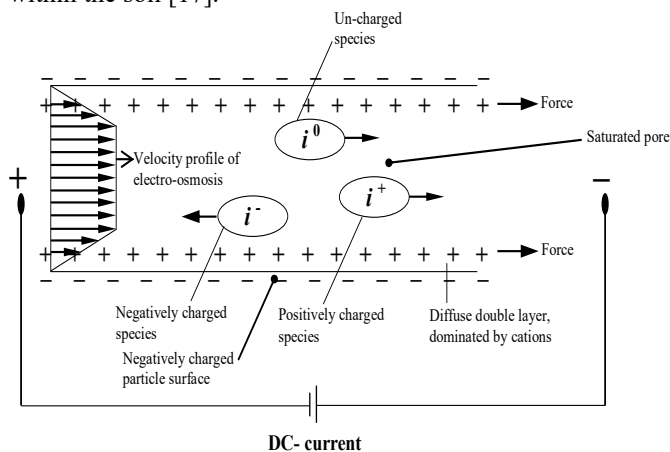


Fig. 1. The scheme of electrokinetic transports [18].

In 1994, Azzam demonstrated the utility of an injection technique using environmentally safe chemicals such as calcium and soda water for improving the bearing capacity of soft and uniform sandy silt underneath the foundation of the historic St. Nicolaus church tower in Waldbeck-Geldern, Germany. After the injection treatment, the results of the standard penetration test increased by almost 100%, as measured at a depth of 1.7 to 2.7 m below the ground surface [18,23,19]. Ozkan et al. performed the electrokinetic stabilization of kaolinite by injecting Al^{3+} and PO_4^{3-} ions [22]. An electrical gradient of 2 V/cm or less constituted the predominant driving force for ion transport under a 433 $\mu A/cm^2$ constant direct current density. They found that the undrained shear strength of the treated soil increased by 500 to 600% (on average). Alshawabkeh and Sheahan (2003) conducted electro-grouting on BBC (Boston Blue Clay) under a constant voltage gradient of 1 V/cm DC for two weeks [5]. The greatest strength gain of about 160% over the initial strength was measured in the specimen section near the cathode after treatment. Phosphoric acid solutions were used

in their experiments. An increase in shear strength also occurred using the depolarization of the anolyte to decelerate the acidification process at the anodic zone [17].

The main aim of this research is to evaluate the effectiveness of injection of Ca^{2+} , CO_3^{2-} , and HPO_4^{2-} ions as soil stabilizers under the influence of an electric field in increasing the shear strength of fine-grained soil.

2. Materials and Methods

The test program was performed using natural silty loam soil, which is classified as CL according to the USCS classification. Two electro-chemical injection experiments were performed to assess the change in the soil strength after treatment. In experiment 1, Ca^{2+} ions in 0.5M $CaCl_2$ and CO_3^{2-} ions in 0.5M Na_2CO_3 solutions were used as the anolyte and catholyte respectively. The formation of calcite ($CaCO_3$) within the soil may lead to soil particle bonding as a result of precipitation reactions. In experiment 2, Ca^{2+} ions in 0.5M $CaCl_2$ solutions and $(HPO_4)^{2-}$ ions in K_2HPO_4 solutions were used as the anolyte and catholyte respectively. The formations of $CaHPO_4$ or $Ca_3(PO_4)$ were expected to bind soil particles resulting in an increase in soil strength. In addition, precipitation resulted in cemented particles, and crystalline or microscopic particles were obtained, which might fill soil pores. The details of the experiments are summarized in Table 1.

Silty soil was taken from Flog-Hauset in Belgium at a depth of 30 to 50 cm below ground surface. The physical properties are summarized in Table 2. Based on soil consistency parameters and grain size distribution analysis, soil samples were classified into the soil group with low plasticity (CL - ML) according to USCS (Unified Soil Classification System), or identical to silty soil (A-4 - A-5) according to AASHTO (American Association of State Highway and Transportation Officials) classification.

A bench-scale apparatus of the electro-chemical injection system was constructed. The dimensions were accommodated in accordance with the bench-scale experiment, which had a width of 12 cm, a length of 50 cm, and a depth of 12 cm. Soil specimens were placed into a container between electrodes (i.e. anode and cathode). Both ends of the soil specimen were placed iron-metal electrodes. Passive electrodes made of tungsten wires were immersed into the soil along the distance between the anode and the cathode. Electrical potential could be measured at any time during the treatment test using these passive electrodes. Meanwhile, the DC current was generated by a DC power supply (Mc. Voice DF-1731SB5A) and was supplied constantly during the treatment test.

Both the soil and the electrode were separated by a filter to prevent a direct contact between the electrolyte (i.e. chemical species solution or stabilizing agent) and the soil specimen. The thickness of the filter was 10 mm, and its pore sizes were 200 μm . However, the electrode had a contact with the soil specimen directly. The electrode compartments were filled with solutions (i.e. anolyte and catholyte) and their level was kept constant during the test to avoid the transport of various species due to hydraulic head.

Table 1. Description of experiment

Test No.	1	2
Soil Specimen	Silty soil	Silty soil
Initial al moisture content (%)	22.93	22.64
Initial al strength, Su (kPa)	8.63	9.40
Treatment time / duration (hour)	336	336
Anolyte solution	0.5M CaCl ₂	0.5M CaCl ₂
Catholyte solution	0.5M Na ₂ CO ₃	0.5M K ₂ HPO ₄
Cation	Ca ²⁺	Ca ²⁺
Anion	CO ₃ ²⁻	(HPO ₄) ²⁻
Anolytes pH:		
Initial	6.85	6.88
Final	3.28	3.00
Catholytes pH:		
Initial	11.46	9.25
Final	12.59	12.09
I (A)	0.04	0.04
j (A/m ²)	3.08	3.08
U (Volt):		
Initial	47.25	19.51
Final	11.50	4.67
I _c (Volt/m)		
Initial	256.42	103.67
Final	11.90	30.50
Electric Power Consumption (kWh/m ³)	57.59	30.33

Table 2. Geotechnical properties

Natural water content	21%
Soils pH	4.93
Classification	
Atterberg limits:	
Liquid limit	23.63%
Plastic limit	16.95%
Plasticity Index	6.68%
Specific gravity	2.7
Grain size analysis:	
Clay	9.51%
Silt	61.02%
Sand	29.30%
Los on ignition	2.64%

The schematic diagram of the electrochemical injection experiment is shown in Fig. 2. The soil specimens were prepared by mixing air-dried and pulverized soil with distilled de-ionized water. The water content of the soil mixture was to be close to the liquid limit value. Before being placed into the polymer container for the electro-chemical injection test, the soil mixture was cured for 24 hours in a covered container to achieve equilibrate condition (i.e. relatively homogeneous moisture). After 24 hours, the moist soil was placed into the polymer container in four layers. There was no special compaction effort applied to the surface of each layer, only by kneading and mixing to remove air bubbles.

Experiments were performed by applying a constant DC current of 0.04A for 336 hours. The voltage of the system and the pH of the anolyte and catholyte were measured at the beginning, during, and after the test. After the completion of the test, the shear strength was measured by placing miniature vane blades into the soil at a depth of 5 cm from the soil specimen surface, and then applying torque. Final water content, Atterberg limits, and soil pH were also measured after treatment.

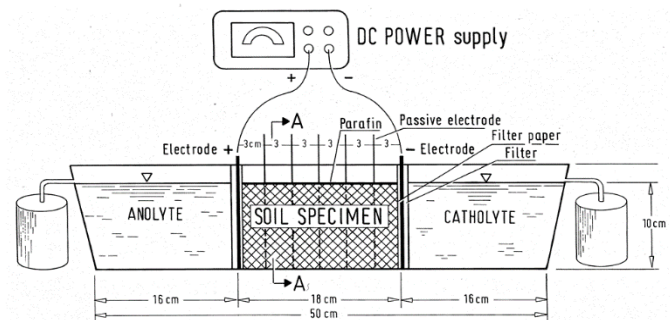


Fig. 2. Schematic diagram of the experimental set-up on a bench scale model

3. Results and Discussion

3.1. Electrical potential profile

The distributions of electrical potential across the soil specimen are shown in Fig. 3 and Fig. 4. Electrical potential was non-linearly distributed in time. Nevertheless, it was not so at the beginning of the test as electrical potential gradient was linear from the anode to the cathode. The electric potential at 0 o'clock at a distance of 0 cm from the anode was the initial electrical gradient between the anode and cathode. The gradient of electrical altered some parametrs such as pH, chemical composition, ionic strength, mineral phases and microfabric of the soil [1]. The water electrolysis reaction produced a large number of ions, increasing the conductivity of pore water at the beginning of the test; therefore, the current of all the tests firstly reached a peak and then dropped sharply due to the development of soil-contact resistance and electrode corrosion [24]. As time elapsed by, the electrical gradient changed gradually and became non-linear [18]. A change in electrical potential is related to the chemical changes or ionic concentrations and their compositions within pore fluid. A drop in electrical potential corresponds to a precipitation reaction at which the resistivity in this region is also high, as demonstrated

by a drop in electrical potential [14,21]. The propagation of acid and alkaline fronts, sorption and precipitation processes could cause a decrease in electrical conductivity of the soil [21].

The electrical potential of both test-1 and test-2 dropped significantly in less than 24 hours. Moreover, it was almost homogenous across the soil after 24 hours in test 2. At the beginning, the electrical potential in test 2 was lower than that of test-1. This might be caused by the solubility of the anolyte and catholyte solutions, which had an influence on the conductivity of the system [21] where the more conductive a system, the smaller the electrical gradient required to produce a certain constant electric current. In addition, this depended on the process of dissociation and dissolution of soil minerals followed by precipitation reactions.

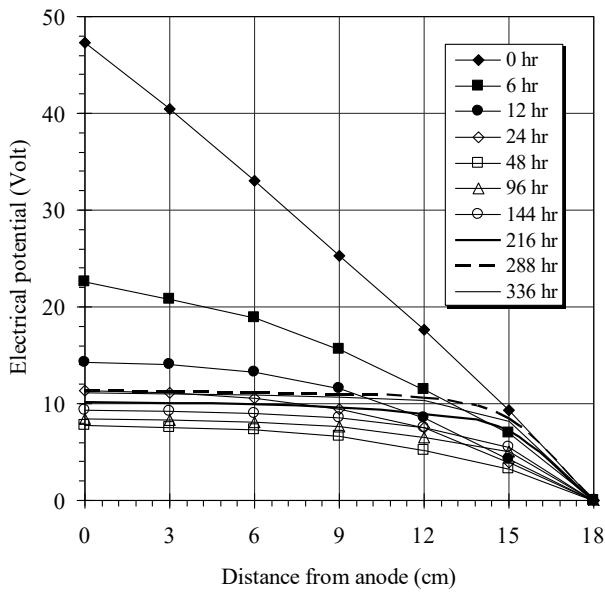


Fig. 3. Test-1 (anolyte: CaCl₂ and catholyte: Na₂CO₃)

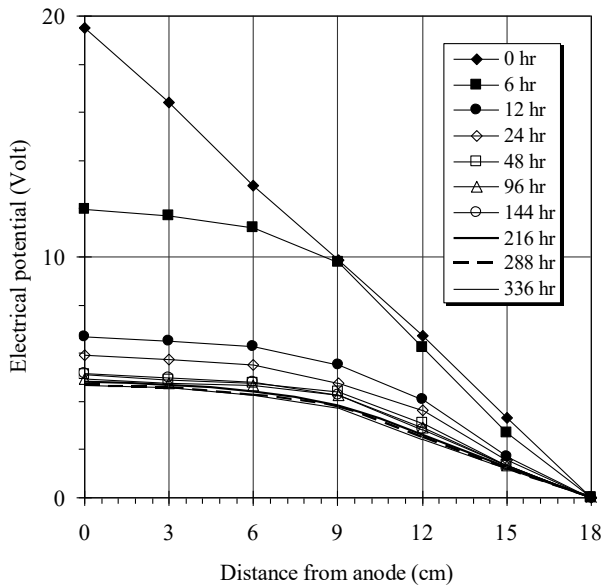


Fig. 4. Test-2 (anolyte: CaCl₂ and catholyte: K₂(HPO₄)_i)

A lower electrical potential means a lower electric power consumption during the treatment process (see Fig. 5). Test-2 consumed 30.33 kWh/m³ of electric power during 336 hours, which was lower than that of test-1 (57.59 kWh/m³). The

amount of electrical energy consumption was a critical parameter in this method. It can be seen that the increase in electrical energy occurred very significantly in the first 20 to 30 hours. The amount of electrical energy consumption is closely related to the electrokinetic transport mechanism, as well as electrochemical processes (for example electrolysis) caused by electric fields, which require large electrical energy consumption [13,24].

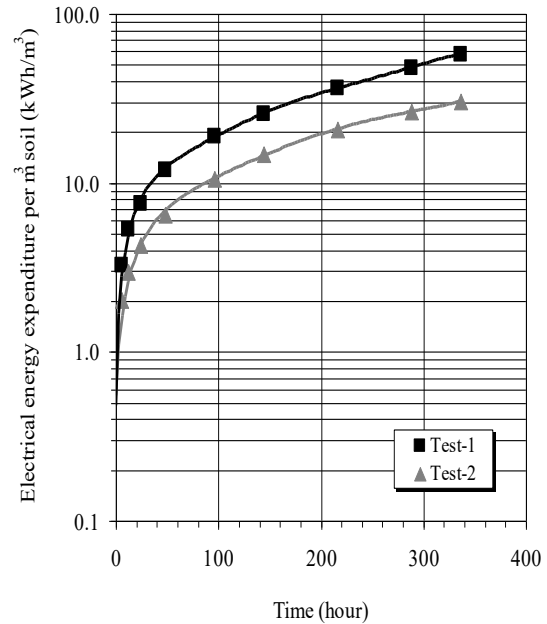


Fig. 5. Electrical power consumption

3.2. Anolyte and catholyte's pH, soil's pH, and electrical conductivity of the soil

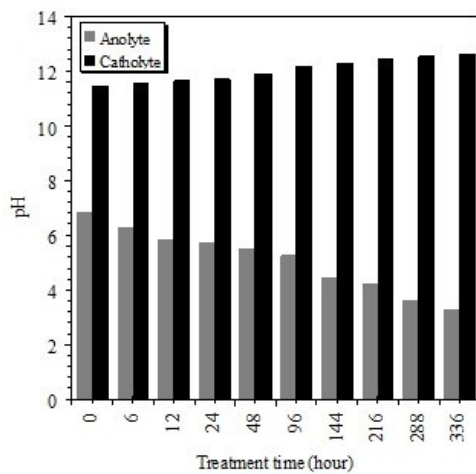
When electrolysis took place at the surface of a negative electrode, the negative charge created by the DC power supply created an electrical pressure to push electrons into the catholyte at this end. Electrolysis reactions at the cathode resulted in a reduction of the catholyte. Water was reduced to hydrogen gas H₂ and hydroxyl ions OH⁻ were produced. At the anode, there was a positive charge so electrons would be absorbed by this electrode. Water was oxidized and oxygen gas O₂ and hydrogen H⁺ ions were generated. Due to the reduction and oxidation processes, electrolysis resulted in an acid front (i.e. decreased pH) at the anode and an alkaline front (i.e. increased pH) at the cathode [18].

Fig. 6 presents the time-dependent anolyte and catholyte pH during the treatment process. A decrease in pH was associated with a decrease in the absolute value of zeta potential, related to the conductivity of the electrokinetic system [1,12,21].

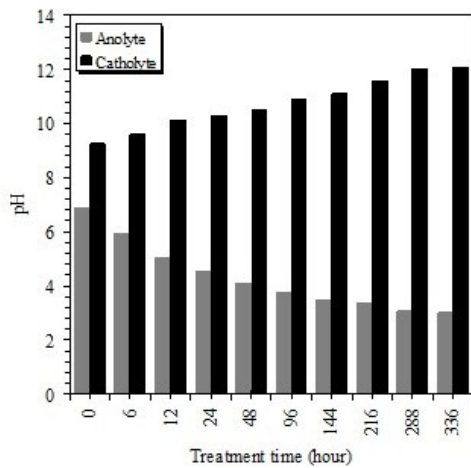
The anolyte and catholyte became acidic and alkaline after treatment respectively [6,10]. The formation of hydrogen H⁺ ions in the anolyte and hydroxyl OH⁻ ions in the catholyte led to changes in the anolyte and catholyte pH. Later on, H⁺ and OH⁻ ions would be transported to the cathode and anode respectively, passing through the soil. The presence of these ions within the soil specimen led to a change in soil pH (Fig. 7).

Soil specimens in the anodic regions became more acidic than those in cathodic regions, and the electrical conductivity

of the soil was greater in the anodic than in cathodic regions. Changes in anolyte and catholyte pH had an influence on the ionic strength of pore water, soil pH, solubility, and charge condition of soil particles, as well as on soil surface properties such as cation exchange capacity (CEC), magnitude of the electrokinetic zeta potential [21], and level of absorption of the species [14,18,20]. The pH of the soil media influences the success of the settling reaction, while this reaction will be effective in alkaline conditions. Soil pH less than the required alkaline condition will inhibit the settling reaction in the soil, resulting in the pozzolan reaction being ineffective. Meanwhile, the pozzolan reaction produces a cementation event that can bind soil particles to each other more compactly, and later their shear strength can increase [4].



(a) Test-1



(b) Test-2

Fig. 6. Time dependent of anolyte and catholyte pH changes

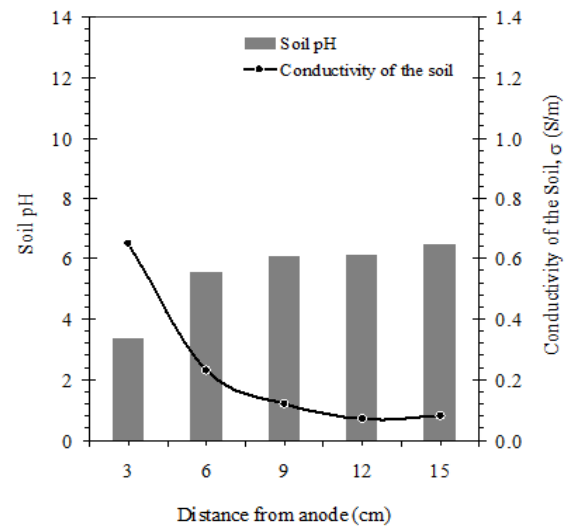
3.3. Water content, liquid and plastic limits, and undrained shear strength

The distributions of water content, liquid and plastic limits across the soil specimen are shown in Fig. 8. Liquid and plastic limits of the soil increased slightly after the treatment process. The alteration of the liquid limit was related to total moisture potentially held in the diffuse double layer and any water held by absorption [22]. The plastic limit was related to the innermost moisture plus absorption, thus the plastic index was

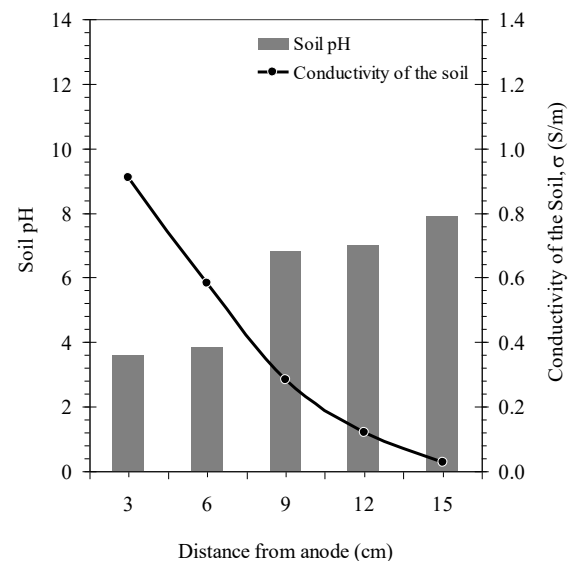
related to potential water content changes of the diffuse double layer. A reduction in water content reduced the thickness of the diffuse double layer and moves particles closer together, and this then increased the plasticity of the soil [22].

The curve of undrained strength and water content changes is presented in Fig. 9. After the test completion, water content was measured to assess the changes and its effect on the increasing strength of treated soil. The strength increased after treatment (Fig. 10); however, it was not homogenous throughout the specimen [2,25]. The highest strength of treated specimen was measured in the regions close to the cathode.

The non-homogeneous strength distribution might be due to chemical precipitation processes which were enabled under neutral pH and due to the availability of cementing agents depending on the soil pH [5,17,22,21,23]. The pH value plays an important role in the occurrence of precipitation reactions, and acidic conditions inhibit precipitation reactions. However, electrolysis causes an acidic milieu in the anodic zone and vice versa, and an alkaline milieu has formed in the cathodic zone. Controlling pH is the key to the success of strengthening soil specimens, which is expected to provide a uniform increase in undrained shear strength.

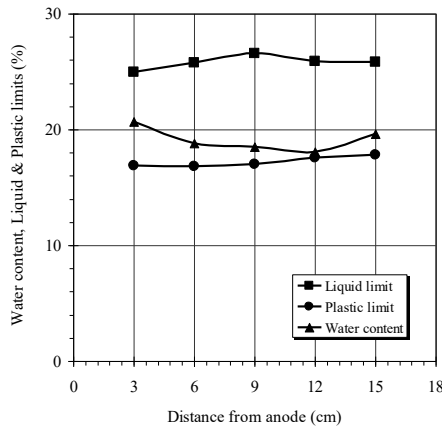


(a) Test-1

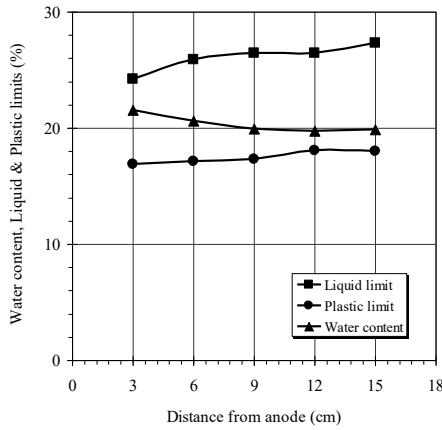


(b) Test-2

Fig. 7. Soil pH, electrical conductivity (measured at the end of test)



(a) Test-1



(b) Test-2

Fig. 8. Liquid limit, plastic limit and water content of treated soils

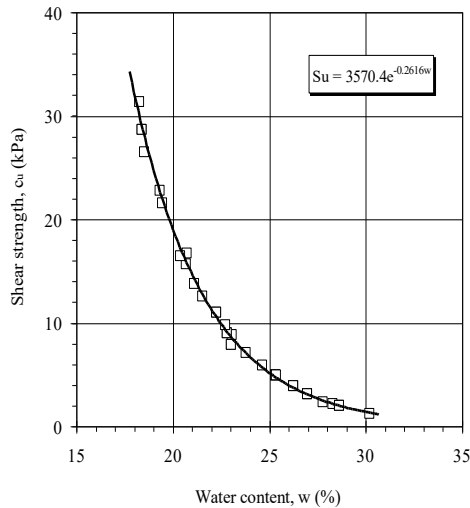
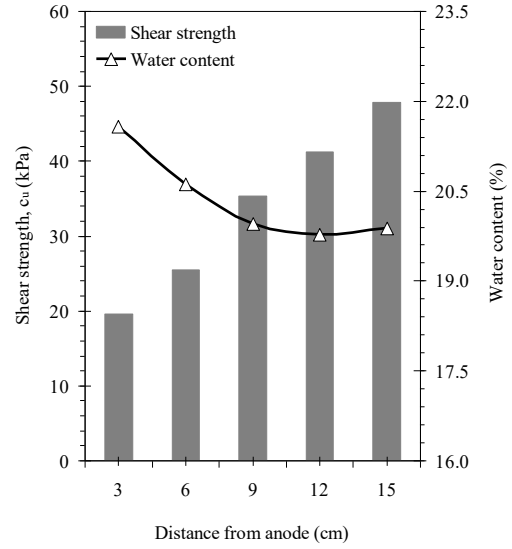


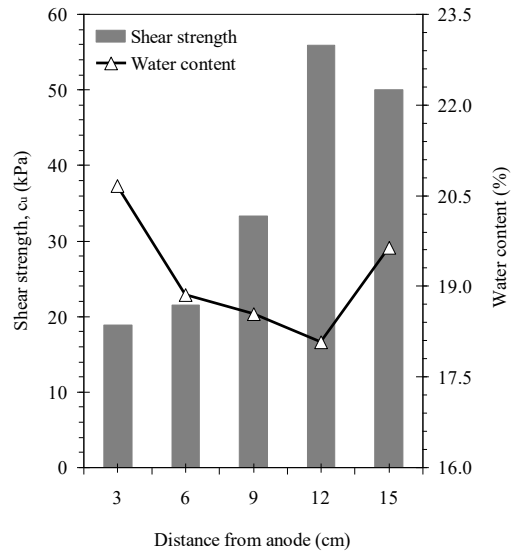
Fig. 9. Undrained shear strength vs water content

Strengthening was achieved since treated soil strengths were greater than the undrained strength of untreated soil as shown in Fig. 11. In test 1, treated strengths were distributed above the straight line, meaning that treated strength was greater than untreated strength for certain water content. The straight line represented the untreated strength and was calculated using the equation in Fig. 9. Therefore, strengthening achieved in test 1 was due to both electroosmosis and electro-chemical soil

processing (i.e. chemical precipitation). In test 2, strengthening was also greater toward the cathode than in the center and anodic zones. This was because the distribution of treated strength in anodic and center regions fit the straight line. In such cases, strengths changed proportionally to the change in water (i.e. osmotic strengthening).



(a) Test-1



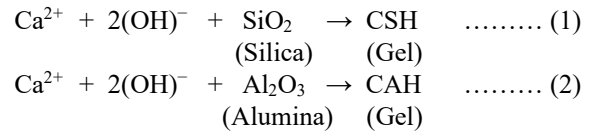
(b) Test-2

Fig. 10. Undrained shear strength (kPa) and water content (%) (measured at the end of test)

Since OH^- ions were generated by reduction at the cathode and transported to the anode, the movement of Ca^{2+} ions from the anode to the cathode enabled the formation of hydrated lime ($\text{Ca}(\text{OH})_2$) within the soil. Hydrated lime has been added to clay soil to improve its physical properties for centuries. Lime stabilization is well known as a stabilization method that has been beneficial in improving the strength and stiffness characteristics of road foundations [7]. Hydrated lime in soil can lead to a significant alteration in the physicochemical properties of the soil. The reactions that occur provide both immediate and long-term changes to the soil. The hydration reaction can result in some significant improvements in soil

workability purely as a result of dewatering. When the concentrations of Ca^{2+} and OH^- ions are present significantly in the pore water of the soil, several reactions occur, affecting soil composition, mineralogy, and pore water chemistry. The short-term result of hydration is the cation exchange process. Modification reactions take place initially by the cation exchange of Ca^{2+} ions with the existing cations at the negatively charged sites on the clay mineral lattice. The intensity of these charged sites in soil or clay minerals is determined by soil pH, where the number of charged sites is enhanced by the presence of OH^- ions, as indicated by the increase in pH value. The flocculation of mineral particles and changes in the plasticity properties of the soil are the results of the cation exchange [7]. The long-term result is caused by a pozzolanic reaction that occurs through a process termed solidification [17]. Pozzolanic reactions occur under highly alkaline soil pore conditions, involving the dissolution of silicon and aluminum from the clay minerals. The pozzolan reaction is influenced by the pH value. This reaction can take place well in alkaline conditions and results in an increase in soil strength and changes in the Atterberg limit [15].

Since Ca^{2+} ions were electrically injected into the soil, they would dissolve in the soil pore water. Furthermore, the dissolved Ca^{2+} ions reacted with the dissolved components of clay minerals, known as pozzolanic reactions. These pozzolanic reactions then generated the formations of CSH (Calcium Silicate Hydrates) and CAH (Calcium Aluminate Hydrates). CSH is the result of the reaction between the silicate phase of Portland cement and water and is the main product of hydration of Portland cement, which mainly plays an important role in cement-based strength, and is the main binding phase in most concrete. Therefore, CSH plays a very important role with respect to seeding additives for cement-containing materials [9]. CAH is formed any compound of Calcium Aluminate (CA) that reacts with water. The anhydrous contained in CA reacts with water to form calcium ions and aluminate ions. Both CSH and CAH compounds crystallize with time and bring about changes in soil properties, e.g. changes in soil plasticity [7], increase in shear strength, and reduction in permeability [16]. The formation reactions of CSH and CAH are given as follows [25]:



The end result of these reactions is the obtained improved soil, containing hardened cement particles and soil particles hardened by their pozzolanic reactions with the products of the hydration processes [3,17].

Pozzolanic reactions also improved the soil by forming CSH and CAH (Eq. 1 & 2). The overall chemical composition of pozzolan was considered as one of the parameters governing long-term performance. The pozzolan reaction is a long-term reaction that forms a strong cementation matrix, and this process is often irreversible. These formations composed hardened cement particles or cemented crystalline structures under the hydration process [17].

Even though there was a hardening of the soil specimen, especially in the cathodic area, there was a tendency for the water content to increase in the same area, especially in test 2 which was anomalous, but the increasing water content did not reduce the undrained shear strength. This was related to the propagation event between the acid front and the alkaline front. In this case, the acid face moved faster than the alkaline face because the mobility of H^+ was found higher compared to the mobility of OH^- [12,25]. The formation of water is also an indication of acid and alkaline propagation [18].

3.4. Environmental considerations

The electrokinetic phenomena is not only used for soil stabilization but also used for the purpose of remediation of contaminated soil. Electrokinetic Remediation (ER) is an innovative technique used in environmental technology to efficiently remove contaminants from the soil. This method utilizes electric current and the principles of electromigration, electroosmosis, and electrophoresis to transport charged particles in the soil matrix to specified electrodes. ER has received great attention due to its potential in remediating

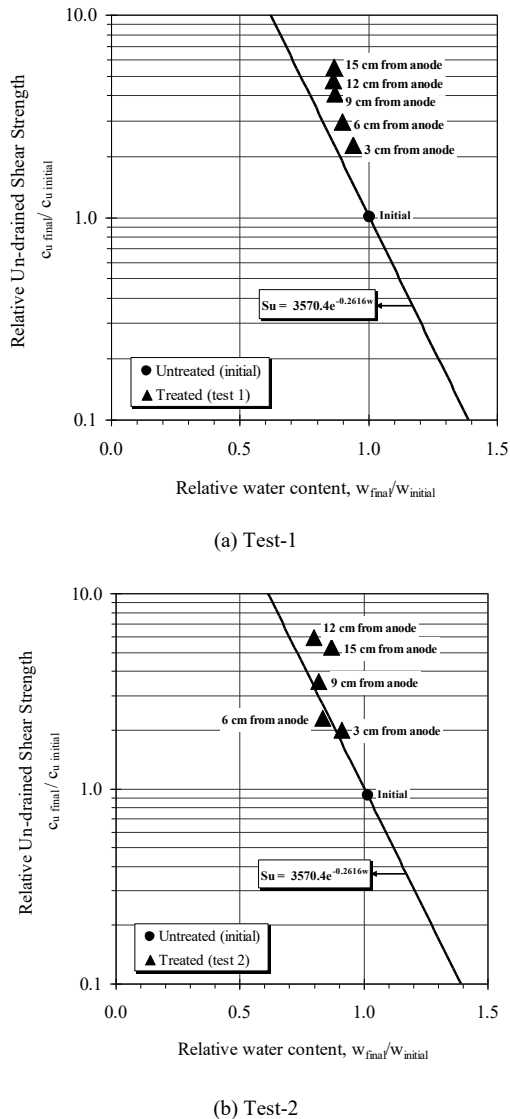


Fig. 11. Undrained shear strength and relative water content (measured at the end of test)

various pollutants, including heavy metals, organic compounds, and radionuclides [20].

In the case of electrokinetic soil stabilization, the soil stabilizer used is the alkaline earth group, which is the main constituent of soil and is also found in soil, such as calcium, or aluminum; thus, the use of electrokinetics poses relatively no risk to the environment.

4. Conclusion

Based on experimental tests undertaken to determine the changes in the strength of treated soil, overall strength increased by ECI treatment. The strength, however, was inhomogeneous, with the greatest increases observed closest to the cathode (or cathodic regions). After being treated with calcium chloride (anolyte) and sodium carbonate (catholyte) under a constant DC-current of 0.04A and a treatment period of 336 hours, the least amount of increase in test 1 was 127% (at 3 cm from the anode), and the largest was 454% (at 15 cm from the anode). In test 2, after being treated with calcium chloride (anolyte) and potassium hydrogen phosphate (catholyte), the smallest amount of increase was 100.32% (at 3 cm from the anode), and the largest was 494.66% (at 12 cm from the anode). Liquid and plastic limits of the soil increased slightly after ECI treatment. H^+ and OH^- ions generated by electrolysis reactions result in decreasing and increasing the pH of the anolyte and catholyte respectively. The gradient of electric power consumption increases exponentially over time; it sharply increased in the first 24 hours. The transport mechanism, as well as the electro-chemical processing (e.g., electrolysis) that was induced by the electric field in ECI, were largely consumed of electric power. Finally, the significant increase in soil strength using the proposed method was achieved; thus, the process can cope with bearing capacity problems in soft fine-grained soils with low hydraulic conductivity.

References

- Ahmed Abou-Shady, Wenzheng Yu, *Recent advances in electrokinetic methods for soil remediation. A critical review of selected data for the period of 2021-2022*, International Journal of Electrochemical Science 18 (2023) 1-16.
- A. Rachmansyah, L. Darmiyanti, R. Kusumaningrum, Harimurti, *Expansive Soil Improvement Using Electrochemical Injection*, Earth and Environmental Science 1249 (2023) 1-7.
- Arash Hosseini, S. Mohsen Haeri, Siavash Mahvelati, Aria Fathi, *Feasibility of using electrokinetics and nanomaterials to stabilize and improve collapsible soil*, Journal of Rock Mechanics and Geotechnical Engineering 11 (2019) 1055-1065.
- Adekemi Loretta Ayodele, Sibel Pakmucu, Reena Amartya Shrestha, Oluwole Akinyele Agbede, *Electrochemical Soil Stabilization and Verification*, Geotechnical and Geological Engineering (2017) 1283-1293.
- A. N. Alshawabkeh and T.C. Sheahan, *Stabilizing Fine Grained Soils by Phosphate Electro-Grouting*, Ground Improvement 7 (2003) 177-185.
- Ding Han, Xingyi Wu, Rui Li, Xianqiang Tang, Shangbin Xiao, Miklas Scholz: *Critical review of electro-kinetic remediation of contaminated soils and sediments: mechanisms, performances and technologies*, Water Air Soil Pollution (2021) 1-29.
- D.I. Boardman, S. Glendinning, and C.D.F. Rogers, *Development of stabilization and solidification in lime-clay mixes*, Géotechnique 50, No. 6 (2001) 533-543.
- Hamed A. Keykha, Bujang B. K. Huat, Afshin Asadi, *Electrokinetic Stabilization of Soft Soil Using Carbonate Producing Bacteria*, Geotechnical and Geological Engineering (2014) 739-747.
- I. G. Richardson, *The calcium silicate hydrates*, Cement and Concrete Research, 38 (2) (2008) 137–158.
- J. Akansa et al., *Technological and economic analysis of electrokinetic remediation of contaminated soil: A global perspective and its application in Indian scenario*, Heliyon 10, Review Article (2024) 1-19.
- K. Senneset and Y. B. Acar: *A glimpse at electrokinetic soil improvement*, Proceeding of Bengt. B. Broms Symposium on Geotechnical Engineering, Singapore, 13-15 December 1995, pp. 362-382.
- Lucas Martin, Vahid Alizadeh, Jay Meegoda, *Electro-osmosis treatment techniques and their effect on dewatering of soils, sediments, and sludge: A review*, Soils and Foundation (2019) 407-418.
- Lei Zhang, Liping Jing, Ningwei Wang, Chen Fang, Zhendong Shan, and Yongqiang Li, *Electro-Osmotic Chemical Treatment of Marine Clayey Soil Using $CaCl_2$ Solution*, Geomechanics and Geoengeering (2018) 36-48.
- L. J. West, D. I. Stewart, A. M. Binley and B. Shaw, *Resistivity imaging of soil during electrokinetic transport*, Engineering Geology 53 (1999) 205-215.
- Mona Malakzadeh, Julie Lovisa, Nagaratnam Sivakugan, *An Overview of Electrokinetic Consolidation of Soils*, Geotechnical and Geological Engineering, State of The Art review (2016) 1-18.
- N.M. El-Rawi and A.A. Awad, *Permeability of lime stabilized soils*, Transportation Engineering Journal (1981) 25-35.
- P. Asavadorndecha and U. Glawe, *Electrokinetic strengthening of soft clay using the anode depolarization method*, Bulletin Engineering Geology and Environment 64 (2005) 237-245.
- R. Azzam and W. Oey, *The utilization of electrokinetics in geotechnical and environmental engineering*, Transport in Porous Media 42 (2001) 293-314.
- R. Azzam, D. Tondera, and St. Höppner, *Elektrochemische Bodenverfestigung des Baugrundes der St. Nikolauskirche Wallbeck-Geldern*, Geotechnik 20, No. 3 (1997) 204-215.
- R. F. Probstein and R. E. Hicks, *Removal of contaminants from soils by electric fields*. Science 260 (1993) 498-503.
- Serin Issac, and Geetha Varma, *Dewatering and stabilization of Black cotton soil using Electrokinetic Geosynthetics*, Earth and Environmental Science (2018) 1-8.
- S. Ozkan, R.J. Gale, and R. K. Seals, *Electrokinetic stabilization of kolinite by injection of Al and PO_4^{3-} Ions*, Ground Improvement 3 (1999) 135-144.
- W. Oey and R. Azzam, R.: *Electrokinetic processes and their applications in environment geosciences*, 28th Annual Convention Indonesian Association of Geologist, Jakarta, Nov. 1999.
- Yongqiang Tang, Ningwei Wang, Tie Liu, *Electrokinetic Stabilization of Marine Clayey Soils by Different Injection Procedures*, Electrochemical Science (2021) 1-11.
- Yimin Liu, Xinyu Xie, Lingwei Zheng, Jinc Zhu Li, *Electroosmotic Stabilization on Soft Soil*, Electrochemical Science 13 (2018) 9051-9068.