Clay is a soil with low permeability. Clay is considered a problematic soil besides peat soil. The main problem with clay is its mineralogy. Expansive clay soils contain the minerals kaolinite, illite, and montmorillonite. Montmorillonite has weak bonds between its layers. These weak bonds make the soil easily incorporated, one of which is water. Water approaching expansive soil will bond with it and cause swelling.

Expansive soil improvement studies have been conducted. One of them is electrokinetic. Expansive soil from Karawang, Indonesia is one of the soils with a high swelling index. This is because montmorillonite is inside. The Karawang expansive soil will be improved by flowing several salt solutions with various voltages. The applied voltage will flow the solution from the anode to the cathode and fill the clay minerals. Four voltage variants will be applied with the same electrokinetic application time.

The mineralogy of soil before and after electrokinetic improvement undergone changes. The changes can be seen from SEM and XRF testing. The improved soil changed its physical properties from clay with high plasticity to clay with low plasticity. Chemical elements from salt solution trap in montmorillonite then make positive changes in soil mineralogy, soil physical properties, and mechanical properties. The mechanical properties can be seen in a decrease in the C value and an increase in the soil friction angle after electrokinetic improvement. After electrokinetic improvement using calcium chloride, the lowest soil cohesion value was 12.356 kg/cm^2 at 12 V. After electrokinetic improvement with calcium dioxide, the lowest cohesion value at 12 V voltage is 19.22 kg cm^2. In barium sulfate solution, the lowest soil cohesion at 15 V is 12.16 kg/cm^2. The soil swelling value decreased after improvement with calcium chloride to 0.008 % from 0.027 %. The research results in calcium chloride with 12 V give optimized results on soil improvement with electrokinetics

Keywords: expansive soil, electrokinetic, salt solution, swelling, shear strength, montmorillonite, improvement

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IDENTIFICATION OF THE INFLUENCE OF ELECTROKINETIC SOIL IMPROVEMENT ON THE MICROSTRUCTURE, PHYSICAL AND MECHANICAL PROPERTIES OF EXPANSIVE SOIL

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1. Introduction

Road infrastructure development is one way to accelerate the economic growth of a region. This infrastructure cannot avoid problematic soil. Expansive clay is a problematic soil besides peat. This condition makes geotechnical experts to improve the physical and mechanical properties of clay. The problem with expansive clay is its mineralogy: montmorillonite, illite, and kaolinite. Expansive clay containing montmorillonite has a mineral structure of 2:1 between silica (SiO_2) and alumina (Al_2O_3) and has a soil capability for cation exchange called cation exchange capacity (CEC). Divalent cations bind to the clay surface more strongly than monovalent cations, following a CEC such as $Na^+ < Li^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$. This condition makes montmorillonite easy to catch any element. Water (H_2O) was a mineral most easily bound by montmorillonite. H_2O enters montmorillonite and causes swelling. The swelling index increased linearly with a proportion of montmorillonite. Electrokinetics is a method of removing water from soil.

The main advantage of electrokinetic soil improvement is that it can be carried out on land with buildings. So there is no need to change the existing structure and building.

Electrokinetic improvement using calcium chloride solution has been carried out on clay soils and has proven to improve soil mechanical properties.

Calcium chloride solution in electrokinetics is known to change the physical and mechanical properties of soil by reducing LL, PL, IP, and growth potential, while also changing the soil friction angle and cohesion values of the soil. Minerals in the soil are also changed by injection chemical solutions. Changes in soil cohesion and soil friction angle can affect soil shear strength. There was an increase in the shear strength of the expanded soil treated with brine at the anode. The electrokinetic method using salt water injection can reduce LL, PL, and IP values and affect soil development value. The electroosmosis process causes water to move from the anode to the cathode, and at the same time introduces a salt solution, leading to changes in the physical and mineral properties of the soil, and soil compaction occurs at anytime distance.

It is known that salt solutions used for electrokinetics achieve better consolidation effects when using $CaCl_2$. Because the exchange capacity in the electrical double layer and the hydration capacity of cations are different, $CaCl_2$ can provide a greater enhancement to the electroosmotic fusion process than KCl and NaCl.

Electrokinetic soil improvement with $CaCl_2$ solution can improve the physical and mechanical properties of soil. Electrokinetic improvement research on expansive clay soil needs to be done to see the differences that occur because it has different montmorillonite contents.

Research using other solutions needs to be conducted to find out how they affect expansive soils. Therefore, research on electrokinetic improvement with the best solution is relevant.

2. Literature review and problem statement

The spread of problematic soils in Indonesia is a challenge. Expansive clay is a problematic soil with low permeability and high shrinkage. Expansive soil improvement has been done with various methods and stabilizers. Electrokinetic soil improvement is the most effective solution for low-permeability clay soil.

Expansive soil improvement research with electrokinetic $CaCl_2$ yielded good and effective results [1]. The research results show there was a decrease in the Atterberg limit, an increase in the shear strength, and an increase in the consistency of soil. Electrokinetics was applied in 6 days with different readings. Aluminum plates were used as electrical conductors. Tests of the Atterberg limit, consolidation, and shear strength were done for this research. Mineralogy is known from the XRD results. The results of this study showed an increase in the Atterberg limit on LL, which is 79.72–86.14 % and plastic limit (PL). Its compressibility decreased, as can be seen from the results of *Cc*, there was an increase in soil shear strength and an increase in soil strength reaching 304–556 %. However, the limitation of this research is that no testing is done within a certain time after electrokinetics so that the long-term possibility does not influence it in terms of physical, mechanical, and mineralogical strength.

The approach used in this study is to use $CaCl_2$. $CaCl_2$ is decomposed by Ca^{2+} and Cl^2. $CaCl_2$ is used in electrokinetic soil improvement but this paper didn't explain the potential effect on the environment.

Research on soil improvement by electroosmosis was conducted on Na-bentonite soil [2]. Na-bentonite soil has similar characteristics to expansive soil. The research used 4 kinds of electrodes: copper, iron, graphite, and stainless steel. The results showed that there was an influence on physical and chemical properties: plasticity, swelling, zeta potential, and CEC.

LL values decreased for copper, iron, and graphite electrodes, and LL increased for stainless steel electrodes. PL increased so that the IP value decreased. The copper electrode is the best conductor of the others, this can be seen from the lower water content obtained on the copper conductor. The weakness of this research is that it does not explain the duration of electroosmosis and how long the test is carried out after electroosmosis is complete.

Laboratory-scale research was conducted using one-dimensional columns with model scale conditions as in the field, but this cannot describe with certainty the real conditions in the field.

Improvement of expansive clay soil by adding K^+ and Ca^+ ions as stabilizers resulted in various effects on the soil [3]. The result of this research is the swelling value of the soil from 14 % to 3.1 % for the Ca^+ stabilizer and 0.4 % for the K^+ stabilizer – the plasticity index for the K^+ ion stabilizer to 8 while for the Ca^+ ion to 32. The increase in soil friction angle is also seen greater for soil with the K^+ stabilizer, which is 36 degrees while the Ca^+ soil friction angle is 30.9 degrees. The weakness of this study is that it does not discuss the source of the soil although there are physical test results and the soil is included in the inorganic soil with high plasticity. The percentage of K^+ and Ca^+ ion addition was also not explained in the study. However, the paper didn't discuss any impact on the environment.

Improvement of kaolin soil from the USA by electrokinetics was carried out by conditioning the soil at 65 % LL [4]. The stabilizing solution used was $CaCl_2$. Tests were conducted on soil with variants: electrokinetic (EK) + vacuum drainage (VAC), EK, and VAC. $CaCl_2$ solution was placed in the anode reservoir with a constant voltage of 25 V for 7 days. This study reads the current, voltage, electrical resistance, drainage, and geotechnical properties of the soil. The results of the study for the Atterberg limit value in EK+VAC increased from 17 % to 12 %. Soil shear strength increases as the distance from the anode to the cathode increases. The temperature and current during the electrokinetic process were seen to decrease from the anode to the cathode and simultaneously with an increase in the electrokinetic time. Soil subsidence was seen to be greatest at the cathode area. The limitation of this research is that the concentration of $CaCl_2$ solution is not explained. And only one salt solution was used. Electrokinetic research with 3 salt solutions namely $CaCl_2$ 0.1 % and 1 %, KCl 0.1 %, and NaCl 0.1 % was carried out with 3 voltage variations namely 8 V, 10 V, and 12 V for 7 days. What makes the research unfeasible is that the soil condition is 100 % kaolin clay. In comparison, the original clay condition will have other mineralogical contents besides kaolin.

Electrokinetic research on salty soils of Ain Nouissy origin has been carried out [5]. Measurements of electric current, effluent flow, and water content were made with voltage variants. Chemical properties are known from the XRF results while mechanical properties are known from French testing standards. The natural soil has a clay mineral content of SiO_2, Al_2O_3, and Fe_2O_3. The addition of Na^+, Ca^{2+}, K^+, and Mg^{2+} ions with concentrations of 1917.2 mg/kg, 1,165 mg/kg, 136 mg/kg, and 94 mg/kg was applied to the soil with a 30 V voltage. An increase in shear strength was also obtained from this study with a greater value at the anode area. The limitation of this study is the non-uniformity of the concentration of stabilizers given, so it is impossible to see the relationship between the incoming ions and the length of the electrokinetic process. The results of this study are irrelevant due to the different salt content of each salty soil in the world.

Electrokinetic stabilization of sandy clay soil has been carried out using Na_2CO_3 and $CaCl_2$ solutions with a concentration of 10 % [6]. The experiment was done with electrokinetics for 10 days with a voltage between electrodes of 10 V. Tests before and after the electrokinetic process were carried out: water content, USC, unconsolidated triaxial UU, and XRD. This research resulted in physical testing of soil before injection, it was clay with low plasticity. XRD showed the formation of new compounds after electrokinetics, including calcium, magnesium, aluminum, silicate (Ca-Mg-Al-Si-O) and amorphous compounds in the soil samples. From mechanical testing there are changes. There was an increase in the soil friction angle but a decrease in the soil cohesion. What is expected to be done in this study is testing the physical properties of soil after electrokinetics. So, the overall effect of 10 % Na_2CO_3 and $CaCl_2$ solution can be concluded. The absence of a discussion of the dissolving properties of the two chemicals is a limitation in this study.

Electrokinetic stabilization research using 2 types of expansive soil was conducted [7]. The voltage applied was 25 V and 2 A for 21 days. Microstructure testing conducted by XRD and SEM before and after the electrokinetic process did not find new minerals. The purpose of this research is only to see the changes that occur in the mineralogy. So we do not know the influence of the electrokinetic process on the physical and mechanical properties of soil. The results of numerical and statistical research are also not obtained so it cannot be known with certainty how this process affects the electrokinetically stabilized soil.

Much electrokinetic research has proven that there are changes in the mineralogy, physical properties, and mechanical properties of soil stabilized by electrokinetic injection. Changes in soil mineralogy can be seen from the results of SEM, XRF, and XRD, while the physical properties of the soil can be seen from the Atterberg limit value and specific graphite value. Mechanical testing of the soil can be done with several tests by knowing the cohesion value, soil friction angle, and development value of the soil.

Ions and chemicals are used in the electrokinetic process as stabilizing agents so that the soil is completely improved and will no longer have an effect on positively charged minerals approaching the positively charged clay soil.

Ca^{2+} ions are considered to have very good improvement ability. Some ions with good exchange capacity and positive charge need to be researched further. One of them is barium sulfate ($BaSO_4$), which functions as an oil well drilling fluid. $BaSO_4$ flowing to the seabed will increase density, and accelerate hydrostatic pressure so that it is not followed by oil when pumped out of the seabed [8], which is the basis for the decision to use $BaSO_4$ in soil improvement. The limitation of previous research that did not consider the time of binding of stabilizer ions after electrokinetic injection is a strong input for further research. With this background, further research is needed on electrokinetic soil improvement using $CaCl_2$, $Ca(OH)_2$, and $BaSO_4$ at the same solution concentration using certain voltage variants and treatment times.

3. The aim and objectives of the study

The aim of the study is to identify the influence of the electrokinetic improvement of expansive soil by using three kinds of salt solutions. This will make it possible to choose one of the solutions that gives the best effect on the mechanical properties.

To achieve the aim, the following objectives were accomplished:

– to identify the influence of electrokinetic improvement on the microstructure properties of the soil;

– to identify the influence of electrokinetic improvement on the physical properties of the soil;

– to identify the influence of electrokinetic improvement on the mechanical properties, namely soil shear strength, and swelling. The chosen solution gives optimum results.

4. Material and methods

The object of this research is expansive soil from Karawang, West Java, Indonesia. The soil samples taken were disturbed soil at a depth of 3 m. The electrokinetic improvement test used 3 kinds of salt solutions namely $CaCl_2$, $Ca(OH)_2$ and $BaSO_4$.

$Ca(OH)_2$ and $Ba(SO)_4$ solutions were chosen in this study. $Ca(OH)_2$ has a CaO base material that is commonly used in soil improvement. $Ba(SO)_4$ solution is a solution used in petroleum drilling. $Ba(SO)_4$ solution makes the soil have a large mass so that it is not lifted when oil is removed from the earth.

From the three solutions used, the optimum solution for electrokinetic soil improvement will be taken. The best solution is seen from the mineralogy, physical properties, and mechanical properties of the soil after electrokinetic repair. This solution will be used for field application for expansive soil improvement.

The natural soil used has characteristics as shown in Table 1.

Table 1

Physical testing of soil

Liquid limit (LL)	%	65.068
Plastic limit (PL)	%	30.977
Shrinkage limit (SL)	%	18.14
Plasticity index (PI)	%	34.1
Specific gravity (Gs)	%	2.625
OMC	%	22
ɣd	%	1.418
Swelling	%	7.177

According to Table 1, the soil is classified as clay soil with high plasticity (USCS). The swelling potential index is 7.177 % meaning a high potential for swelling. Specific gravity (Gs) for soft soil ranges from 2.6 to 2.7 % with an OMC of 22 % meaning the soil is clay soil. Gs of soil is influenced by water content, soil density, and mineralogy. ɣd of clay soil is 1.4–1.9 gr/cm^3. Standard testing for soil data is shown in Table 2.

Table 2

Soil testing standards

Soil Test	ASTM
Sieve analysis	D-1921
Specific gravity	D-854
Atterberg limit	D-4318
Triaxial	D-4767
Consolidation	D-2435

The overall research stages can be seen in Fig. 1.

The electrokinetic soil improvement process with three variants of salt solution can be seen in Fig. 2.

Fig. 2 shows the research process from the initial stage to completion. Tools are prepared in the form of a soil sample testing box, a DC power supply is used to provide voltage and current to the specimen, cables as voltage and current conductors are attached to both copper plates that function as electrical conductors, filter paper is placed between the copper plate and the soil sample, which serves to hold the soil into solution. A measuring cup serves to measure the amount of water that comes out of the electrokinetic improvement process.

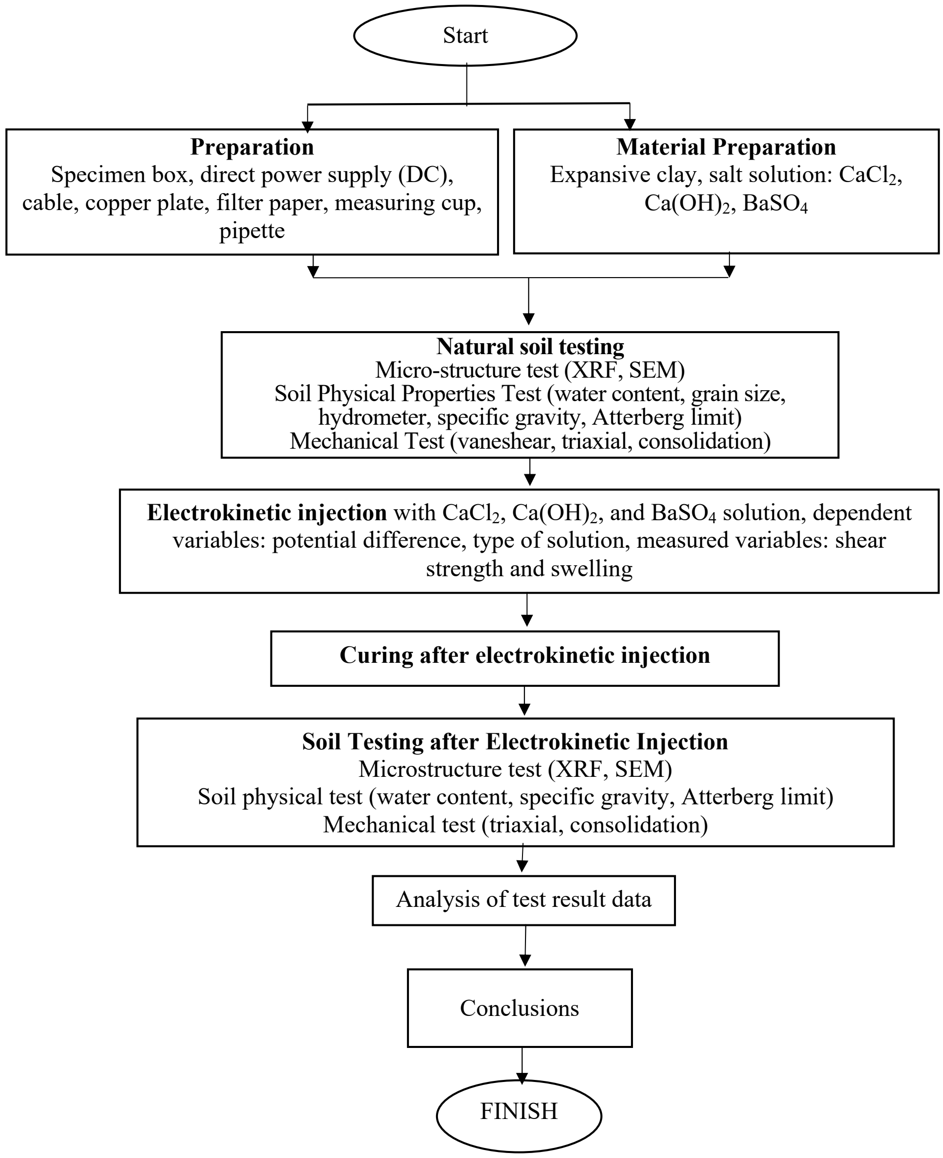
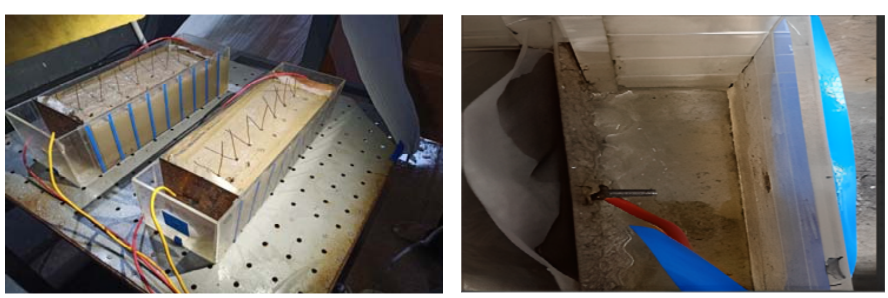


Fig. 1. Research flowchart



a *b*

Fig. 2. Electrokinetic improvement: *a* – electrokinetic improvement process; *b* – water flowing from the electrokinetic process

Microstructure testing in the form of SEM and XRF was carried out on the natural soil and soil after injection with 3 solutions. The electrokinetic injection method was carried out for 7 days with 24-hour readings. Preparation of tools for the electrokinetic improvement process was made using the aclyric box, which is given 4 voltage variations 12 V, 15 V, 18 V, and 24 V. Copper plates were installed on both sides of the box, which functioned as electrical conductors. Negative electricity is given to the cathode plate and positive electricity is given to the anode plate. $CaCl_2$, $Ca(OH)_2$, $BaSO_4$ solutions flowed from the anode to the cathode. The voltage and current were read every hour for every 50 mm.

Soil physical properties testing was conducted before and after electrokinetic improvement to determine changes in soil classification. Mechanical testing before electrokinetic injection was also carried out to determine changes after soil improvement. Soil samples after injection were subjected to curing and subsequent mechanical testing to determine soil shear strength and swelling.

The variable of interest in this study is the mechanical properties of the soil as indicated by the shear strength and swelling of the soil after repair. The influencing variables are the type of chemical solution and voltage variation.

This research will answer several research hypotheses, namely:

– there are differences in the elements contained in the soil after electrokinetic repair;

– there is a change in the type of soil that has been subjected to electrokinetic soil improvement;

– there is a difference in the shear strength parameters of soil that has been improved by electrokinetic soil improvement as indicated by the value of soil cohesion, soil friction angle, and swelling.

The basic assumption used in the research is that the amount of voltage affects the speed of the solution from the anode to the cathode. In this situation, the amount of the salt solution that enters the soil also increases.

5. Research results on electrokinetic soil improvement with calcium chloride, calcium dioxide, and barium sulfate solution

5. 1. Microstructure testing

SEM testing was carried out to determine the image and mineral form of clay. The magnification of the image was taken 10,000 larger than the natural image (Fig. 3).

Soil microstructure testing can also be seen from the X-ray fluorescence results in Table 3.

From the XRF results (Table 3), the oxides and elements of the 4 samples, namely natural soil, soil with $CaCl_2$, $Ca(OH)_2$, and $BaSO_4$ injection are known. It is known that the natural soil contains the largest quartz mineral (SiO_2) with a percentage of 52.6 %, with $CaCl_2$ injection there is 51 % SiO_2, $Ca(OH)_2$ injection there is 48.3 % SiO_2 and increases to 53.5 % after $Ba(SO)_4$ injection.

Quartz, feldspar, smectite, calcite, kaolinite, and some chlorite indicate that the soil is an expansive clay [9]. The oxide results of the aski natural did not contain osmium tetroxide (OsO_4). After injection with the three chemical solutions, OsO_4 was found in the specimen with $CaCl_2$ and $BaSO_4$ injection. From the results of the elements, it can be seen that Ca is bound to the soil with the largest percentage of $CaCl_2$ injection of 5.57 %. Besides that, for $BaSO_4$, it can be seen that there is no element of barium (Ba) bound and contained in the soil.

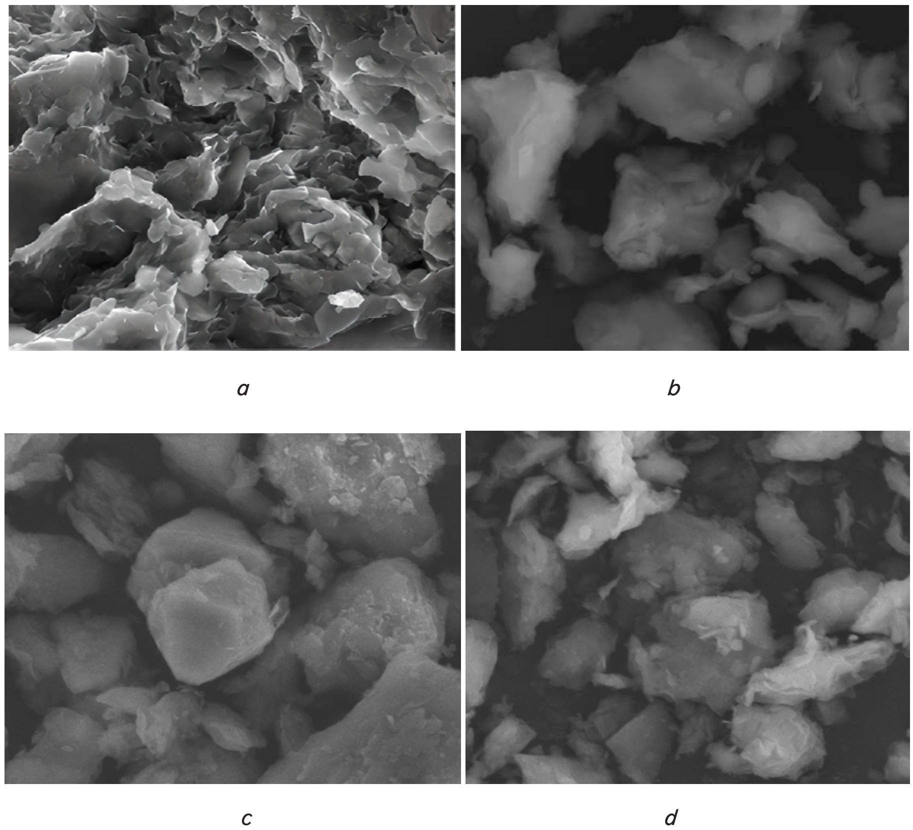


Fig. 3. SEM images of clay soil: *a* – natural soil; *b* – soil with $CaCl_2$ injection; *c* – soil with $Ca(OH)_2$ injection; *d* – soil with $BaSO_4$ injection

Table 3

XRD results from natural soil and soil after electrokinetic improvement with $CaCl_2$, $Ca(OH)_2$ and $BaSO_4$

Oxide	Natural	$CaCl_2$	$Ca(CO)_2$	$BaSO_4$	Element	Natural	$CaCl_2$	$Ca(CO)_2$	$BaSO_4$
Al_2O_3	11	12	13	13	Al	9.0	10	10	10
SiO_2	52.6	51.0	48.3	53.5	Si	39.5	38.3	35.8	40.8
SO_3	2.6	2.0	1.5	2.1	S	1.6	1.4	1.0	1.5
K_2O	2.23	1.84	1.74	1.97	K	3.44	2.8	2.58	3.05
CaO	1.87	4.17	1.52	1.48	Ca	2.57	5.57	1.96	2.00
TiO_2	1.66	1.6	1.63	1.54	Ti	1.91	1.85	1.81	1.78
V_2O_5	0.05	0.05	0.054	0.04	V	0.086	0.05	0.057	0.05
Cr_2O_3	0.068	0.057	0.071	0.059	Cr	0.088	0.076	0.092	0.079
MnO	0.14	0.074	0.17	0.16	Mn	0.26	0.12	0.26	0.26
Fe_2O_3	23.7	20.9	28.64	21.5	Fe	36.0	31.0	41.70	32.3
CuO	0.069	2.24	0.24	2.18	Cu	0.13	4.15	0.43	4.13
ZnO	0.095	0.064	0.088	0.078	Zn	0.19	0.12	0.16	0.15
MoO_3	3.3	3.2	2.9	2.4	Mo	4.5	3.8	3.4	2.9
Eu_2O_3	0.33	0.27	0.07	0.28	Eu	0.45	0.47	0.1	0.49
Re_2O_7	0.10	0.07	0.1	0.06	Re	0.2	0.1	0.2	0.1
OsO_4	–	0.09	–	0.10	Os	–	0.2	–	0.2

5. 2. Soil physical testing

Physical testing of the soil was carried out to determine whether the natural soil and the improved soil would change in type. The physical tests carried out after electrochemical injection include the Atterberg limit and specific gravity values.

From Fig. 4, the LL value of the natural soil is 65.1 %, PL 31 %. IP 28.2 %, SL 34.1 %, with the USCS classification system, and based on the Casagrande plasticity chart, the natural soil is an inorganic clay with high plasticity (CH). The soil injected with $CaCl_2$ solution at 12 V voltage has an LL value of 48.3 %, Pl 27.1 %. PI 21.2 % and SL 25.4 % indicate the type of inorganic clay with low plasticity (CL). $CaCl_2$ injection with 15 V showed LL 47.4 %, PL 27.1 %, IP 20.3 %, and SL 25.6 % including CL soil. $CaCl_2$ injection with 18 V showed LL 46.6 %, PL 26.4 %, IP 20.2 %, and SL 25.7 % including CL soil. $CaCl_2$ injection with 24 V showed the results of LL 46 %, PL 25.9 %, IP 20.2 %, and SL 25.8 % including CL soil. Electrokinetic improvement with $Ca(OH)_2$ with 4 voltage variants showed similar results to $CaCl_2$ injection. The soil injected with $Ca(OH)_2$ solution at 12 V voltage had LL values of 46.9 %, and Pl 26.6 %. PI 20.3 % and SL 24.5 % indicating the type of inorganic clay with low plasticity (CL). $Ca(OH)_2$ injection with 15 V showed LL 46.1 %, PL 26.3 %, IP 19.9 %, and SL 24.1 % belonging to CL soil. $Ca(OH)_2$ injection with 18 V showed LL 45.4 %, PL 25.8 %, IP 19.6 %, and SL 23.4 % belonging to CL soil. $Ca(OH)_2$ injection with 24 V showed the results of LL 45 %, PL 25.7 %, IP 19.4 %, and SL 23.2 % belonging to CL soil. Electrokinetic improvement with $BaSO_4$ with 4 voltage variants showed similar results to $CaCl_2$ and $Ca(OH)_2$ injection. The soil injected with $BaSO_4$ solution at 12 V voltage has an LL value of 45.4 %, Pl 26 %. PI 19.5 % and SL 25.7 % indicating the type of inorganic clay with low plasticity (CL). $BaSO_4$ injection with 15 V showed LL 48.6 %, PL 25.4 %, IP 22.7 %, and SL 25.4 % including CL soil. $BaSO_4$ injection with 18 V showed LL 41.7 %, PL 20.7 %, IP 18.4 %, and SL 16.7 % including CL soil. $BaSO_4$ injection with 24 V showed the results of LL 46.3 %, PL 25.1 %, IP 21.1 %, and SL 25.3 % belonging to CL soil. The Gs value of all samples that have been improved showed no significant change and the Gs value of 2.6 to 2.7 is the Gs for clay soil.

From Fig. 4, it can be concluded that the changes in soil type that have been carried out with 3 variants of chemical solutions show that the soil type changes from CH to CL.

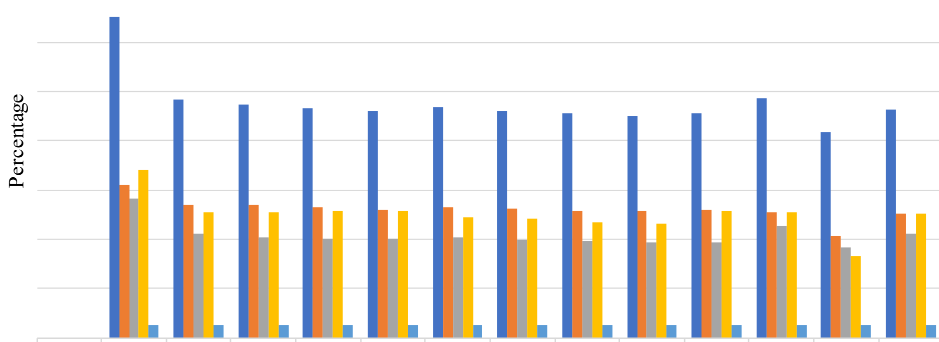
5. 3. Soil mechanical testing

One of the changes in soil mechanical properties is by knowing the shear strength of the soil. The value of soil shear strength is influenced by the value of soil cohesion and soil friction angle. Soil shear strength is linearly related between the cohesion value and the soil friction angle in the soil. Tests were conducted by ASTM D – 4767. Clay is a soil that has high cohesion. Mechanical testing of the soil was carried out before and after electrokinetic injection. The test results can be seen in Fig. 5, 6.

The natural soil cohesion value of 29.5 kPa indicates that the natural soil is clay soil having a soil cohesion value of 0 to 30 kPa. The natural soil cohesion was obtained in OMC soil conditions. The injection improvement process was carried out in the LL soil condition of 60 %. The soil after improvement experienced a change in cohesion value, which was influenced by the amount of voltage applied. The cohesion value for the soil with $CaCl_2$ solution at 12 V voltage was 12.36 kPa, the cohesion at 15 V voltage was 18.83 kPa, the cohesion at 18 V voltage was 19.42 kPa and the cohesion at 24 V voltage increased to 19.51 kPa.

From the test results, the cohesion value for soil with $Ca(OH)_2$ solution at 12 V voltage was 19.22 kPa, cohesion at 15 V voltage was 19.42 kPa, cohesion at 18 V voltage was 24.52 kPa, and cohesion at 24 V voltage increased to 21.57 kPa. The cohesion value for soil with $BaSO_4$ solution at 12 V voltage was obtained at 14.8 kPa, cohesion at 15 V voltage was 12.16 kPa, cohesion at 18 V voltage was 13.24 kPa, and cohesion at 24 V voltage increased to 18.24 kPa. The results showed that the amount of voltage applied affected the value of soil cohesion.

From Fig. 6, the value of the soil friction angle in the natural soil was calculated under the condition of OMC soil moisture content of 1.48°. The change in the soil friction angle of the soil after being electronically stabilized with three chemical solutions changed based on the applied voltage. soil friction angle of the soil with $CaCl_2$ solution at 12 V voltage was 1.95°, the soil friction angle at 15 V voltage was 1.42°, for 18 V voltage was 1.43° and for 24 V voltage was 1.43°.



	Unit	Soil Natural	CaCl2 12V	CaCl2 15V	CaCl2 18V	CaCl2 24V	Ca(OH)2 12V	Ca(OH)2 15V	Ca(OH)2 18V	Ca(OH)2 24V	BaSO4 12V	BaSO4 15V	BaSO4 18V	BaSO4 24V
LL	0%	65.1	48.3	47.4	46.6	46.0	46.9	46.1	45.4	45.0	45.4	48.6	41.7	46.3
PL	0%	31.0	27.1	27.1	26.4	25.9	26.6	26.3	25.8	25.7	26.0	25.4	20.7	25.1
PI	0%	28.2	21.2	20.3	20.2	20.2	20.3	19.9	19.6	19.4	19.5	22.7	18.4	21.1
SL	0%	34.1	25.4	25.6	25.7	25.8	24.5	24.1	23.4	23.2	25.7	25.4	16.7	25.3
Gs	0	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.6

Voltage Variant and Chemical Solution

Fig. 4. Atterberg limit and Gs of natural and stabilized soils

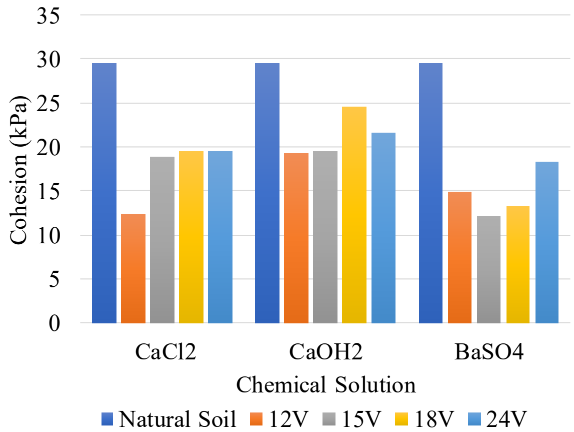


Fig. 5. Soil cohesion values before and after electrokinetic improvement

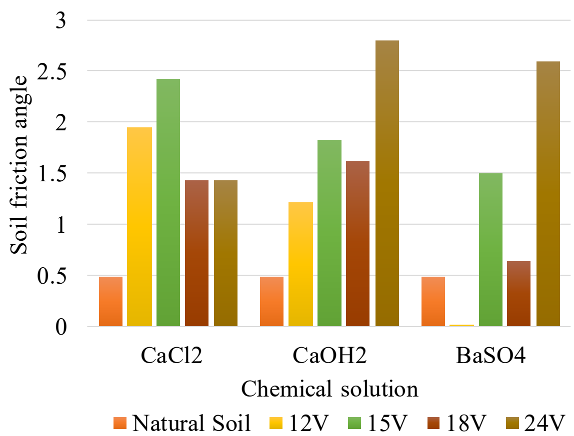


Fig. 6. Soil friction angle in the soil before and after electrokinetic improvement

The soil friction angle of soil with $Ca(OH)_2$ solution with 12 V voltage is 1.21°, the soil friction angle at 15 V voltage is 1.82°, for 18 V voltage is 1.62° and for 24 V voltage is 2.8°. The soil friction angle of soil with $BaSO_4$ solution with 12 V voltage is 0.01°, the soil friction angle at 15 V voltage is 1.5°, for 18 V voltage is 0.64° and for 24 V voltage is 2.59°.

One of the weaknesses of expansive clay is its high shrinkage properties. The value of soil development can be known from several tests. In this study, one-way consolidation testing was conducted to evaluate soil development. The compressibility value is indicated by the soil compression index (*Cc*). The development index can be seen in Fig. 7.

Fig. 7 shows the *Cc* values for the natural soil and the soil stabilized with three different chemical solutions and voltages. *Cc* for the natural soil is 0.070. The *Cc* value for the soil stabilized with $CaCl_2$ with different voltages changes when compared to the natural soil. Specimens given a voltage of 12 V experienced a change in the *Cc* value to 0.040, *Cc* in specimens with 15 V to 0.033, *Cc* in 18 V specimens to 0.054, and specimens given a voltage of 24 V experienced a change to 0.056. The *Cc* value for the soil stabilized with $Ca(OH)_2$ changed when compared to the natural soil *Cc*. Specimens treated with 12 V voltage experienced a change in the *Cc* value to 0.040, *Cc* in specimens with 15 V to 0.033, *Cc* in 18 V specimens to 0.054, and specimens treated with 24 V voltage experienced a change to 0.040.

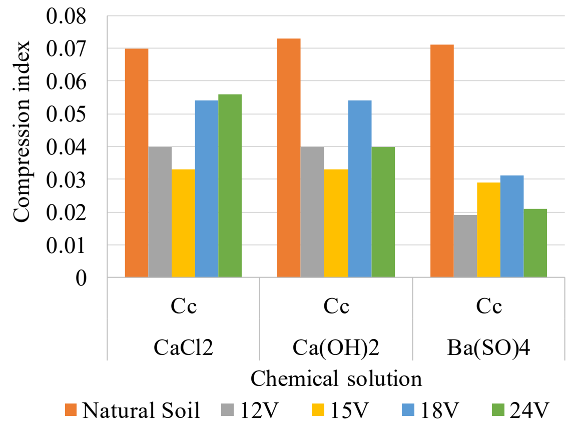


Fig. 7. *Cc* for soil friction angle and electrokinetically stabilized soil

The *Cc* value for the soil stabilized with $BaSO_4$ at 12 V voltage changed to 0.019, *Cc* for the specimen with 15 V to 0.0029, *Cc* for the specimen with 18 V to 0.0313, and the specimen with 24 V voltage changed to 0.0125. The swelling index from electrokinetic improvement is shown in Fig. 9.

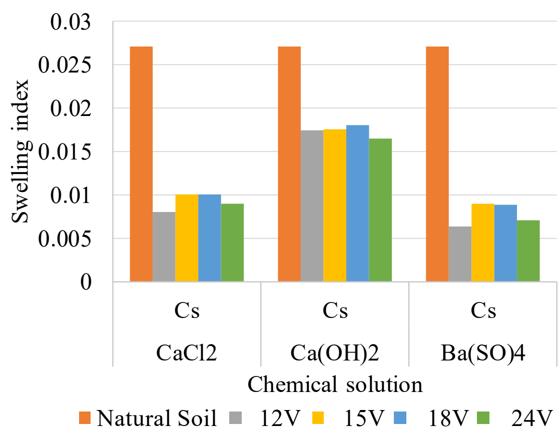


Fig. 8. *Cs* for natural soil and electrokinetically stabilized soil

Fig. 8 shows the *Cs* values for the natural soil and the soil stabilized with three different chemical solutions and voltages. *Cc* for the natural soil is 0.027. The *Cs* value for the soil stabilized with $CaCl_2$ with different voltages changes when compared to the natural soil. Soils given a voltage of 12 V experienced a change in the *Cs* value to 0.008, *Cs* in specimens with 15 V to 0.01, *Cs* in 18 V specimens to 0.001, and specimens given a voltage of 24 V experienced a change to 0.009. The *Cs* value for the soil stabilized with $Ca(OH)_2$ changed when compared to the natural soil *Cs*. Specimens treated with 12 V voltage experienced a change in the *Cs* value to 0.0174, *Cs* in specimens with 15 V to 0.0175, *Cs* in 18 V specimens to 0.018, and specimens treated with 24 V voltage experienced a change to 0.0165.

The *Cs* value for the soil stabilized with $BaSO_4$ at 12 V voltage changed to 0.0063, *Cs* for the specimen with 15 V to 0.009, *Cs* for the specimen with 18 V to 0.0088, and the specimen with 24 V voltage changed to 0.00705.

6. Discussion of the research results on electrokinetic soil improvement with calcium chloride, calcium dioxide, and barium sulfate solution

Expansive clays have special mineralogy such as montmorillonite, illite, and kaolinite. Scanning Electron Microstructure testing needs to be done to determine the natural of the clay structure to be improved. The results of SEM for the natural soil in this study look like the mineralogy of smectite, namely montmorillonite [1]. Mineralogies consisting of 2 tetrahedral layers and 1 octahedral layer have weak van der Waals bonds between each layer. These bonds make the soil very easy for other mineralogies to get close to, and then get trapped in. Clays with a negative charge also attract other minerals with a positive charge very easily.

Fig. 2 is an SEM image of two soil samples with a magnification difference of 10,000x. The difference in magnification can make a significant difference in the interpretation of soil mineralogy [2]. Chemical solutions that enter will fill the pores and affect the porosity. From the mineralogical image of the natural soil with the soil that has been an electrokinetic injection of $CaCl_2$, $Ca(OH)_2$, and $BaSO_4$ solutions. The natural soil shows mineralogical sheets of the smectite group (montmorillonite). Fig. 2, *a–c* shows a change where the mineralogy sheet is no longer visible. This is known to have trapped other minerals with a positive charge on the clay. Ionization of $CaCl_2$=$Ca^{2+}2Cl^{-}$ makes Ca^{2+} bound to the negatively charged clay. Ionization for $Ca(OH)_2$=Ca^{+}+$2(OH)^{-}$ and $BaSO_4 = Ba^{2+} + SO_4^{2-}$ also makes Ca^{2+} and Ba^{2+} enter the clay minerals with negative charge.

Another microstructure test is X-ray fluorescence (XRF) to know the elements in the soil and soil oxides so that the soil mineralogy can be known. The XRF test results show the amount of elements weathered from the mineral composition contained in the siliciclastic sandstone bedrock. From the previous study [6], new compounds were found: calcium, magnesium, aluminum, silicate (Ca-Mg-Al-Si-O). The levels of elements including Si^{4+} and Fe^{2+} have the largest percentage and Al^{3+}, Ca^{+}, and K^{+} are elements with small amounts. In the form of compounds, SiO_2, Fe_2O_3 and Al_2O_3 are compounds with the highest ratio contained in all residual soils. Chemical compounds in residual clay soil contain SiO_2, Fe_2O_3, Al_2O_3, CaO, K_2O, and TiO_2. The XRF table shows that natural soil contains the most chemical compounds resembling residual soil. Chemical compounds in the natural soil, namely from quartz, namely SiO_2 52.6 %, Fe_2O_3 23.7, Al_2O_3 11 %, K_2O 2.23 %, CaO 1.87 %, and TiO_2 1.66 %, are residual soils. The residual soil formed is a clay soil that has montmorillonite mineralogy [10]. The elements of chemical solution in the process of electrokinetic improvement of expansive clay soil were obtained. The natural soil contains 2.57 % Ca, and the XRF result after electrokinetic improvement of the largest Ca element of the $CaCl_2$ solution is 5.57 % Ca. The increase reached 200 %. This happens because the ability to dissolve the three chemicals is different. All solutions were made with the same concentration of gram/liter. However, $CaCl_2$ has a very large dissolving ability.

The physical testing of soil aims to find the classification of the natural soil and electrokinetically stabilized soil with 4 voltage variants. Fig. 4 shows that there is a change in the Atterberg limit value and the specific graphite value of the soil. There is an increase in the Atterberg limit value of the natural soil with electrokinetically stabilized soil. The increase in the Atterberg limit value seen from LL of natural soil with LL, PL, PI, and SL of stabilized soil ranges from 74.27 % to 151 %. The increased Atterberg value is due to an increase in calcium and barium ions entering the pore water, so that the electrostatic attraction increases on the positive and negative surface of the clay. This increase in the Atterberg value resulted in a change in soil type. According to the USCS soil classification system, the soil type changes from CH to CL.

Soil mechanical testing was conducted to determine the soil shear strength and swelling value. Soil shear strength is influenced by the soil friction angle and cohesion value. The soil object in the study is expansive clay soil according to the data in Table 1. Clay soil is soil that has closeness between the grains. The amount of soil adhesion is reflected in the magnitude of the cohesion value (C) of the soil. In Fig. 5, the soil friction angle of the natural soil and electrokinetically stabilized soil with four voltage variants shows a decrease in the C value. From 3 chemical solutions and 4 variants of applied voltage, the cohesion value drops significantly. For the specimens treated with $CaCl_2$ solution, there was an increase in the cohesion value as the applied voltage increased. For specimens given $Ca(OH)_2$, the same thing happened with $CaCl_2$. The difference occurs in the specimen with a voltage of 18 V. For $BaSO_4$ in general, there is a change in the cohesion value, which decreases at voltages of 15 V and 18 V. The value of the soil friction angle in the soil can be seen in Fig. 6, there is a significant change. The amount of soil friction angle that occurs is different for each voltage difference.

The process of increasing the shear strength of the soil will be linear with a decrease in the cohesion value and an increase in the soil friction angle of the soil. In the soil with electrokinetic stabilization with Ca^{2+}, the cohesion value will decrease from 174 kPa to 121 kPa, and the friction angle will increase from 24° to 30.9° [3]. And the other studies found the same result [6]. A decrease in the cohesion value from 0.0328 kg/cm^2 to 0.018 kg/cm^2 while increasing friction angle from 1.8677° to 6.9822°. For this study, the electrokinetic improvement with $CaCl_2$, $Ca(OH)_2$, and $BaSO_4$ can increase the shear strength of clay soil caused by a decrease in the cohesion value and an increase in the friction angle.

The limitation of this research is that the applied voltage will affect the selection of the conductor material (electrical conductor) used. Corrosion of the conductor material will occur faster if the voltage applied is too large. The amount of voltage given affects the speed of drying water in the soil [11]. The electrical conductor material used is only one type, namely copper plates. Copper is the best material to conduct electricity but the fastest to defeat corrosion, so it cannot be used for a long time.

From various soil improvements with electrokinetics, it is known that $CaCl_2$ has a significant effect. It is necessary to conduct research with 2 different chemical solutions, in addition to $CaCl_2$ for comparison. The chemical solution that has the best results in microstructure, physical, and mechanical testing will be used for further research.

Further research will be developed with several other variables that affect the electrokinetic soil improvement process. Then a Taguchi experimental design will be carried out to optimize the results of electrokinetic soil improvement. Taguchi method has long been known as a statistic and applied in multiple fields [12]. This statistical method will applied to produce an optimization of electrokinetic soil improvement.

7. Conclusions

1. Soil microstructure testing was carried out by SEM and XRF testing. From the SEM results, it can be seen that the natural soil mineralogy image resembles the mineralogy image of expansive clay soil, namely montmorillonite, SEM results for electrokinetically stabilized soil with $CaCl_2$, $Ca(OH)_2$, and $BaSO_4$ with 4 variants of applied voltage showed a change in the shape of its mineralogy with naturally looked like a sheet to be closed.

While the XRF results are known to contain elements that are used as improvement materials, for soil stabilized with $CaCl_2$ and $Ca(OH)_2$ solution, the XRF results show the Ca element with an increasing percentage. While Cl_2 binds H and becomes chlorine gas (HCl), it is found in the XRF results. The Ba elements are also not visible in the XRF results due to the evaporation process.

2. Electrokinetic improvement can change the Atterberg value and plasticity of the soil. These changes result in a change in soil type from CH to CL. There was an increase in the Atterberg limit of the soil before and after electrokinetic improvement. Of the three salt solutions used, the LL value decreased by about 30 to 35 %. The original soil LL reached 65.07 % and after electrokinetic improvement, the LL value became 41 % to 48 %, a decrease of about 30 %.

The IP value of the natural soil, which was 28.18 %, decreased from 18.370 % to 22.688 %. The original soil PL value of 30.98 % decreased from 20.733 % to 26.597 %. The decrease in the PL value reaches 20 % of the original soil PL. For the original soil SL value of 28.18 %, there was a decrease of about 25 %.

3. The shear strength of soil can be determined from the values of C and Ø. The more the value of these two parameters increases, the more the shear strength of the soil increases. From this study, it is known that there is a change in the value of C and Ø. With the increasing voltage, the value of C and Ø also increases. For the cohesion value of soil after electrokinetic improvement with calcium chloride solution, the largest decrease is at 12 V, which is 0.196 kg/cm^2 with the soil friction angle being 1.21°. After electrokinetic improvement with calcium dioxide, the optimum change is at C 0.086 kg/cm^2 with the soil friction angle in the soil being 1.95°. For barium sulfate solution, the value of cohesion and shear shrinkage that produces optimum shear strength is at the C value of 0.251 with a soil friction angle of 0.01°.

Therefore, the maximum voltage generated is 12 V for the chloride calcium solution. Expansive clay soil that is electrokinetically stabilized also has a decrease in its swelling value. From the consolidation test, the compressibility index is obtained for each voltage.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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