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EVALUATING THE EFFECTS OF ELECTROKINETIC STABILIZATION VARIABLES ON ATTERBERG LIMITS AND SHEAR STRENGTH OF CLAY SOIL USING TAGUCHI METHOD

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Clay soil often poses a significant challenge in construction projects due to its plasticity, low bearing capacity, and tendency to shrink or expand as moisture levels change. The properties and characteristics of clay soil make it have a low bearing capacity. Electrokinetic stabilization is an effective technique to overcome this clay soil problem. Previous research has identified the variables that influence electrokinetic stabilization, namely the voltage applied, the electrokinetic application time, the type of solution, the pH solution concentration, and the drying of the soil after electrokinetic stabilization. Of all the variables that influence electrokinetic stabilization, it is known that it can increase the Atterberg limit value and the bearing capacity (qu). This study aims to determine the percentage contribution of each variable to the increase in IP and qu values. A Taguchi experimental design was used to determine the contribution of each electrokinetic stabilization variable to the IP and qu values. The variables used in this study were solution concentration, voltage, electrokinetic duration, and curing time. The experiment was carried out by identifying the soil, determining the control and input factors based on the L27 orthogonal matrix, performing electrokinetic stabilization, testing the Atterberg limits and unconfined compressive strength, and analyzing the effect of each variable using statistical analysis. The results showed that the most influential variables in increasing the bearing capacity of the soil (qu) were the duration of the electrokinetic application, the voltage applied, and the concentration of the solution used.

The most influential variable in increasing the qu value is the duration of electrokinetic application, which is 66.9 %; then the concentration of the solution is 29.72 %, and the voltage applied is 16.91 %. The treatment duration variable has no effect on increasing the qu value.

From the results of this study, the application in the field in electrokinetic stabilization for clay soil needs to be considered for the duration of application, voltage, and concentration of the solution used so that there is optimum soil improvement

Keywords: electrokinetic stabilization, clay soil, Taguchi experimental design, Atterberg limit, shear strength

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1. Introduction

Clay soils have a low limited bearing capacity (*qu*). This is due to the physical and mineralogical properties of the soil. Clay soils have low permeability, high plasticity, low permeability, and are cohesive. Clays contain the minerals illite, montmorillonite and kaolinite. These physical and mineralogical properties make clay soil have a low limited bearing capacity (*qu*).

Clay deposits are found across Indonesia, particularly in Java, Kalimantan, Sulawesi, and Sumatra, and make up 60.1 % of the country's total land area, or around 115 million hectares.

This wide distribution of soil is a challenge in soil stabilization to increase the carrying capacity of the soil in supporting infrastructure development.

West Java soil is known to be a clay soil with low *qu* value. Some research results show the free compressive strength (*qu*) values of clay soils in various locations in West Java. Cicalengka District, Bandung Regency, *qu* ranges from 18.6 kPa to 32.4 kPa, In Cihideung Village, Parongpong District, West Bandung Regency, *qu* value is 27.5 kPa, Clay in Cihampelas District, West Bandung Regency, has a *qu* value ranging from 14.7 kPa to 24.5 kPa and in Jatisari Village, Karangampel Kec, Indramayu, *qu* is 7.8 kPa.

Stabilization using kinds of chemical proven significantly worked for soil and many other materials. The most effective clay stabilization is electrokinetic stabilization. From several studies that have been conducted, the increase in soil bearing capacity reached more than 200 % with the electrokinetic method.

The variables that are proven to be effective in electrokinetic stabilization are voltage, type of chemical solution, concentration of solution, length of time of electrokinetic application, type of clay soil is also influential, because it has a different clay soil structure.

The type of chemical solution used in electrokinetic stabilization affects soil stabilization. This happens because clay has a negative charge. The cation exchange capacity of clay allows it to attract ions from the chemical solution and enter the clay structure. The process of inserting these ions makes the cement process occur in the clay, resulting in an increase in *qu*. Previous research was conducted with 3 types of chemical solutions, namely $CaCl_2$, $Ca(OH)_2$ and $BaSO_4$. $CaCl_2$ proved to be the most effective in increasing *qu*. So, it is necessary to conduct further research with different concentrations of $CaCl_2$.

The voltage applied to the stabilization will affect the speed of the chemical solution flow rate in the soil. Electrokinetic application time and maintenance time will affect the *qu* value.

Therefore, studies that are devoted on electrokinetic stabilization of clay soil are scientific relevance.

2. Literature review and problem statement

Research that challenges in the treatment of sewage sludge generated from wastewater purification, with the aim of exploring and discussing aspects affecting the electro-dewatering of sewage sludge as well as its feasibility, taking into account the latest technological developments [1–3]. The methods employed include various electro-dewatering techniques, including the use of electric fields with voltage variations and vertically arranged perforating electrodes, as well as the use of chemical solutions in some experiments. The results showed that electro-dewatering can significantly reduce the water content in the final sludge, remove pathogens, reduce energy and transportation costs, and prevent filter clogging. However, the study also noted challenges in predicting dewatering improvements for sewage sludge due to variations in sludge pretreatment practices and lack of standardized testing methodologies. Suggestions for future research are to focus on developing harmonized testing methodologies and standardization in pretreatment practices to improve accuracy in predicting electro-dewatering results. Unresolved issues include the need to better understand variations in sewage sludge characteristics and their effect on electro-dewatering effectiveness, as well as the development of more efficient and environmentally friendly technologies [4]. Unresolved issues include the need to better understand variations in sewage sludge characteristics and their effect on the effectiveness of electro dehydration, as well as the development of more efficient and environmentally friendly technologies.

The aim of this study was to determine the effect of electroosmosis on settling and chemical and physical reactions of soil. The applied voltage is 15 V and 45 V with copper foil material with conductive polymer coating. The chemical solution used was a solution with Ca and Mg stabilizing ions. From this study, it is found a significant increase in soil settlement and undrained soil strength. From the variation of stress and the type of ion stabilizer used, it is not known which variable is the most significant in increasing the bearing capacity. It is not yet known how the long-term results of this soil breeding. So, it is necessary to conduct further research to find out the effect of the length of soil treatment after electrokinetics [5]. The study did not determine which variable – the applied voltage or the type of ion stabilizer used – had the most significant effect in improving the bearing capacity of the soil. This leaves the open question of how to optimize the parameters of the electroosmosis treatment for maximum benefit.

Electrokinetic treatment research was conducted on clay soil to examine the effect of electrokinetic treatment (EKT) on sediment properties, focusing on the characteristics of anaerobic digestion and hydrogen sulfide (H_2S) removal. The methods used included the charging of an electric current of 100 °C or 300 °C, the use of anode electrodes of carbon cloth without prior treatment, and tap water solutions filled over the sediments in analysis bottles. The results showed variations in pH and redox state (ORP) of the sediments after EKT treatment, as well as improved electrokinetic properties and enrichment of microorganisms observed through polarization curves and cyclic voltammetry. Nonetheless, this study has limitations in terms of the variety of environmental conditions not fully represented in the laboratory setting and the limited number of samples. For future research, it is recommended to explore a wider variety of field conditions and use more diverse methods in evaluating the effects of EKT on sediments from different sources. An issue that has not been fully resolved is a deeper understanding of the mechanisms of H_2S removal and the long-term impacts of EKT treatment on sediment ecosystems [6]. This study has limitations in terms of the diversity of environmental conditions that were not fully represented in the laboratory setting and the limited number of samples.

The main objective was to evaluate the performance of EVDs and understand the effect of various operational variables on dewatering efficiency. The methods used included voltage variations, such as the application of constant current (1 A and 2 A) and constant voltage (0 to 45 V), the use of electroconductive electrodes and nonwoven fabric with varying spacing, and the injection of high concentrations of saline solution in some experiments. The results showed a significant increase in dewatering efficiency with EVDs, a reduction in energy consumption using thinner filter cloths, and an advantage of combining electro-osmosis with mechanical compression over mechanical dewatering methods alone. Nonetheless, this study has limitations in terms of the variety of soil types tested and environmental conditions that may not fully reflect more complex field situations. Suggestions for future research include exploring a wider variety of soil types and environmental conditions, as well as testing new methods to further improve dewatering efficiency. Unresolved issues include a deeper understanding of the long-term effects of the electro-osmosis process on the physical and chemical properties of soils, as well as the potential environmental impacts of using EVDs on a large scale [7]. Future research includes exploring more soil types and environmental conditions, as well as testing new methods to further improve dewatering efficiency. Unresolved issues include a deeper understanding of the long-term effects of the electro-osmosis process on soil physical and chemical properties.

This research examines the mechanism of clay strength enhancement through electroosmosis chemical treatment with the aim of understanding how the process can increase the strength of clay, particularly kaolinite, using specific chemical solutions. The methods used include the use of an increased voltage to create a high alkaline environment, the installation of electrodes in an electroosmosis cell to apply an electric current, and the injection of a calcium chloride ($CaCl_2$) solution to increase the concentration of calcium ions in the clay. The results show that increasing the concentration of $CaCl_2$ solution, increasing the applied voltage, and extending the treatment time can significantly increase the strength of the clay, with the formation of C-S-H and/or C-A-H around the clay particles contributing to the uneven increase in strength. Nonetheless, this study may have limitations in terms of the variety of soil types tested and different environmental conditions, which may affect the results and generalizability of the findings. Suggestions for future research include exploring variations in other types of chemical solutions and their effects on different soil types, as well as conducting further studies on the mechanisms underlying the interaction between ions and soil particles. Unresolved issues include a deeper understanding of the spatial distribution of soil strength enhancement and how external factors such as moisture and temperature can affect the effectiveness of electroosmosis treatment [8].

This study provides important insights into the potential of electroosmosis chemical treatment to improve clay strength. However, further research is needed to fully understand the mechanisms involved and how various factors may influence its effectiveness.

This research examines the consolidation behavior of bentonite used as a liner material in waste disposal sites, with the aim of exploring the effect of salt solution concentrations (NaCl and $CaCl_2$) on the mechanical properties of compacted bentonite, as well as understanding how the mineralogical composition of bentonite affects consolidation behavior in salt solution. The methods used included using various concentrations of salt solutions to observe their effects on bentonite, with NaCl and $CaCl_2$ as the chemical solutions used. The results showed that increasing the salt concentration caused a decrease in the compression index, volume change coefficient, and time to reach 90 % consolidation, while the consolidation coefficient increased, indicating the influence of the presence of salt on the mechanical behavior of bentonite. Nonetheless, this study may have limitations in the variety of bentonite types tested and the lack of in-depth analysis of the interaction between bentonite and different types of ions in salt solutions. Some aspects that have not been fully resolved include the specific mechanisms underlying the interaction between bentonite and ions in salt solution, the long-term impact of exposure to salt solution on the stability and performance of bentonite as a liner, as well as the development of mathematical or simulation models to predict the consolidation behavior of bentonite under various salt solution conditions [9]. Further research is needed to fully understand the mechanisms involved and the long-term implications of salt exposure on bentonite performance. Future research should focus on the exploration of different types of bentonite and salt solutions, a more in-depth analysis of ion-bentonite interactions, and the development of predictive models and how each variable is affected.

This research addresses the challenges faced by structures built on shallow foundations in expansive soils, especially during drought conditions, and explores the use of electrokinetic techniques to address these issues. The research objective was to investigate the feasibility of electrokinetic techniques in mobilizing groundwater from deep saturated layers and hydrating desiccated expansive soils, as well as reducing the negative pore pressure formed due to desiccation. The method used included the use of cylindrical electrodes buried in the soil, although the voltage used was not specified. Results from the laboratory model show that the process of electroosmosis is capable of moving water molecules into the soil horizontally and vertically, restored pore pressure and moisture content in areas affected by desiccation, with average moisture content more than doubling within 8 hours and suction measurements showing a significant reduction. However, this study was limited to laboratory scale and did not include full-scale testing in the field. A suggestion for future research is to conduct full-scale testing at a site with desiccated soil and existing trees. Unresolved issues include the effect of larger electric fields on water movement patterns and changes in expansive soil microstructure during the electro-osmosis process, as well as how this technique can be effectively applied in a broader context [10]. Unresolved issues include the influence of larger electric fields on water movement patterns and changes in expansive soil microstructure during the electro-osmosis process, as well as how this technique can be effectively applied in a broader context.

This study examines the changes that occur in the liquid limit (LL) and plastic limit (PL) of residual tropical lateritic soils with high plasticity subjected to electro-chemical stabilization, with the aim of evaluating the effect of calcium (Ca^{2+}) and phosphate $\left(PO_4^{3-}\right)$ ion injection on the plasticity of tropical lateritic soils through the electro-chemical stabilization process. The method used included the application of direct electric current (DC) over a 5-day period, with calcium chloride ($CaCl_2$) solution for calcium ions and phosphoric acid for phosphate ions. The results showed a significant decrease in the LL and PI values of the treated soils, with the highest accumulation of $\left(PO_4^{3-}\right)$ and Ca^{2+} ions, and the greatest decrease occurring in the soil treated with Ca^{2+} ions. Nonetheless, this study may have limitations in the variety of soil types tested, as well as the duration and frequency of measurements that may not cover all relevant field conditions. Suggestions for future research are to explore a wider variety of soil types and test the long-term effects of electro-chemical treatment on soil mechanical properties. Unresolved issues include a deeper understanding of the interaction mechanism between the injected ions and soil minerals, as well as the long-term impact of electro-chemical treatment on soil stability in the field [11]. This study provides important insights into the potential of electro-chemical stabilization to improve the plasticity properties of tropical lateritic soils. However, further research is needed to fully understand the mechanisms involved and the long-term effects on soil behavior. how the treatment process affects the soil after electrochemical stabilization.

This research provides an overview of the application of electroosmosis techniques, specifically in the sludge dewatering process, with the aim of providing useful information for researchers pursuing solid-liquid separation of difficult-to-dehydrate materials, such as sludge, using electroosmosis techniques. The methods used include the use of constant voltage in the electroosmosis process, although the specific type of electrode and chemical solution are not mentioned in detail. The results show that electroosmosis can significantly reduce the water content in sludge, with the efficiency affected by the strength of the electric field and the initial condition of the sludge. However, this study may not cover all variables that can affect the dewatering process, such as variations in sludge types and different environmental conditions. Suggestions for future research are to explore the use of different types of electrodes and chemical solutions, as well as conduct further studies on the effect of environmental conditions on dewatering efficiency. Unresolved issues include the optimization of the electroosmosis process for different types of sludge and the development of more efficient methods to reduce energy consumption during the dewatering process [12]. Future research should focus on exploring different types of electrodes, chemical solutions, and environmental conditions, as well as on developing more efficient methods.

This research addresses the problem of soil pollution by heavy metals, particularly cadmium, and aims to understand the effect of chelating agents on the zeta potential of cadmium-contaminated clay, which may improve the efficiency of electrokinetic remediation. The objectives of the study were to explore the effect of pH, cadmium concentration, and type of chelating agent on the zeta potential of the soil particle surface, as well as improve understanding of the geochemical processes involved in remediation of contaminated soil. The methods used included the use of KCl solutions of varying concentrations, varying cadmium concentrations, as well as binding agents such as EDTA and various phosphonates. The results showed that the zeta potential of cadmium-contaminated clay was affected by pH, cadmium concentration, and the type of binding agent used, providing insight into how setting these conditions can improve effectiveness of electrokinetic remediation. Nonetheless, this study may have limitations in the variety of environmental conditions that were not fully represented and the lack of in-depth exploration of the specific interactions between the bonding agent and the clay. Suggestions for future research are to further explore the interactions between different types of bonding agents and clays under more realistic field conditions, as well as testing more innovative remediation methods. Unresolved issues include a better understanding of the specific mechanisms affecting the interaction between heavy metals, clay and binding agents in the broader context of environmental remediation [13]. Future research should focus on further exploration of realistic field conditions, testing of innovative remediation methods, and in-depth analysis of the underlying mechanisms.

This research addresses the effect of salinity on the geotechnical properties of Champlain Sea clay, with the aim of obtaining a comprehensive picture of the changes in the physical and mechanical properties of the clay due to leaching with varying levels of salinity. The methods used included the application of a constant pressure of 100 kPa during the leaching process to maintain consistent water flow through the clay samples, as well as the use of distilled and deionized water to achieve the desired salinity levels. The results showed that salinity affected the geotechnical properties of the Champlain Sea clay, although specific details about the test results were not described in the available citations. One shortcoming identified was that the composition of the leachate solution was not determined in this study, which may limit further comparisons. Suggestions for future research would be to further explore the composition of the leachate solution and its impact on the clay properties, as well as using more diverse methods in testing. Unresolved issues include a better understanding of how variations in solution composition affect the rheology and mechanical properties of clay, as well as the need for further research to confirm the uniformity of salinity levels in washed samples [14]. Suggestions for future research are to further explore leach solution composition and its impact on clay properties, as well as using a wider range of testing methods. Unresolved issues include a better understanding of how variations in solution composition affect the rheological and mechanical properties of the clay, as well as the need for further research to confirm the uniformity of salinity levels in the samples.

This study evaluates the effectiveness of using polymers, specifically polyethylene oxide (PEO) and sodium carboxymethyl cellulose (CMC), in improving clay stability through electrokinetic techniques. The method used includes the use of a DC voltage of 50 V for a period of 7 days, electrodes made of stainless steel, and PEO and CMC polymer solutions prepared by mixing the polymers with distilled water. Measurements were taken at different time intervals to monitor changes in pH, electrical conductivity (EC), and strength of the treated soil. The results showed that the use of PEO and CMC polymers significantly improved the mechanical properties of the clay, including shear strength and consolidation, with the improvement dependent on the concentration of polymer used. However, this study may have limitations in terms of the variety of clay types tested and environmental conditions that do not fully reflect field conditions. Suggestions for future research are to explore the use of other polymer types and polymer combinations, as well as conducting field testing to validate the laboratory results. Unresolved issues include further understanding of the mechanism of interaction between polymers and clay and the long-term impact of using polymers in soil stabilization [15]. Overall, this study provides important insights into the potential use of polymers in improving clay stability through electrokinetic techniques. However, further research is still needed to fully understand the complex interactions between polymers and soils and their long-term effects.

Based on the studies that have been conducted, the use of electrokinetic techniques in soil remediation and stabilization has shown significant results. Various studies have explored the effect of variables such as electrical voltage, electrode type, chemical solution, and treatment duration on soil physical, chemical, and mechanical properties. The results consistently show improvements in shear strength, consolidation, and soil stability after electrokinetic treatment, although the degree of improvement varies depending on the specific conditions used. In addition, electrokinetic techniques have also been shown to be effective in sludge dewatering and remediation of heavy metal-contaminated soils.

Nonetheless, most of the summarized studies have limitations in terms of the variety of soil types, scale of testing, and environmental conditions that do not fully reflect the complexity of the field situation. Therefore, further research is needed to better understand the long-term effects of electrokinetic treatment on soil properties and the stability of structures built on them. In addition, optimization of variables such as electrical voltage, electrode type, chemical solution concentration and composition, and treatment duration need to be further explored to develop the most effective and efficient treatment protocols for different soil types and environmental conditions. With a better understanding of these factors, electrokinetic techniques can be applied more widely and effectively in future soil improvement and environmental remediation projects.

3. The aim and objectives of the study

This study aims to determine the stabilization of soil by the electrokinetic method using calcium chloride seen from the changes in soil physical and mechanical testing.

To achieve this aim, the following objectives were accomplished:

– investigate the effect of electrical resistance and electric current that occurs in stabilization with calcium chloride solution with voltage variations in the electrokinetic stabilization process;

– investigate the Atterberg limit of clay after electrokinetic stabilized;

– determine the influence of each variable on the value of soil shear strength.

4. Material and methods

This study used clay soil from West Java, Indonesia as the research object. The electrical conductor used a graphite sheet. Electrokinetic stabilization was conducted using calcium chloride solution of 5 %, 10 %, and 15 % concentration. The voltage applied was 15 V, 18 V and 24 V. The duration of the electrokinetic application was 6 days, 9 days, and 12 days. The Taguchi research design is shown in Table 1. The hypothesis used in this study is that the four variables used in electrokinetic stabilization have a significant effect on increasing the soil bearing capacity (*qu*).

The experiment was divided into four stages, the stages shown in Fig. 1.

Stages of electrokinetic stabilization of clay were carried out in accordance with research in previous studies, with differences in electrically conductive materials.

The research was conducted with 4 variables and 4 level. The independent variables were solution concentration, applied voltage, electrokinetic application time and curing time. The dependent variable is soil shear strength. The variable and the level shown on Table 1.

The research stages are shown in Fig. 2.

The initial stage carried out before electrokinetic stabilization is by testing the soil moisture content, preparing materials and materials, then the soil is saturated with saturation close to LL and left 1×24 hours.

After 1×24 hours, the soil sample was put into the test box and electrokinetic behavior was carried out in accordance with the research design. After electrokinetic stabilization, physical and mechanical properties of the soil were tested for analysis (Fig. 1).

Table 1

Level of process variable

Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Concentration	A	%	5	10	15
Voltage	B	Voltage	15	18	24
Electrokinetic duration	C	day	6	9	12
Time curing	D	day	7	10	14

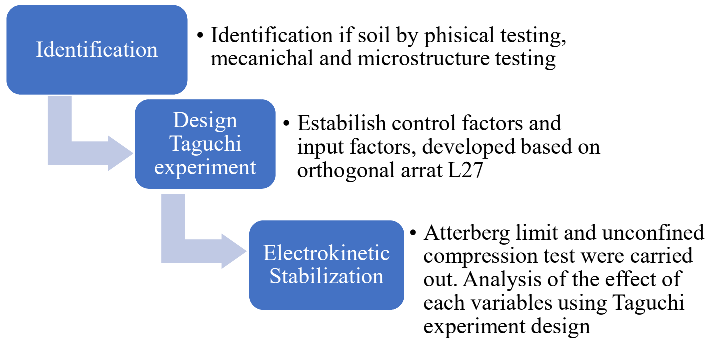

Fig. 1. The stages of experiment

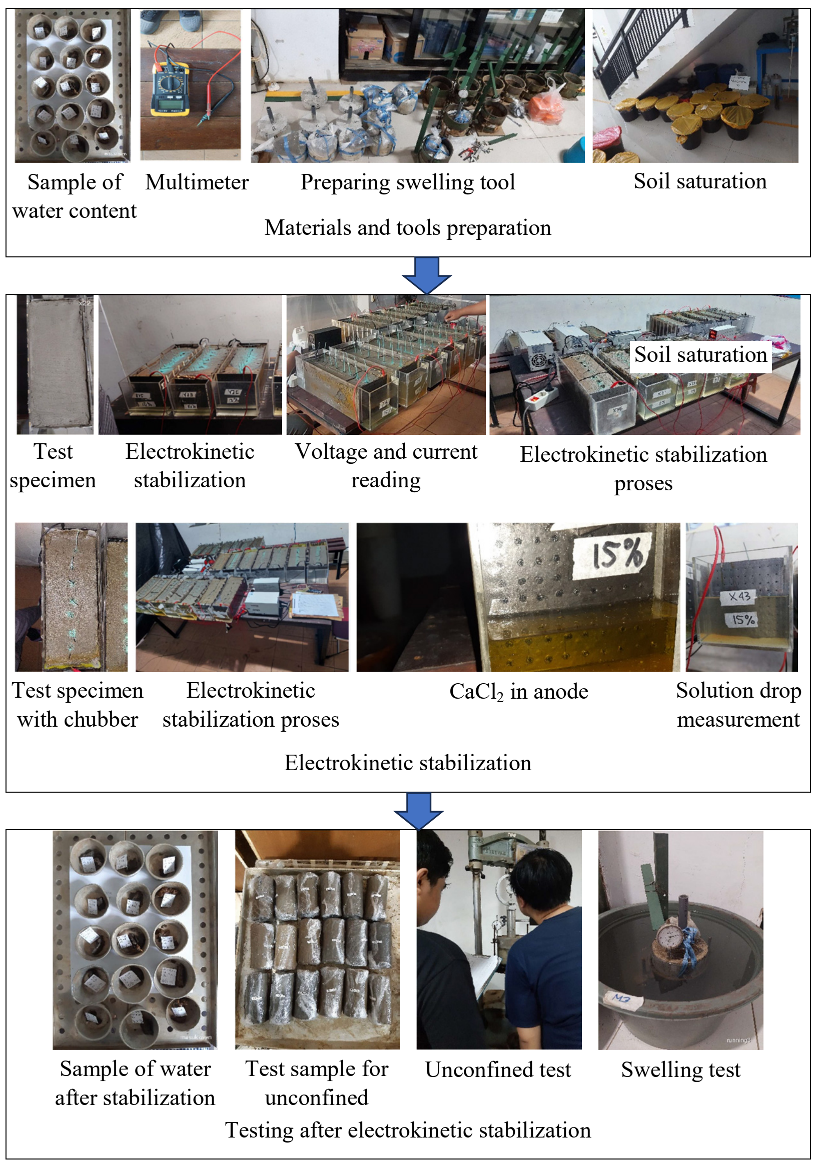

Fig. 2. Research stages

5. The research results on stabilization electrokinetic with calcium chloride with a variation of concentration

5. 1. Effect of solution concentration on resistance and current in electrokinetic stabilization

The relationship between resistance and electric current can be seen in Fig. 3

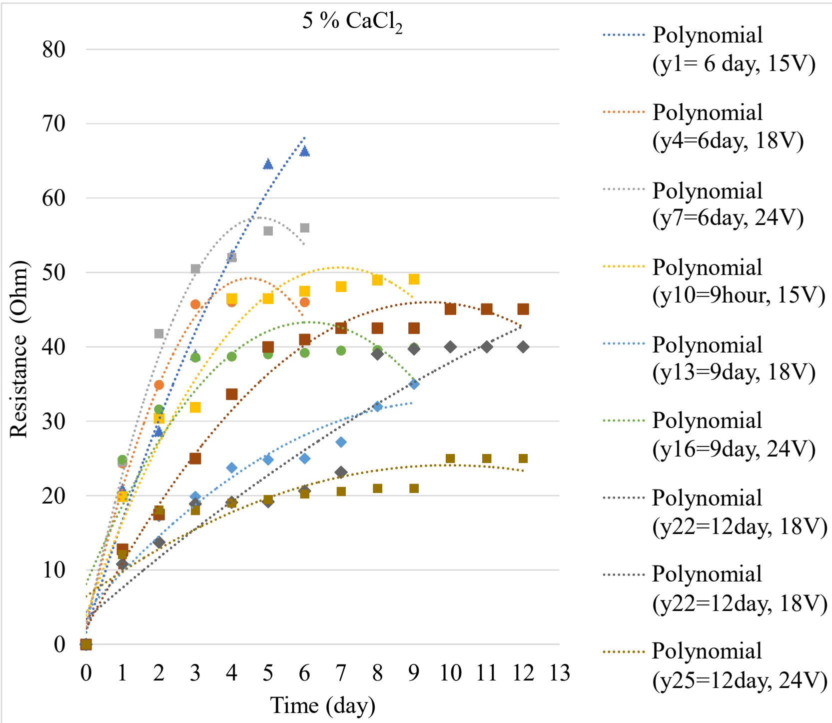

Fig. 3. Relationship between resistance and time current at 5 % electrokinetic stabilization

In almost all experiments, resistance tended to increase from day to day. The most significant increase occurred in the early days, then tended to level off or stabilize towards the end of the period (day 12).

The largest increase in resistance occurred in experiments with higher duration and voltage, such as *y*7 (6 days 24 V), *y*16 (9 days 24 V), and *y*25 (12 days 24 V), reaching a range of 65–68 Ohms.

Experiments with lower duration and voltage, such as *y*1 (6 days 15 V) and *y*10 (9 days 15 V) showed a smaller increase in resistance, only reaching around 56–59 Ohms. In general, increasing the experimental voltage and duration resulted in a greater increase in resistance. However, the difference was not very significant, ranging from 55–68 Ohms at the end of the period for all experiments. After a few days, the trend of increasing resistance tends to slow down and even becomes constant with time. This phenomenon was observed in all 9 experiments with 5 % $CaCl_2$, although with slightly different stabilization rates and times. For example, in *y*1 (6 days, 15 V), the resistance increased rapidly until around day 4, then began to stabilize in the range of 55–56 Ohms on days 5 and 6. Similar trends were observed in other experiments such as *y*4, *y*7, *y*13, *y*16, *y*22, and *y*25 where the resistance increased significantly at the beginning of the period, then gradually sloped and tended to be constant after passing the 6th to 9th day.

This phenomenon of resistance stabilization is consistent with the findings of several previous studies on electrokinetic solidification (ECS) of soils. Some relevant points.

The resistance of clay soil increases rapidly at the beginning of the EKS process, then gradually stabilizes after about 7 days of treatment using 5 % $CaCl_2$ solution as electrolyte [16].

Stabilization elektrokinetics of soft clay soil, where resistance increased significantly in the first 5–7 days, then leveled off and remained relatively constant until the end of the 14-day period [17]. The steady state in resistance can be explained by the rate of electrolyte decomposition being proportional to its electro-osmotic rate after a certain period of time [18]. That is, the system reaches equilibrium between electrolyte formation and depletion. The trend observed in this experiment, where the resistance becomes constant after a few days, is in accordance with the understanding from previous studies of the electrokinetic solidification process. Although the details may vary depending on soil type, electrolyte concentration, and other process parameters, this resistance stabilization phenomenon appears to be a common characteristic of electrokinetic treatment.

Electrokinetics for 10 % $CaCl_2$ is shown in Fig. 4

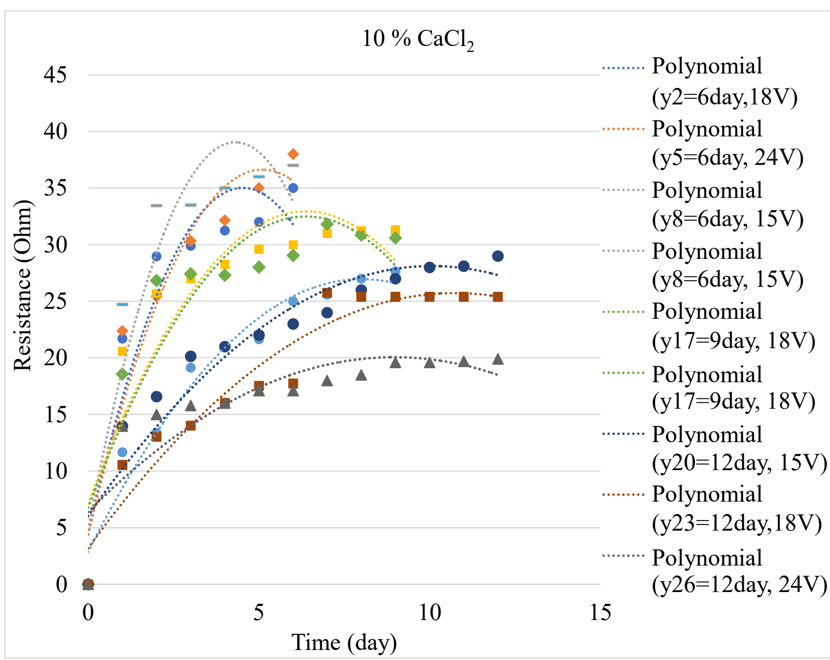

Fig. 4. Relationship of resistance and time at 10 % electrokinetic stabilization

Resistance increases over time, but is more gentle and peak values are lower (25–34 Ω) than 5 % $CaCl_2$ (55–68 Ω). Peak on days 6–9, then stable/declining. Higher voltage gives higher resistance.

Electrokinetic theory: Higher $CaCl_2$ concentration increases conductivity, decreases resistance. Migration of Ca^{2+} and Cl^- causes deposition of $Ca(OH)_2$ at the cathode which increases resistance. Little potential for Cl_2 gas to form at the anode.

Resistance value for electrokinetics with 15 % $CaCl_2$ shown at Fig. 5

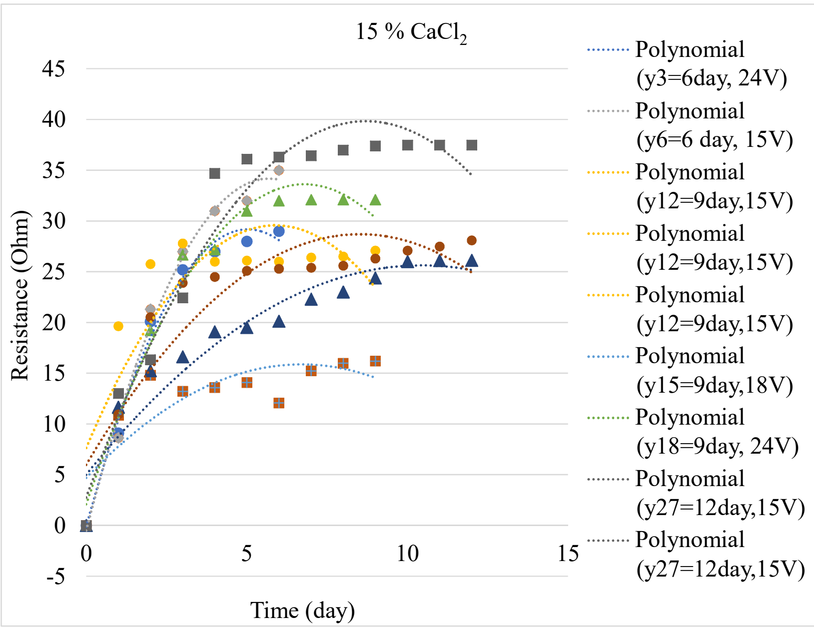

Fig. 5. Relationship between resistance and time at 15 % electrokinetic stabilization

The Fig. 5 shows the relationship between resistance and time in 15 % $CaCl_2$ solution under various duration and stress conditions. In general, the resistance increases sharply at the beginning of the period, especially in the first 3–5 days, before reaching a stable point at day 5 or 6 for most conditions. Conditions with longer duration and higher stress tended to result in greater resistance. This is clearly seen in the curve with the 12-day condition, 24 V ($y24$), which reaches its highest resistance around values 37–38 and stabilizes after day 5. In contrast, conditions with shorter durations, such as 6 days, 24 V ($y3$), show lower resistance despite being at high voltage, with stabilization around values of 15–18. This suggests that exposure duration plays an important role in increasing resistance, in addition to the voltage factor. Finally, although resistance continued to increase in the early stages, most curves showed a consistent stabilized point after a few days, signaling the achievement of equilibrium conditions in the system. The combination of high voltage and longer duration provided optimal resistance results in a 15 % $CaCl_2$ solution.

5. 2. Effect of Atterberg limit on electrokinetic stabilization

5. 2. 1. Liquid limit relationship with voltage

Fig. 6 interpreted the relationship between the voltage applied to the electrokinetic stabilization to the change in the liquid limit (LL) value of the soil as follows.

The original soil LL value is 59.55 %. After applying the electrokinetic stabilization process with a voltage of 15 V, the LL value decreased to range from 45.984 % to 56.940 %, with an average of 51.334 %. This shows a decrease in LL value of 8.216 % compared to the original soil.

When the voltage was increased to 18 V, the LL value decreased further, ranging from 46.116 % to 53.060 %, with an average of 50.479 %. The decrease in LL value at 18 V was greater than that at 15 V, which was 9.071 % of the original soil LL value.

At 24 V voltage, the decrease in LL value is more significant. The LL values ranged from 47 % to 52.649 %, with an average of 51.162 %. Although the average LL value at 24 V voltage was slightly higher than that at 18 V voltage, the overall LL value decreased by 8.388 % from the original soil LL value.

Fig. 7 illustrates the relationship between the applied stress in electrokinetic stabilization and the change in Plasticity Index (PI) value.

The original soil PI value was 31.49 %. After electrokinetic stabilization with a voltage of 15 V, the PI value decreased significantly, ranging from 9.620 % to 27.241 %, with an average of 18.902 %. This shows a decrease in PI value of 12.588 % compared to the original soil.

When the voltage was increased to 18 V, the PI value decreased further, ranging from 11.610 % to 27.775 %, with an average of 19.764 %. Although the average PI value at 18 V was slightly higher than that at 15 V, the overall PI value decreased by 11.726 % from the original soil PI value.

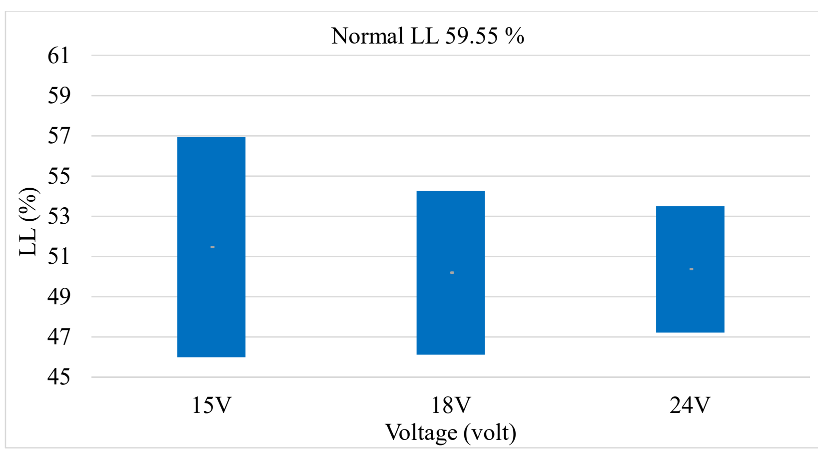

Fig. 6. Relationship between LL and voltage

At 24 V voltage, the decrease in PI value still occurred, but with a smaller percentage compared to the 15V and 18V voltages. The PI value ranged from 14.694 % to 20.921 %, with an average of 18.971 %. The decrease in PI value at 24 V voltage is 12.519 % of the original soil PI value.

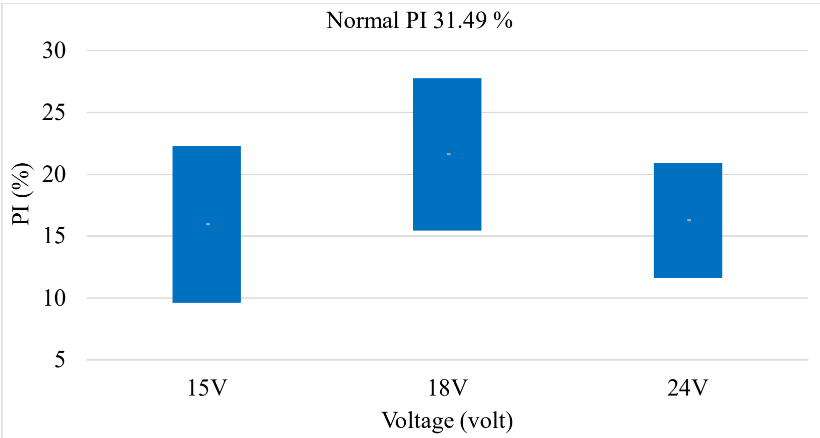

Fig. 7. Relationship between LL and voltage

5. 3. Effect of *qu* on electrokinetic stabilization

From the Taguchi experimental design with orthogonal array L27, *qu* results from 27 tests were obtained. The test results are shown in Table 2.

From the test results in Table 2, the effect of each variable on soil compressive strength is obtained. The most significant variable that gives the highest rank is the solution concentration.

Table 2

Analysis S/N for Taguchi experiment

S/N ratio analysis of variance program. Fractional factorial TAGUCHI method with pooling UP											
Input						Output					
Data						Parameter	DF	SS	MS	SS'	ρ (%)
y_1	3.980	y_{10}	4.595	y_{19}	4.802	*A*	2	27.070	13.535	23.131	29.72
y_2	4.067	y_{11}	4.673	y_{20}	5.930	*B*	2	17.105	8.553	13.167	16.91
y_3	6.063	y_{12}	7.557	y_{21}	7.065	*A*×*B* (1)	4	5.866	1.467	0.000	0.00
y_4	4.466	y_{13}	4.889	y_{22}	7.137	*A*×*B* (2)	4	0.000	0.000	0.000	0.00
y_5	4.335	y_{14}	4.114	y_{23}	3.902	*C*	2	56.018	28.009	52.079	66.90
y_6	6.458	y_{15}	6.305	y_{24}	7.070	*A*×*C* (1)	4	4.172	1.043	0.000	0.00
y_7	4.875	y_{16}	4.409	y_{25}	7.998	*A*×*C* (2)	4	0.000	0.000	0.000	0.00
$y8$	4.291	y_{17}	6.474	y_{26}	7.657	*D*	2	0.000	0.000	0.000	0.00
y_9	6.691	y_{18}	8.367	y_{27}	8.883	Error	12	23.630	1.969	–	–
Factor	4	Level	3	N	27	Total	26	77.844	–	–	–
qu											

The variables *A*, *B*, and *C* have the largest contribution, about 29.7 %, 16.91 %, and 66.9 %, respectively. This indicates that the interaction between *A*, *B*, and *C* is the most influential factor.

The variables *A*×*B* (2), *A*×*C* (1), *A*×*C* (2), and *D* have a zero percent contribution, indicating that the interaction of these variables does not have a significant effect.

The Error variable is quite large, at 23.63 %, indicating that there are still other factors that have not been accounted for in the model.

Overall, this figure shows that the interaction between variables *A*, *B*, and *A*×*B* (1) has a dominant influence, while the other variables do not contribute significantly. It is worth considering other factors that may not have been included in the model to improve the accuracy of the analysis. The value of the multivariant regression results in Fig. 7 R^2=0.001 indicates that the linear regression model does not fit the data. The relatively random distribution of the data (not forming a linear pattern) indicates that the relationship between the independent and dependent variables may be non-linear.

From the analysis, the most influential factor on *qu* is concentration (29.72 %), followed by electrokinetic duration (66.90 %), and applied voltage (16.91 %). Curing time has minimal influence and there is no significant interaction between variables. It is therefore necessary to conduct a non-linear analysis to generate a model of the study.

The Fig. 8 displays a scatter plot between the Regression Model (X-axis) and the Experiment (Y-axis). Here are some analyses that can be done based on the graph:

Weak correlation: the R^2 value of 0.001 indicates a very weak correlation between the Regression Model and the Experiment. This means that the variation in the Experiment can only be explained by 0.01 % by the Regression Model. In other words, the Regression Model cannot predict the experiment well.

From the Non-Linear Model Analysis, a non-linear mathematical model was obtained:

$$qu=2.34+0.134A-$$
$$-0.406B+1.439C-0.077D.$$

The results of the analysis of variance (ANOVA) presented in Tables 5, 6 show the effect of the independent variables on the free compressive strength (*qu*. Based on the P-value, solution, stress, and duration of application significantly affect the *qu* value, with a P-value<0.05. Meanwhile, treatment time showed no significant effect on *qu*, as indicated by a P-value>0.05.

The ANOVA results revealed the relative contribution of each independent variable in explaining the variability of *qu*. Application duration had the largest contribution, amounting to 43.37 %, as the most dominant factor in influencing *qu*. Solution concentration and stress had relatively equal contributions of 16.34 % and 16.45 %, respectively, indicating the importance of both variables in determining the *qu* value. Although the interactions between solution concentration and stress and duration of application contributed less, at 8.84 % and 61.61 %, they still need to be considered in comprehensively understanding the behavior of *qu*.

The variable relationship model generated from the ANOVA analysis showed a non-linear relationship between the independent variables and *qu*, involving interactions between variables. Interpretation of the model coefficients indicated that there was a positive correlation of solution concentration and application duration in increasing *qu*, while a negative correlation was obtained from stress and treatment time, assuming other variables were constant.

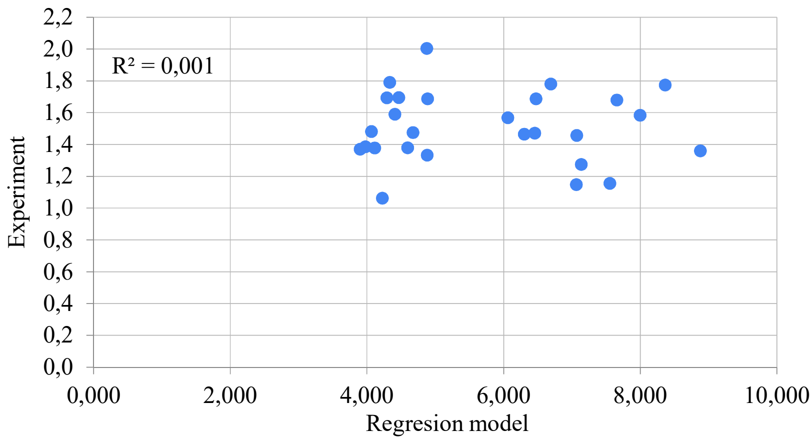

Fig. 8. Multivariant regression

The findings of this study are in line with several previous studies investigating the effect of electrokinetic parameters on soil stabilization. Previous reset also found that the concentration of electrolyte solution and duration of application had a significant influence on the free compressive strength of electrokinetically stabilized clay soils. However, the study did not consider the interaction between variables as was done in this study. Another study also reported an increase in the free compressive strength of clay stabilized by electrokinetic method, with a significant effect of solution concentration and duration of application.

6. Discussion of the research results on electrokinetic stabilization

The resistance of the 5 % $CaCl_2$ specimen shows a increasing trend until the end of the measurement. However, the increase in resistance is not as sharp as in specimens with higher $CaCl_2$ concentrations. The lowest resistance value was recorded at 9.605 ohms at the 2nd hour, higher than the lowest values in the 10 % $CaCl_2$ (11.9 Ohms) and 15 % $CaCl_2$ (1.6 Ohms) specimens. This indicates that the increase in conductivity at lower $CaCl_2$ concentrations is not as fast as the increase at higher concentrations (Fig. 3).

The trend observed in the 5 % $CaCl_2$ specimen is consistent with the basic theory regarding electrolyte solutions. Lower $CaCl_2$ concentrations result in fewer Ca^{2+} and Cl^- ions in the solution, so their contribution to the increase in electrical conductivity is smaller. This explains why the initial resistance of 5 % $CaCl_2$ specimens is higher and the decrease in resistance over time is more gradual than in specimens with higher $CaCl_2$ concentrations (Fig. 3).

These results are in line with previous studies that investigated the effect of $CaCl_2$ concentration on the electrical properties of materials. For example, research by [16] showed that increasing $CaCl_2$ concentration in solution resulted in a more significant decrease in resistance in graphene oxide-based humidity sensors. In addition, [17] reported that the electrical conductivity of concrete increased proportionally with the concentration of $CaCl_2$ added, with a greater increase at higher concentrations.

However, it is important to note that the resistance behavior of 5 % $CaCl_2$ specimens showed larger fluctuations and less predictable patterns than specimens with higher $CaCl_2$ concentrations. This may be due to more complex interactions between Ca^{2+} and Cl^- ions with the specimen surface at lower concentrations. Further studies are needed to clarify the mechanism underlying this phenomenon.

Although there were fluctuations, overall, the specimen resistance tended to decrease with time. At the beginning of the measurement, the resistance was in the range of 50–60 Ohms, then gradually dropped to a value below 20 ohms at the end of the measurement. This decrease in resistance may indicate a change in the structure or composition of the specimen material due to exposure to 10 % $CaCl_2$ solution over a long period (Fig. 4).

The trend of decreasing resistance and increasing current over time is consistent with the basic theory of electrical conductivity in electrolyte solutions. $CaCl_2$ solution is a strong electrolyte that ionizes completely in water, producing Ca^{2+} and Cl^- ions that act as electrical charge carriers. The longer the specimen is exposed to $CaCl_2$ solution, the more ions can move freely and contribute to the increase of electrical conductivity, which is reflected in the decrease of resistance value.

The results of this study are also in line with findings from previous studies. For example, research conducted by [21] showed that increasing the concentration of $CaCl_2$ in the electrolyte solution led to a decrease in resistance and a significant increase in electrical conductivity. In addition, a study [20] revealed that the duration of exposure of the material to the electrolyte solution plays an important role in the change of electrical properties, where a longer exposure time results in a greater decrease in resistance.

The trend of decreasing resistance and increasing conductivity over time in 15 % $CaCl_2$ specimens is in accordance with the basic theory regarding electrolyte solutions. $CaCl_2$ solutions with higher concentrations contain more Ca^{2+} and Cl^- ions that act as charge carriers. The longer the exposure to solutions with higher ion concentrations, the greater the observed increase in electrical conductivity (Fig. 5).

The results of this study are also consistent with findings from previous studies. For example, research [19–21] showed that increasing the concentration of $CaCl_2$ in the solution led to a greater decrease in resistance in the concrete material over time. In addition, [23] reported that continuous exposure to $CaCl_2$ solutions with higher concentrations resulted in more significant microstructural changes, contributing to an increase in electrical conductivity.

However, it is important to note that although the general trend shows a decrease in resistance over time, there are fluctuations and complex behaviors observed in 15 % $CaCl_2$ specimens. For example, a significant increase in resistance between the 172nd hour to the 180th hour, as well as a sharp decrease in resistance thereafter. This phenomenon may be related to dynamic changes in the structure of the specimen-solution interface or the presence of complex electrochemical reactions.

The results showed that the application of electrokinetic stabilization with voltage variations (15 V, 18 V, and 24 V) influenced the decrease in Liquid Limit (LL) and Plasticity Index (PI) values in the soil. The higher the applied voltage, the greater the decrease in LL and PI values that occur. This indicates that electrokinetic stabilization can improve soil plasticity properties (Fig. 7).

The decrease in LL and PI values in the soil after electrokinetic stabilization can be explained by the double layer theory. When an electric current is passed through the soil, a water electrolysis process occurs which produces H+ ions at the anode and OH- ions at the cathode. These ions migrate towards the opposite electrode, resulting in changes in soil pH and affecting the double-layer structure of soil particles. These changes can lead to flocculation of soil particles and alter the plasticity characteristics of the soil.

This study is in line with the findings of previous studies. Research by [23] reported that electrokinetic stabilization with 30 V voltage for 7 days can reduce LL value by 13.8 % and PI value by 14.6 % in clay soil. They explained that the decrease in soil plasticity was caused by ion exchange and neutralization of negative charges on soil particles due to the migration of ions during the electrokinetic process. investigated the effect of voltage variations (10 V, 20 V, and 30 V) on the electrokinetic stabilization of expansive clay soils. Their results showed that increasing the voltage resulted in a greater decrease in LL and PI values. At 30 V, the LL value decreased by 21.8 % and the PI value decreased by 18.3 %. They concluded that electrokinetic stabilization with higher voltage can be more effective in improving soil plasticity properties (Fig. 6).

The effect of electrokinetic parameters on soil shear strength using Taguchi L27 method and non-linear analysis. The parameters studied included solution concentration, applied voltage, electrokinetic duration, and curing time. Results showed that the non-linear model could explain the relationship between variables better than the linear model, with solution concentration as the most influential factor.

This statistical analysis shows how much influence each of the electrokinetic stabilization variables has, so that these variables can be applied to the electrokinetic stabilization of clay soils in the field.

Although the decreasing trend of LL and PI values in this study is similar to previous studies, the magnitude of the decrease can vary depending on the soil type, treatment duration, and electrode configuration used. Further research is needed to optimize these parameters and assess the effectiveness of electrokinetic stabilization on various soil types.

7. Conclusions

1. This study investigates the effect of electrokinetic stabilization parameters on clay soil's physical and mechanical properties using the Taguchi method with L27 orthogonal matrix and non-linear analysis. The parameters studied include solution concentration, applied voltage, electrokinetic duration, and curing time. Results show that the non-linear model could explain the relationship between the variables better than the linear model, with solution concentration as the most influential factor. The Taguchi method with L27 orthogonal matrix successfully optimizes the process parameters, with significant contributions from three main parameters:

– solution concentration (A): 18.70 %;

– electrokinetic duration (C): 13.99 %;

– applied voltage (B): 9,37 %.

2. The non-linear model characteristics show a positive influence of electrokinetic duration and solution concentration on *qu* with constant values of 0.134 for solution concentration and 1.439 for duration of electrokinetic application, while the negative effect is generated from voltage and curing time. The constant value for curing time is very small at 0.177 so that this variable has no significant effect on changes in *qu*.

3. Overall, this study shows the potential of electrokinetic stabilization in improving plasticity and shear strength of clay. The resulting numerical model shows the significant and insignificant influence of the variables on the *qu* value. The resulting model is the maximum combination value that can be carried out and applied directly to the electrokinetic repair of clay soils in the field.

Conflict of interest

We certify that they have no conflict of interest about 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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