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Experimental Evaluation of Electro-Osmotic Flow in the Improvement of Saturated Cohesive Soils

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ABSTRACT

Improving saturated cohesive soils remains a significant challenge in geotechnical engineering due to their low shear strength and high compressibility. Electro-osmotic flow presents a promising technique for enhancing soil performance without the need for large-scale mechanical intervention.

Objective: *This study evaluates the behavior of saturated cohesive soils under electro-osmotic treatment, focusing on changes in physical and consolidation properties over time. Key variables include applied voltage, electrode material, and treatment duration.*

Methodology: *Laboratory tests involved preparation of cohesive soil samples (pure clay and a clay-silt mix), followed by electro-osmotic treatment using stainless steel 316 electrodes at 15V and 30V. The experiments incorporated moisture content analysis, compaction, and one-dimensional consolidation tests, with durations ranging from 7 to 28 days. Aluminum and iron electrodes were excluded to prevent corrosion-related interference.*

Findings: *Electro-osmotic flow significantly affected moisture migration, soil density, and consolidation behavior. The clay-silt mix showed higher permeability, resulting in greater water movement and improved settlement. Extended durations (28 days) amplified the electro-osmotic effects, while higher voltages (30V) accelerated consolidation. The maximum consolidation coefficient was recorded in the mixed soil under high voltage after 21 days.*

Conclusion: *The results demonstrate that electro-osmotic flow can effectively improve saturated cohesive soils, especially when considering soil type, voltage level, and treatment period. These findings support the use of electrokinetic stabilization methods in soft ground improvement for infrastructure and foundation projects*

Keywords: *Experimental Evaluation, Electro-Osmotic, Flow, Improvement of Saturated Cohesive Soils*

1. *INTRODUCTION*

Electro-osmotic flow is a physicochemical phenomenon that involves the movement of pore water and ions through a saturated soil matrix under the influence of a direct electric field. This method has garnered significant attention in geotechnical engineering for improving the mechanical behavior of low-permeability soils, especially saturated cohesive soils that typically exhibit high compressibility and low shear strength [1].

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The electro-osmotic process begins by inserting two electrodes—an anode and a cathode—into the soil, followed by the application of a low-voltage direct current. This electric field initiates the migration of water molecules and dissolved ions from the anode to the cathode through the soil pores. As water moves, it redistributes moisture content and modifies the soil structure, leading to enhanced strength, reduced settlement, and improved consolidation characteristics.

This technique is particularly useful in situations where traditional drainage or compaction methods are ineffective or infeasible due to soil conditions or space constraints. Electro-osmotic treatment has shown promising results in various ground improvement projects, especially in clayey and silty soils under saturated conditions [2].

In this study, an experimental investigation is conducted to evaluate the effectiveness of electro-osmotic flow in improving the geotechnical properties of saturated cohesive soils. The research explores the influence of different electrode materials, such as iron and stainless steel (grades 304 and 316), along with the effect of applied voltage levels (15V to 30V) and treatment durations (7 to 28 days). Key soil behavior metrics, including moisture migration, density changes, and consolidation performance, are monitored to assess the overall improvement potential of the method.

1. Literature Review

In 2024, Bi-Bak and colleagues conducted a study to evaluate the impact of electroosmosis on the mechanical properties of soft clay soils. The study focused on stabilizing fine-grained soils, especially clay soils in saturated conditions, by reducing the thickness of the double electrical layer through an electric current. In this experiment, a layer of the soil was prepared with specific moisture content and bulk density in a laboratory chamber measuring 20 cm in length, 30 cm in width, and 50 cm in height. The soil was compacted into five layers, and electric currents of 1 and 1.5 volts were applied for 48 hours. The electrodes used were made of aluminum and graphite in both rod and plate forms. The laboratory results showed that compressive strength increased by up to 128%, moisture content decreased by 37%, and the plasticity index and porosity ratio decreased by 58% and 34%, respectively. The results were validated using electron microscope images. Among the electrodes tested, the aluminum plate electrode at 1.5 volts showed the best performance[1]. In the same year, Sun and colleagues examined a special cyclic and progressive electroosmosis method. Their study found that the cyclic electroosmosis (CPE) method provided less drainage compared to conventional electroosmosis. However, the combination of two charged states can increase the shear strength of the soil near the designated electrode. The formation of transverse cracks in the soil was mainly due to differences in drainage caused by electroosmosis and the adjacent electric field. When the electroosmosis current was strong, longitudinal cracks formed along the path of the stronger electroosmosis current. In practical and engineering applications, the CPE charging method was more energy-efficient than conventional charging methods for the same processing duration[2]. In another study, Sun and colleagues investigated a method to stabilize in-situ soft clay soils using electroosmosis and electrophoresis (electric current in the liquid state) under an electric field. The experiments were designed to clarify the principles and analyze the application of this technique in the field. The results indicated that for electroosmosis and electrophoresis to occur in soft clay, the threshold current was approximately 15 milliamps. Below the threshold current, electrophoresis predominated, accompanied by weak electroosmosis. Soil particle size, dry density, and the height of the anode protrusion were mainly influenced by the soil moisture content, electrode length in the electrolyte, and electrode distance from the soil surface. As the soil moisture content approached the plastic limit and liquid limit, electrophoretic compaction of the soil increased. Above the threshold current, almost only electroosmosis occurred, and its intensity increased with the current. In practical engineering applications, due to the direct placement of electrodes in soft clay, the current is usually much higher than the threshold, making the electrophoresis phenomenon negligible[3]. Another study investigated the electroosmosis technique as a method for reducing moisture and improving the stability of soft clay. The results of electroosmosis tests on clay samples with various electrical supply times and different boundary conditions for the anode showed that the electroosmosis current formation time (EF) varied in different sections of the soil, from anode to cathode. The section closest to the anode initially reached a minimum moisture content of 22% ± 3%, and the electroosmosis process stopped. Water injection to the anode during the electroosmosis process increased the drainage of other sections of the soil until the second section from the anode reached a minimum moisture content of 30% ± 2%. The use of water injection to the anode during electroosmosis improved the uniformity of electroosmosis flow, enhanced its performance, and provided environmental protection. The experimental results emphasized the significant role of water injection to the anode in improving the electroosmosis process for soft clay[4]. A study conducted in 2021 by Eddy Tunizam Mohamed and colleagues in Malaysia evaluated the impact of electrode material on the electroosmosis process applied to soil. In this study, electrodes made of iron, aluminum, and copper were used at the anode. A voltage of 30 volts was applied for 672 hours, and the amount of water extracted from the soil during the process, along with the changes in soil shear strength before and after the process, was analyzed. The results showed that the type of electrode material at the anode did not affect the amount of water drained from the soil, but the improvement in soil shear strength depended on the electrode material used[5]. In 2020, Abdulrahman and colleagues conducted a study on the effect of electroosmosis on sand soil under near-saturated conditions. The study involved applying a range of voltages over varying times to sand soil in an acrylic plastic cell designed for the experiment. The results demonstrated that the intensity of the applied electric field influenced the distribution of salt from the anode to the cathode during the electric field application. The findings also revealed that the amount of water extracted from the soil and the pH level of the soil changed with the increasing intensity of the current[6]. The electroosmosis method is used to enhance the mechanical strength and stabilize soft soils, particularly under saturated conditions. After applying the electroosmosis process, the soil is dried, and its stability is improved to prevent movement and flooding. In this study, iron and stainless steel electrodes (304 and 316) with voltages ranging from 15 to 30 volts and calcium carbonate additives ranging from 5% to 20% by weight will be used to determine the optimal voltage and calcium carbonate percentage. This technique is investigated as an effective geotechnical solution for improving the stability of structures.

The studies reviewed highlight the significant impact of electroosmosis in enhancing the mechanical properties and stability of soft soils, particularly in saturated conditions. Various electrode materials and voltages have been tested to optimize the process, and it has been found that electroosmosis can effectively reduce moisture content, increase soil strength, and improve compaction. Additionally, the use of additives like calcium carbonate further enhances the soil's stability.

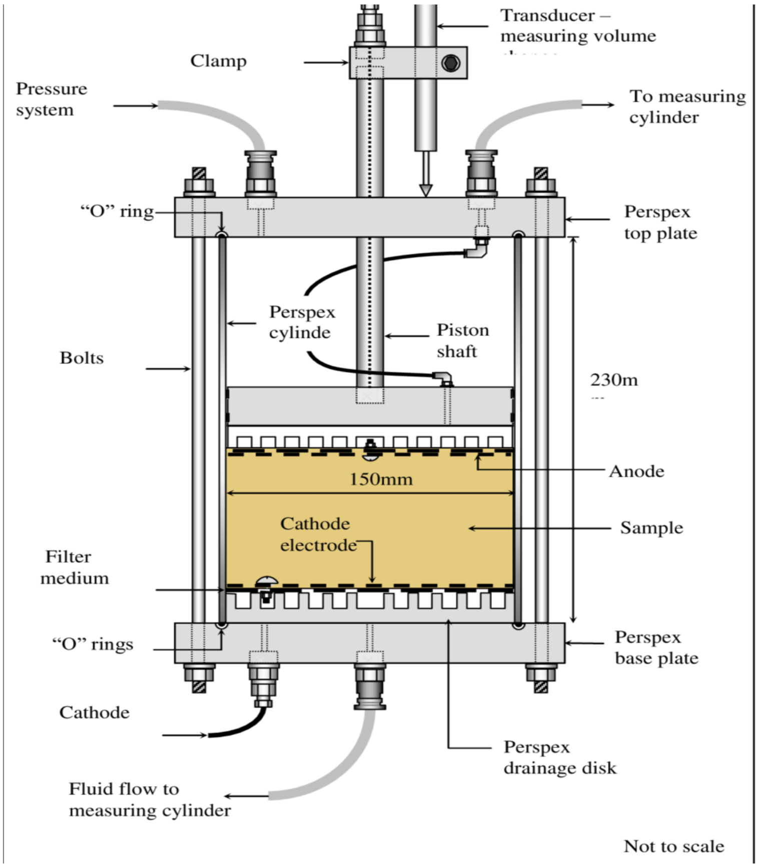

Figure 1: A Vertical Electro-Osmosis Method to Improve the Bearing Capacity of Piles in Marine Soft Clay [5]

2. Methodology

When a potential difference (DC) is applied to fine-grained soil, a current is generated in the direction of the voltage gradient, which is given by equation (1):

$$V_e = K_e \frac{\partial E}{\partial x} \tag{1}$$

In equation (1), VeVe is the flow velocity, KeKe is the electroosmotic permeability coefficient, and ∂E∂x∂x∂E represents the potential gradient. For silty clay soils, KeKe is proportional to the moisture content and decreases with increasing salt concentration.

The components involved in electroosmosis are as follows:

I. Electrodes: These are divided into two categories: anode (+) and cathode (-). The anode is connected to the positive pole, and the cathode is connected to the negative pole. The type of electrode material and their arrangement is very important.

II. Power Supply (DC): Direct current can be provided by regular storage batteries and their series connection to achieve different voltage levels, or from converters capable of converting alternating current (AC) into direct current.

III. Current Transmission System: This consists of connecting wires that transmit current from the power supply to the electrodes.

IV. Vacuum Pump System: This system is used to pump out the water that is removed from the soil and accumulated at the cathode due to electroosmotic flow. It includes a vacuum pump, suction tubes, and a collection tank for the drained water from the soil.

In this research, the following steps will be carried out:

Soil Sampling and Characterization: Soil samples will be collected from the studied region (Langarud city) to identify the soil type and properties.

Chemical, Mechanical, and Strength Testing of Soil: The soil will undergo chemical, mechanical, and strength testing to determine its geotechnical properties. (Tests: Particle size distribution, hydrometry, Atterberg limits (plastic and liquid limits), compaction, consolidation (oedometer), specific gravity (GS), electroosmotic testing, direct shear test, and chemical analysis of clay and sand.)

Determination of Optimal Electrode Type and Voltage: The best type of electrode and optimal applied voltage will be determined through preliminary electroosmotic tests.

Testing of Clay and Clay-Sand Mixtures: The clay will be tested once alone and once with the addition of sand in two different time intervals in the electroosmotic cell with a water-tight setup.

Measurement of Soil Settling: At each stage of the experiment, precise measurements of soil settlement will be taken, which will be plotted in terms of settlement over time for both clay alone and the clay-sand mixture. This will help determine the soil deformation parameters.

Constant Parameters:

I. Electrode type

II. Ambient temperature

III. Waterproofing conditions

Variable Parameters:

I. Clay-sand mixing ratio: 3 conditions

II. Applied voltage: 3 conditions

III. Electroosmotic test duration: 2 intervals (7 and 28 days)

The detailed data required for the experiment will be explained further below.

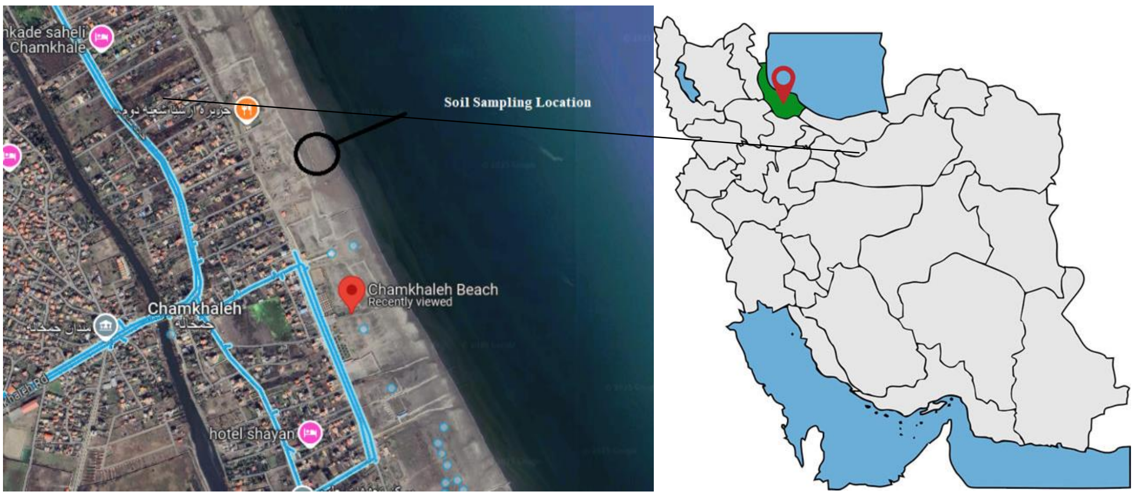

Figure 2: Soil Sampling Location

For soil sampling, as mentioned in previous sections, soil was collected near the coastal area of Chamkhaleh in Langarud city. The clay sample contained some sand, and the particle size distribution of the sand is as follows.

Table 1: Properties of the Collected Soil Sample

Seive No.	Seive size (mm)	Retained on Seive: Average: Weight (g)	Retained on Seive: Average: Percent(%)	Percent Passing Sieve
over	100		0	100
3"	76.2		0.00	100.00
2"	50.8		0.00	100.00
1 1/2"	38.1	0.0	0.00	100.00
1"	24.5	0.0	0.00	100.00
3/4"	19	0.0	0.00	100.00
3/8"	9.51	0.0	0.00	100.00
4	4.75	0.0	0.00	100.00
10	2	1.3	0.25	99.75
40	0.425	8.6	1.66	98.09
100	0.15	88.4	17.01	81.08
200	0.075	62.9	12.11	68.97
Passing 200		2.7	0.52	

According to Table (1), the particle size distribution chart is obtained based on the ASTM D422 standard. It is noteworthy that the sample was taken from a depth of 20 centimeters in the specified area. The following is a detailed description of the soil being tested.

Figure 3: Appearance of the Soil Sample

In this study, preliminary tests, including Atterberg limits (plastic limit and liquid limit), specific gravity, moisture content, particle density, particle size distribution, and hydrometer analysis, were conducted to identify the soil sample. The soil sample was taken from an area in the city of Langarud, Gilan Province, and is primarily clay. To accurately determine its properties, the necessary tests were carried out. These tests were performed according to standard procedures, including particle size distribution based on ASTM D422, standard test method for soil density and unit weight in place using the sand cone method and ASTM D1556, Atterberg limits based on ASTM D4318, and hydrometer tests based on ASTM D421-58 & D422-63.

Approximately 200 grams of soil passing through sieve number 40 were selected and dried in an oven. The soil sample was mixed with a certain amount of water until it reached a plastic consistency. The mixing and kneading process continued until the water permeated all areas of the soil. Then, the soil sample was placed in a sealed plastic bag and left for 24 hours to ensure the water infiltrated all the voids in the soil.

Table 2: Values Obtained in Determining the Liquid Limit

Mold Number	1	2	3
Wet Soil Weight + Mold Weight (grams)	38.52	45.81	53.11
Dry Soil Weight + Mold Weight (grams)	33.57	39.67	46.04
Mold Weight (grams)	16.93	18.16	20.45
Dry Soil Weight (grams)	16.64	21.51	25.59
Wet Soil Weight (grams)	4.95	6.14	7.07
Moisture Content (%)	29.75	28.54	27.63
Number of Impacts (N)	15	23	29

Here is the technical translation of your provided text:

It can be empirically stated that the plastic limit is the maximum moisture content at which the soil can be worked without sticking to the hands. A small amount of the sample is separated for the plastic limit test (approximately the size of a walnut), and the remaining part is placed in the brass section of the apparatus. Using a spatula, the surface of the paste is leveled horizontally and aligned with the bottom edge of the cup (so that the maximum depth of the soil reaches 8 millimeters).

The more fine particles in the soil absorb water, the stickier the soil becomes, and the stickiness results in:
1. An increase in the plastic limit, meaning that a stickier soil requires more moisture to become liquid.
2. A decrease in the liquid limit.

The plastic limit is the moisture content at which a thread with a diameter of 2/3mm, made from the soil paste sample, cracks. The plastic limit is the lowest moisture content corresponding to the plastic state of the soil, and the shrinkage limit is the moisture content at which the soil no longer undergoes volume change.

The ratio of the plastic limit to the shrinkage limit provides useful information about the soil's shrinkage characteristics. If the ratio is large, the soil in the area might undergo undesirable volume changes due to moisture fluctuations. There is a possibility that foundations recently constructed on these soils may show cracks due to the shrinkage or swelling of the soil as a result of seasonal moisture changes. Therefore, the higher the moisture content, the lower the soil's resistance.

Table 3: Values Obtained in Determining the Plastic Limit

Mold Number	1	2	3
Wet Soil Weight + Mold Weight (grams)	13.95	13.83	10.38
Dry Soil Weight + Mold Weight (grams)	13.54	13.44	10.09
Mold Weight (grams)	11.17	11.17	8.35
Dry Soil Weight (grams)	2.37	2.27	1.74
Wet Soil Weight (grams)	0.41	0.39	0.29
Moisture Content (%)	17.30	17.18	16.67
Wet Soil Weight + Mold Weight (grams)	1	2	3

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The determined liquid limit based on the above tables is 28.2%, and the plasticity index is 17%. The percentage passing through the No. 4 sieve is 100%, through the No. 40 sieve is 98.1%, and through the No. 200 sieve is 69%. Based on the Unified Soil Classification System (U.S.C.S), the soil is classified as CL, which is clay. For the sand specifications, the details are provided in Table 4.

Table 4: Granular Specifications of Silty Clay

specifications	amount
D10 (mm)	0.000
D30 (mm)	0.001
D60 (mm)	0.006
Sand (%)	0.8
Silt or clay(%)	99.2
ML-Silt	

According to Table (3), based on the properties of the studied soil, it is classified as a light clay soil with sand.

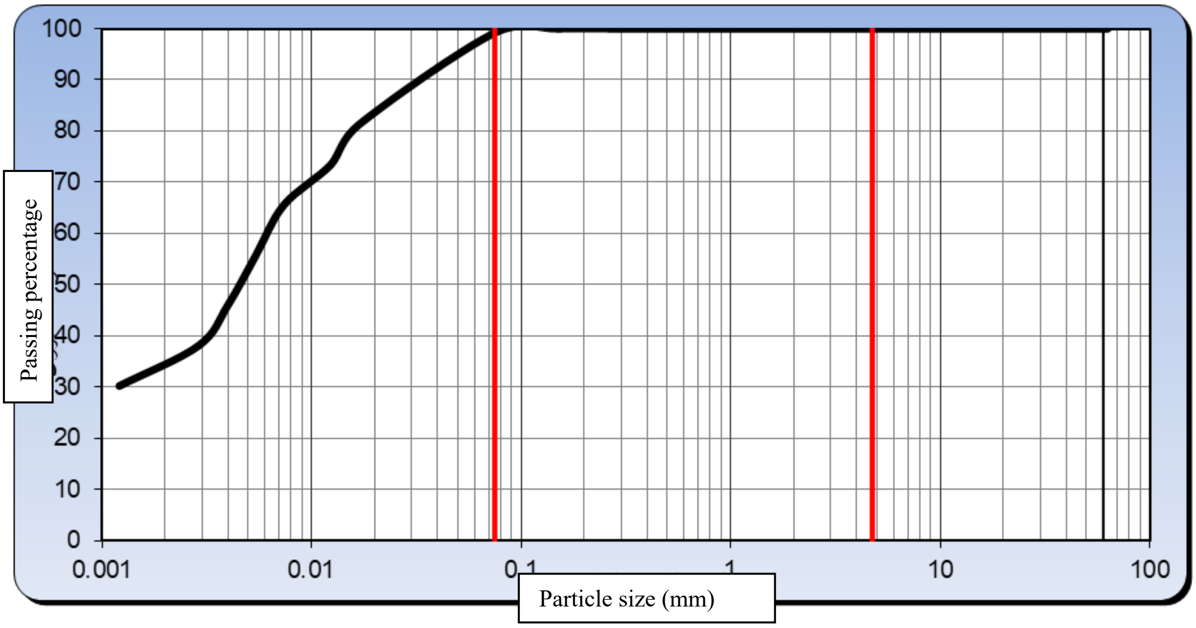

Figure 4: Particle Size Distribution Chart of Clay Soil

Table 5: Particle Size Distribution Characteristics of Clay Soil with 30% Sand

specifications	amount
D10 (mm)	0.001
D30 (mm)	0.003
D60 (mm)	0.025
Sand (%)	29.52
Silt or clay(%)	70.48
CL - Lean clay with sand	

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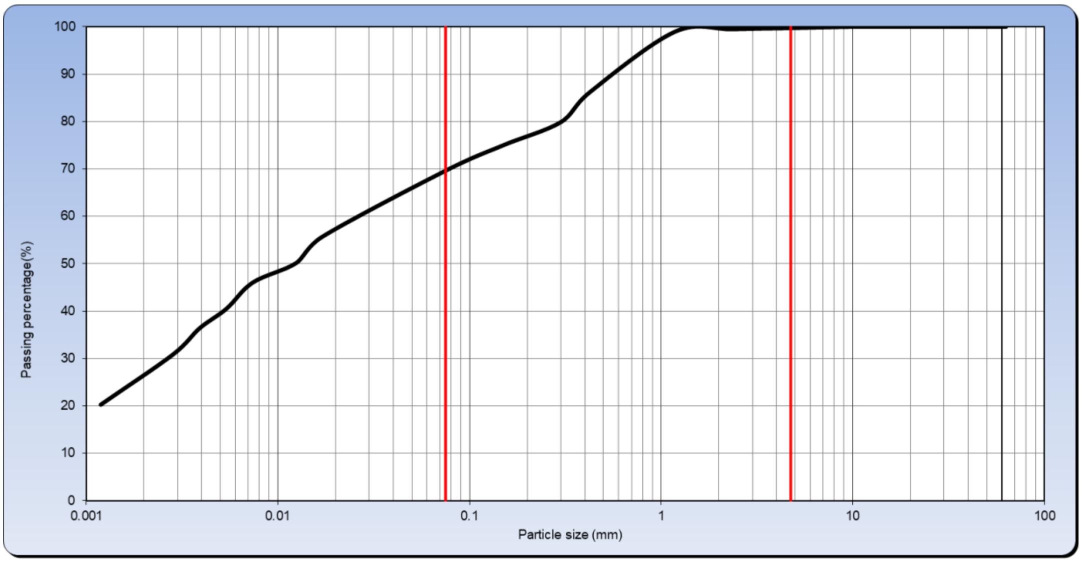

Figure 5: Particle Size Distribution Chart of Clay Soil with 30% Sand

In this test, due to the high corrosion rate of iron within less than 24 hours, which decreased further with the increase in voltage, we had to replace the electrode before the completion of the 3-day test. As a result, this type of electrode is not suitable due to its high corrosion rate in the presence of water and minerals in the soil.

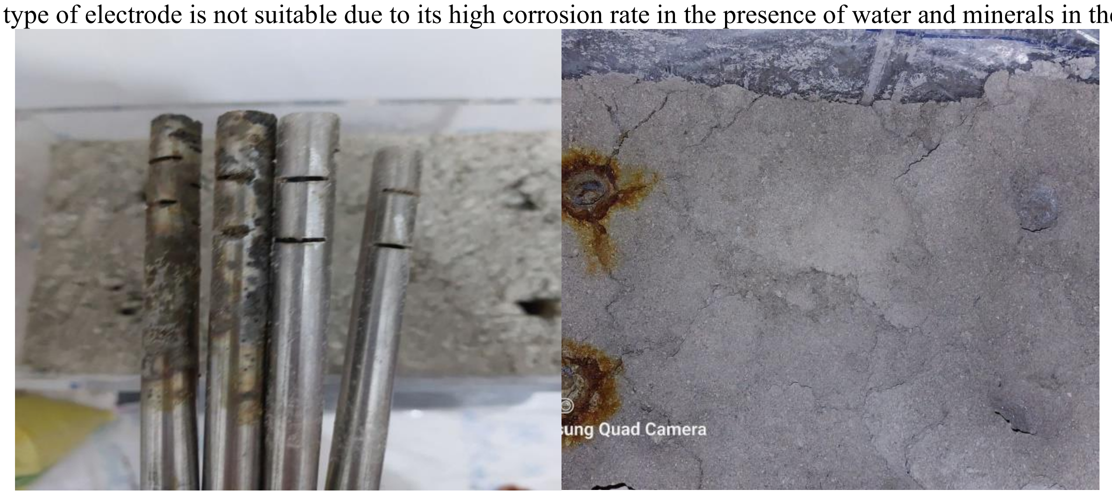

Figure 6: High corrosion of iron electrodes against water and minerals in the soil

Test Chamber with Aluminum Electrode of High Thickness and Diameter at the Best Voltage (30V) in a 3-Day Period: Aluminum is a metal that undergoes anodizing, meaning that when it is used as an anode and subjected to an electric current, an oxide layer forms on its surface. This oxide layer is thicker than the natural oxide layer, and it causes interference in the process, leading to a loss of conductivity on the external surface after a short period.

Test with Special Aluminum Electrode of Lower Thickness and Diameter at the Best Voltage (30V) in a 3-Day Period: As with the previous test, an oxide layer formed on the electrode, but it was thinner. However, over a longer period, this electrode also encounters issues.

Figure 7: Formation of Oxide Layer on Aluminum Electrodes in a 3-Day Period

Test with Stainless Steel Electrode No. 304 (30V) in a 3-Day Period:

In this test, the settlement was acceptable, and rusting was significantly reduced compared to all other electrodes. The results were acceptable, but because our experimental tests were conducted over a 3-day period, while the main tests are 7-day and 28-day tests, we conclude that stainless steel with anti-corrosion properties should be used, as it will remain acceptable in the long term.

Figure 8: Iron and Stainless Steel Electrodes

As a result, the selected electrode is stainless steel number 316. The selection of the electrode type and appropriate voltage is provided through trial and error experiments. To this end, after completing the construction of the device and preparing the soil sample for testing, experimental tests were conducted in sequence. In the selection of the electrode type, trial and error tests were performed using iron, aluminum with both thick and thin variants, and stainless steel 304 and 316. For the appropriate voltage, trial and error experiments were conducted, with voltages ranging from 15 to 30 for each sample.

In the electroosmotic experiment, a 30x30 cm test box was built. Four electrodes are placed at four points, with a 5 cm distance from both sides of the box. Eight points on the outer surface of the box are used for measuring settlement.

Figure 9: Electroosmotic Test Box

4. Findings

Liquid Limit: The liquid limit refers to the moisture content at which the soil transitions from a plastic state to a liquid state. According to the relevant standard, 50 grams of the soil sample passing through a #40 sieve was prepared for this test, and water was added to create a smooth, uniform paste. The paste was placed in a Casagrande cup, and a groove was made across the surface of the sample using a grooving tool, perpendicular to the surface of the cup. The device was rotated at a speed of 2 turns per second until the groove closed by approximately 12.7 mm. To achieve this, water was added to the sample to increase its moisture content, which reduced the number of blows needed to close the groove. This test was performed with 25 blows.

Plastic Limit: Soil is considered solid in its natural state. The moisture content that transforms the soil from a solid to a semi-solid state is called the shrinkage limit. The moisture content that changes the soil from a semi-solid to a plastic state is known as the plastic limit. For the plastic limit test, 20 grams of soil passing through a #40 sieve was used. The sample was mixed with water until it reached a plastic consistency. A 3-gram portion of the paste was rolled under the fingers on a glass plate to form a thread with a diameter of 2-3 mm, which cracked and broke into smaller pieces. The broken pieces were collected and placed in an oven at 105°C for 12 hours. The weight before and after drying in the oven was used to calculate the plastic limit of the soil.

Plasticity Index: The plasticity index of soil is the difference between the liquid limit and the plastic limit, representing the moisture range within which the soil remains plastic. Therefore, the plasticity index gives an indication of the soil's behavior in a plastic state.

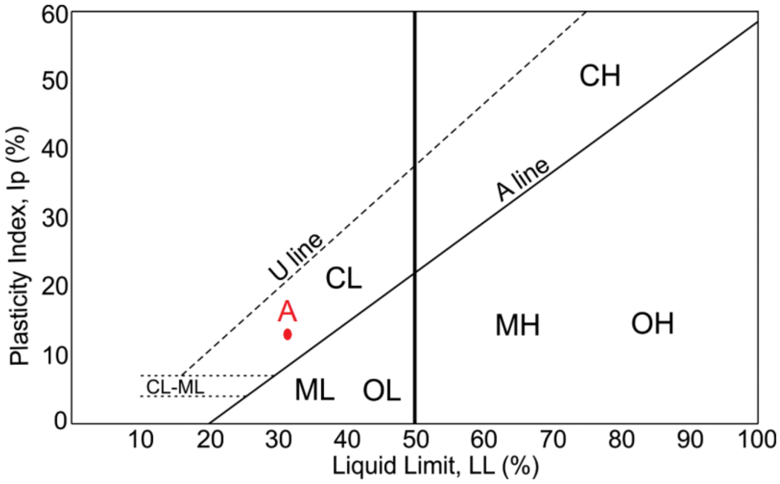

Figure 10: Casagrande Diagram of Pure Clay Soil

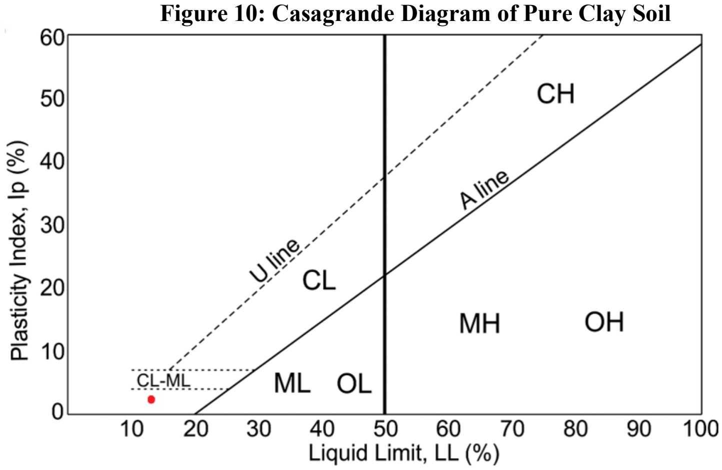

Figure 11: Casagrande Diagram of Clay Soil with 30% Sand

Conclusion: Based on the PI obtained from the Atterberg limits tests and grain size distribution, the soil in question falls within the CL-Sand range (Figure 5) and CL (Figure 13) with low plasticity (Casagrande diagram), and is classified under the Unified Soil Classification System (USCS).

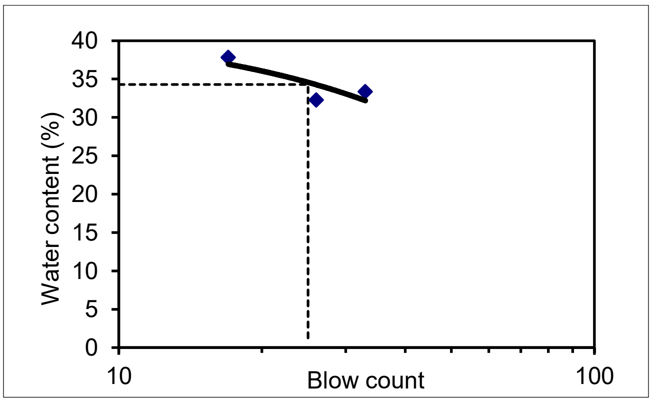

Figure 12: Liquid Limit Chart of CL Clay Soil

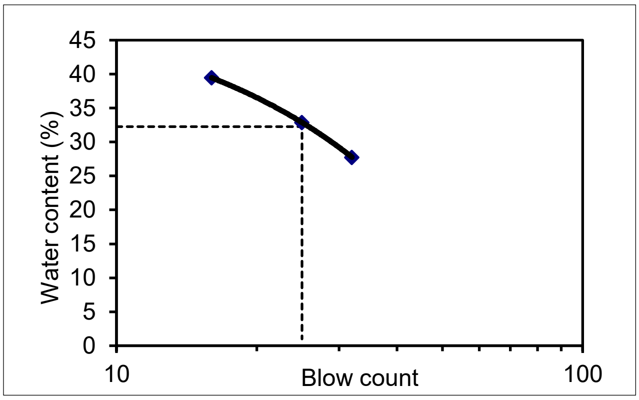

Figure 13: Liquid Limit Chart of Clay Soil with Sand

The results obtained from the Atterberg limits are presented in both table and chart form. The Plasticity Index (PI) is 11.4, indicating that the soil has medium plasticity. Soils with a lower PI (e.g., less than 7) are considered to have low plasticity, while soils with a higher PI (e.g., greater than 20) have higher plasticity. The Liquid Limit (LL) is 34.3, indicating that the soil becomes liquid at a relatively high moisture content. These values can be used for soil classification and to predict its behavior under various conditions, such as compressibility and stability .

The experimental results suggest that using lower voltage over a longer period can be beneficial for gradual and controlled settlement of the soil, aiding in more effective consolidation of composite soils.

Table 6: Summary of Settlement Changes at Points 1 to 8 from Top to Bottom of the Chamber

No.Test	Type of Test	Voltage (Volt)	Duration (Days)	Percentage of Changes (٪)
1	Pure clay	30	7	300
2	Pure clay	30	28	400
3	Pure clay	15	7	325
4	Pure clay	15	28	400
5	Clay + Sand	30	7	Unknown
6	Clay + Sand	30	28	Unknown
7	Clay + Sand	15	7	400
8	Clay + Sand	15	28	400

Table (6) provides information from the soil settlement tests, which examine the effect of soil type, voltage, and duration on the percentage of settlement changes. The following interpretation explains the table:

1. Soil Type:

- Pure Clay: Tests 1 to 4 are for pure clay. The percentage of change in this type of soil is clearly high, especially in tests 2 and 4, which were conducted over 28 days, where the percentage of change reaches 400%. This indicates that pure clay experiences significant settlement under these conditions (high voltage and long duration).

- Clay + Sand: Tests 5 to 8 are related to a mixture of clay and sand. The percentage of change in these tests reaches 400% in tests 7 and 8, both with a 15-volt voltage and 28 days duration. This shows that a clay and sand mixture, under specific conditions, can also exhibit significant settlement.

2. Voltage:

- 30 Volts: In tests 1, 2, 5, and 6, with 30 volts, the percentage of change is high, especially in tests 1 and 2 with pure clay, indicating that high voltage has a significant impact on the settlement of the soil.
- 15 Volts: In tests 3, 4, 7, and 8, with 15 volts, significant changes are observed, especially in tests 4, 7, and This shows that even with lower voltage, notable settlement still occurs in both pure clay and the clay-sand mixture.

3. Duration:

- 7 Days: In tests 1, 3, 5, and 7, with a 7-day duration, the percentage of change is very high. Specifically, in test 3 with 15 volts and pure clay, the percentage of change reaches 325%, indicating significant settlement in this short period.
- 28 Days: In tests 2, 4, 6, and 8, with a 28-day duration, the percentage of change reaches a maximum of 400%. This indicates that the longer the duration, the more significant the settlement becomes.

4. Unspecified Tests:

- In tests 5 and 6, the percentage of change is unspecified. This may be due to issues with data collection, unpredictable test conditions, or other limitations. This requires further investigation to determine the cause of this uncertainty.

The table demonstrates the strong influence of soil type, voltage, and duration on settlement changes. In general, increasing voltage and time results in significant settlement, especially in pure clay. The combination of clay and sand can also exhibit considerable settlement under certain conditions. These data can help engineers and researchers better understand soil behavior under different conditions, which can aid in the design and implementation of engineering projects. According to previous studies, the movement of the anode towards the cathode with a 30-volt electric current results in the highest stabilization.

The results related to the percentage of compaction and consolidation coefficient from the previous section are presented in Table (7).

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Table 7: Density and Consolidation Coefficient of Main Tests

Test Number	Test Type	Voltage (Volts)	Duration (Days)	Wet Soil Weight (kg)	Dry Soil Weight (kg)	Maximum Dry Density (kg/m^3)	Water Weight (kg)	Moisture Percentage (%)	Effective Soil Thickness (mm)	t	Compaction Percentage (%)	Consolidation Coefficient (Cv)
1	Pure clay	30	7	3.266	2.78	2.81	0.486	17.5%	9.54	12	98.93%	0.67
2	Pure clay	30	28	2.524	2.15	2.45	0.374	17.4%	9.20	12	87.76%	0.65
3	Pure clay	15	7	3.146	2.712	2.94	0.434	16.0%	8.54	6	92.24%	1.21
4	Pure clay	15	28	2.668	2.4012	2.65	0.2668	11.1%	8.23	6	90.61%	1.16

Test Number	Test Type	Voltage (Volts)	Duration (Days)	Wet Soil Weight (kg)	Dry Soil Weight (kg)	Maximum Dry Density (kg/m³)	Water Weight (kg)	Moisture Percentage (%)	Effective Soil Thickness (mm)	t	Compaction Percentage (%)	Consolidation Coefficient (Cv)
5	Clay + Sand	30	7	2.946	2.425	2.55	0.521	21.5%	7.44	3	95.10%	2.10
6	Clay + Sand	30	28	2.105	1.765	2.01	0.34	19.3%	5.65	4	87.81%	1.20
7	Clay + Sand	15	7	2.018	1.698	1.84	0.32	18.8%	5.70	4	92.28%	1.21
8	Clay + Sand	15	28	1.55	1.32	1.55	0.23	17.4%	5.81	4	85.16%	1.23

To interpret the results provided, we analyze various parameters in the soil tests. The table presents different tests on soil, which include soil type, voltage, duration, different weights, and physical properties of the soil.

Soil Type:

Two types of soil were examined: pure clay and a mixture of clay and sand.

Pure clay (tests 1 to 4) shows a different behavior in terms of weight and density compared to the clay-sand mixture (tests 5 to 8).

Voltage and Duration:

The voltage in the tests was 30 volts and 15 volts.

The test durations varied between 7 to 28 days, indicating the impact of time on soil properties. Generally, longer tests (28 days) show different results compared to shorter tests (7 days).

Wet and Dry Soil Weight:

The wet and dry soil weights provide us with information about soil moisture and compaction.

For example, in tests 1 and 2 (pure clay), the wet soil weight decreased, which could be due to changes in moisture content.

Moisture Content:

The moisture content in various tests indicates differences in water absorption and retention by different soil types.

The clay + sand mixture generally shows a higher moisture content (especially in test 5 with 21.5%) compared to pure clay, which is related to the higher permeability and water absorption potential of sandy soils.

Dry Density:

Dry density varies across different tests.

Generally, tests conducted for a longer duration (such as tests 2 and 4) show lower dry densities compared to shorter tests (tests 1 and 3).

Compaction Percentage:

The compaction percentage is also a key piece of information.

The highest compaction percentage is observed in test 1 with 98.93%, indicating suitable density and compactness of the soil.

Consolidation Coefficient (Cv):

The consolidation coefficient is another important parameter that indicates the rate of soil consolidation.

Higher Cv values in sandy soil tests indicate better and faster consolidation compared to pure clay.

The tests show that both soil type and duration have a significant impact on the physical properties of the soil. Specifically, the soil mixture (clay + sand) shows a different behavior from pure clay due to its higher permeability. This information can help designers and engineers optimize soil for construction and civil engineering projects.

5. Conclusion

In the initial results of this study, as mentioned in the research topic, the effect of calcium carbonate in improving the conditions for conducting the experiment is used solely for providing a suitable environment for the test. The percentage of added calcium carbonate does not cause significant changes in the test results; it only helps create the appropriate conditions for altering the variables of voltage and time. In other words, calcium carbonate is essential for conducting the experiment, as it sets up the foundation for changing the voltage and time variables.

Voltage and Time Changes

Voltage and time are critical factors that significantly influence soil settlement, particularly in experiments related to clay and sand settlement. Below is a discussion of these two variables and their impact on test results:

1. **Voltage Change:**
    - **Effect of Voltage on Settlement:** Increasing voltage can directly contribute to increased soil settlement. In experiments conducted with higher voltages (such as 30 volts), we observe more significant changes in soil settlement compared to lower voltages (such as 15 volts). The increase in voltage can create a higher electric field in the soil and facilitate the movement of soil particles, especially in saturated conditions.
    - **Effect on Soil Type:** The effect of voltage also varies depending on the soil type. For example, in clay soil tests, higher voltage can promote better separation of clay particles and ease their settlement. In sandy soils, however, increasing the voltage might have less impact, as sand particles, due to their larger size and lower cohesion, are harder to move.
    - **Experimental Settings:** Selecting the appropriate voltage for experiments is crucial depending on the study's goal and the soil's behavior. Different voltage levels can produce varying patterns of settlement and deformation over time.
2. **Time Change:**
    - **Effect of Time on Settlement:** Time is one of the key factors in evaluating soil settlement. Over time, soil settlement increases due to applied loads, physical and chemical changes in the soil structure, and particle compaction. In longer tests (such as 28 days), the amount of settlement is typically greater than in shorter tests (such as 7 days).
    - **Effect of Time on Soil Behavior:** Soil behavior over time can change gradually. In the early stages of settlement, changes are usually faster, and over time, these changes tend to slow down. This means that in the first days of the experiment, more settlement may be observed, whereas in later days, this process becomes slower.
    - **Environmental Factors:** In addition to time, environmental conditions such as humidity, temperature, and pressure can influence soil settlement. For example, in higher temperatures, evaporation rates and moisture changes may have a more significant effect on soil settlement.

Interaction Between Voltage and Time

Voltage and time, as two primary factors in soil settlement experiments, have interactive effects. Increasing voltage generally helps increase settlement, while the passage of time also contributes to the consolidation and increase in settlement. These two variables must be carefully studied to accurately understand and analyze soil behavior under different conditions. Ultimately, a deeper understanding of these factors can assist in optimizing engineering designs and improving soil management.

Overall Conclusion from Soil Test Data:

1. **Soil Type Influence:**
    - The type of soil, especially the clay-sand mixture, significantly affects the physical properties and mechanical behavior of the soil. Pure clay generally has higher density and compaction percentage, while mixed soils (clay + sand) show more diverse behavior in moisture absorption and permeability.
2. **Time and Voltage:**
    - The test duration (7 days vs. 28 days) significantly influences the results. Longer tests generally lead to reduced dry weight and compaction percentage, indicating consolidation

and changes in the soil properties over time. Different voltages may also impact the results, but a direct effect cannot be clearly identified from the data.

3. **Moisture and Density:**
    - Moisture percentage and dry density are crucial parameters in assessing soil conditions. Soils with higher moisture content (especially in combination with sand) show a high water retention capacity and increased permeability, which could be important in construction applications.
4. **Consolidation Coefficient (Cv):**
    - The consolidation coefficient (Cv) reflects the rate of soil consolidation and changes in soil properties. Higher Cv values in mixed soils indicate better and faster consolidation, which can be beneficial in construction projects.

This analysis provides a comprehensive understanding of how soil type, voltage, time, and other factors contribute to the behavior and performance of soils under various conditions.

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Effect on Soil Type: The effect of voltage also varies depending on the soil type. For example, in clay soil tests, higher voltage can promote better separation of clay particles and ease their settlement. In sandy soils, however, increasing the voltage might have less impact, as sand particles, due to their larger size and lower cohesion, are harder to move.

Experimental Settings: Selecting the appropriate voltage for experiments is crucial depending on the study's goal and the soil's behavior. Different voltage levels can produce varying patterns of settlement and deformation over time.

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Environmental Factors: In addition to time, environmental conditions such as humidity, temperature, and pressure can influence soil settlement. For example, in higher temperatures, evaporation rates and moisture changes may have a more significant effect on soil settlement.

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The consolidation coefficient (Cv) reflects the rate of soil consolidation and changes in soil properties. Higher Cv values in mixed soils indicate better and faster consolidation, which can be beneficial in construction projects.

This analysis provides a comprehensive understanding of how soil type, voltage, time, and other factors contribute to the behavior and performance of soils under various conditions

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5.2. Conflicts of Interest

"In this section, you should disclose any potential conflicts of interest that could influence the results or interpretation of the paper. If the authors have any financial interests, personal relationships, or other professional ties that could be seen as influencing their work, they should be disclosed here. If there are no conflicts of interest, a statement such as 'The authors declare no conflict of interest' should be included."

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