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Investigations on Improvement of Expansive Soil Properties using Electrokinetic Method

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Abstract: Expansive soils, rich in active clays with Montmorillonite mineral, undergo large swell–shrink volume changes with moisture variation, causing differential ground movements that damage civil infrastructure and get worsened by their low shear strength and high compressibility in saturated conditions. Conventional methods like compaction and lime or cement stabilisation work well near the surface but are difficult to apply at depth or beneath existing structures. The electrokinetic method of stabilisation offers a non-invasive way to improve deep, low-permeability soils. The fundamental principle of Electrokinetic stabilisation involves the application of a direct current (DC) across a soil mass via electrodes. This electrical field induces coupled flow phenomena, Electro-osmosis (fluid transport), Electromigration (ion transport), and Electrophoresis (charged particle transport), which can be manipulated to introduce chemical stabilizers into the soil matrix, when coupled with the injection of cationic fluids, such as Calcium Chloride, the process evolves into Electrochemical Stabilisation, facilitating profound changes in the physicochemical properties of the clay. This study presents a comprehensive analysis of a specific experimental investigation: the electrokinetic treatment of an expansive soil using Aluminium electrodes and Calcium Chloride Dihydrate ($CaCl_2 \cdot 2H_2O$) solution as a stabilising agent. The study encompasses three distinct trials featuring increasing concentrations of Calcium Chloride: 0.5 M, 1.0 M, and 1.5 M, with a duration of 7 days for each trial. The primary objective is to evaluate the efficacy of these varying concentrations in mitigating swelling, reducing plasticity, and enhancing shear strength. A critical component of this analysis is the interpretation of the specific laboratory data obtained for untreated and treated soil for determining the efficiency of Electrokinetic stabilisation and identifying the optimal concentration of stabilising agent.
From the results, it can be observed that Electrokinetic stabilisation is a viable, robust method for improving the geotechnical properties of soil. Based on the test results from compaction characteristics, Unconfined Compression Strength (UCC), and pH values, the optimal concentration for the selected expansive soil is 1.0M of Calcium Chloride (Dihydrate) achieved better results.

I. INTRODUCTION

Excessive compression, dispersive behaviour, collapsing behaviour, low shear strength, high swell potential, and frost susceptibility are some undesirable properties of expansive soils in geotechnical engineering that can cause severe distress to structures built on them. It is essential to check for the presence of expansive soil and to adopt a suitable treatment method adoption before commencing any construction projects. Conventional remediation methods have been successful in minimising several types of damage; however, they are expensive, time-consuming, and difficult to implement in some existing structures. In this regard, electrochemical or Electrokinetic treatment method can be used as an alternative soil treatment method for remediation of those deficiencies underneath building foundations, roads, railways or pipelines. The use of this technique involves an approach with minimum disturbance to the surface while treating subsurface contaminants and improving the engineering characteristics of subsurface soils. Electrokinetic stabilisation is a physical-chemical method of soil stabilisation that utilizes electrical fields to improve the engineering properties of soil, such as strength, shear resistance, and permeability. It is especially effective for fine-grained soils (such as clay), which tend to exhibit undesirable characteristics like low strength, high plasticity and deformation characteristics. The technique works by inducing electrochemical changes within the soil, which can lead to improved soil structure and stability.

Electrokinetic stabilisation (EKS) works by passing a low-voltage direct current through soil to trigger three primary mechanisms that improve its strength and stability:

1) Electro-osmosis: The movement of water from the anode (positive electrode) to the cathode (negative electrode). This process effectively dewaters the soil, reducing moisture content and increasing density.
2) Electrophoresis: The movement of charged soil particles (like clay) toward the electrodes, which helps in rearranging the soil structure into a more stable configuration.

3) Ion Migration and Cementation: As ions (from added salts or the electrodes themselves) move through the soil, they react with soil minerals. This creates a "cementing" effect that permanently binds particles together and reduces the soil's tendency to swell.

This paper presents the effectiveness of the Electrokinetic method in stabilising selected expansive soil in improving strength and reduction in swelling nature.

II. LITERATURE REVIEW

For the Electrokinetic stabilisation of soils, various works were carried out by researchers, for various purposes, using electrodes. The works referred to in the present work are listed below.

The shear strength of the soil increased up to 127% after treatment when measured near the anode and up to 495% at the cathode, an increase in soil strength overcoming bearing capacity problems in soft fine-grained soils with low hydraulic conductivity. [R. M. Rustamaji (2024)]

The injection of ionic solution $CaCl_2$ and Na_2Co_3 treatment facilitated the formation of the Calcium, interaction between the Calcium or Aluminium ions and the clay minerals. The Plasticity Index (PI) and swelling potential, reduced significantly making the soil more stable and less prone to volume changes. [Abiodunabiola (2021)]

The results reflected an improvement in the strength of the soil, based on the concentration of Calcium Chloride injection into the soil, leading to an increase in the electric current and Electro osmotic permeability. [Estabragh et al. (2020)]

Presented the results of the investigation and concluded that 0.25M of CaOH and $CaCl_2$ were capable of reducing the plasticity and swell-shrink behaviour of the expansive soil with different levels of effectiveness. [Jijo James et al. (2019)]

III. MATERIALS USED

From the literature review, it is clear that the purpose of the Electrokinetic treatment is not just dewatering but also to stabilise the soil. The following materials were used in the present investigations.

A. Soil

The soil samples were obtained at 2.0 to 3.0 m depth from the APIIC (Andhra Pradesh Industrial Infrastructure Corporation) Industrial Park, Athuru village near Tirupati, Andhra Pradesh. The collected soil samples was air dried, pulverised with a wooden mallet to break lumps and then sieved with a 4.75 mm sieve to eliminate the gravel fraction.

B. Model Box

A model test box of size 0.5m (L) x 0.3m(W) x 0.3m (H) with 12 mm thickness, waterproof plywood in a parallelogram shape, open at the top, was used as shown in Figure 1. Two outside compartments were reserved for the anode and the cathode chambers, and with water for saturation. The middle compartment was used for placing soil. The two walls separating the three compartments in the Electrokinetic test box were perforated with 10 mm diameter holes. Aluminium electrode selection based on the often usage of Grey and Schlocker (1969) in their research about electrochemical alteration of clay soils. Aluminium anodes are often used in engineering practice for electro-osmotic dewatering and can be combined with Hydroxide ions to form various Hydroxyls–Aluminium compounds in soil.

Fig. 1. Fabricated Plywood Test Box

Fig. 2. Aluminium Electrodes

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C. Calcium Chloride

Calcium Chloride Dihydrate ($CaCl_2 \cdot 2H_2O$), a common salt with properties that make it particularly suitable for geotechnical applications, was used as a chemical stabiliser. The physical properties and chemical properties of Calcium Chloride (Dihydrate) are provided in Table 1.

TABLE I.
PHYSICAL AND CHEMICAL PROPERTIES OF CALCIUM CHLORIDE (DIHYDRATE) (COMMERCIAL)

Property	Observation
Description	White Crystalline Powder
Physical State at 20 ^{o}C	Solid
Odour	Odourless
Mol. Weight	147.02 g/mol
Melting point	176 ^{o}C
Solubility in water	Water: 147 g/l at 20 ^{o}C – Completely Soluble
pH	6.37
Assay	99.17 %
Sulphate (SO_4)	< 0.01 %
Heavy Metal (as Pb)	< 0.001 %
Iron (Fe)	<0.001 %

IV. METHODOLOGY

A. Tests Conducted

The following Tests were conducted on the collected expansive soil sample as per IS 2720 to determine the properties of the soil samples.

TABLE II.
SOIL TESTS CONDUCTED

S.No	Tests	Reference
1	Natural Water Content	IS 2720 (Part-2)-1973
2	Specific Gravity	IS 2720 (Part-3)-1980
3	Grain Size Distribution	IS 2720 (Part-4)-1985
4	Plasticity Characteristics	IS 2720 (Part-5)-1985
5	Free Swell Index	IS 2720 (Part-40)-1977
6	pH Test	IS 2720 (Part-26)-1977
7	Electric Conductivity of soil	IS 14767-2000
8	Compaction characteristics	IS 2720 (Part-7)-1980
9	Unconfined Compression Strength	IS 2720 (Part-10)-1991

The dried soil sample passing the 4.75 mm I.S Sieve was mixed with the optimum water content (from I.S light Compaction Test) and kept in a bag, closed for 24 hrs. for proper saturation and compacted in layer by layer of 2.5 cm thickness each in the model tank and compacted.

A non-woven geotextile was placed in the inner edge of the middle compartment, i.e. both ends of the soil specimen between the anode and the cathode compartments, for inhibiting the movement of soil particles from each side of the soil specimen inside the test box. An Anode Electrode and a Cathode Electrode arrangement of electrodes was done up to the predefined height, and left untreated for a day for attaining equilibrium state.

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Fig. 3. Arrangement of soil samples and electrodes in the model box.

After 24 hours, Calcium Chloride ($CaCl_2$•$2H_2O$) was mixed with distilled water to prepare a solution. Varying concentrations (0.5M, 1.0 M and 1.5 M) were used to determine the optimal concentration as a stabilising agent.

B. *Electrokinetic Treatment*

After 24 hours of arrangement of soil and electrodes, a regulated Direct Current power supply of 25V (1 V/cm) was applied between the electrodes and the current was observed regularly. The treatment was continued for 7 days for effective results. After treatment, soil samples were collected near the anode and the cathode and the samples were air-dried before testing.

The variation of plasticity characteristics, compaction characteristics, FSI, UCC and pH with $CaCl_2$ concentrations is discussed in a further section. Tests were conducted on soil as per IS:2720; the details of the tests conducted are provided in Table 2.

a. D.C Power Supply Arrangement

b. Model box filled with soil, Anode and Cathode electrodes connection.

Fig. 4. Electrokinetic Treatment Setup

V. RESULTS AND DISCUSSIONS

Properties of untreated soil are presented in Table 3. As per the IS classification of soil, the soil sample is Highly Compressible Clay and is highly expansive as per the FSI Value.

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TABLE III.
PROPERTIES OF SOIL COLLECTED

S.No	Properties	Results	Reference
1.	Natural Water Content	98.3 %	IS 2720 (Part II) - 1973
2.	Specific Gravity	2.79	IS 2720 (Part-3)-1980
3.	Grain Size Distribution		IS: 2720 (part IV) - 1985
	a) Sand (%)	17.9 %	
	a) Silt (%)	34.3 %	
	a) Clay (%)	47.8 %	
4.	Atterberg Limits		IS:2720 (part-5) – 1985
	a) Liquid Limit (%)	**95.3 %**	
	a) Plastic Limit (%)	20.9 %	
	a) Plasticity Index (%)	**74.4 %**	
5.	Free Swell Index (%)	**206.7 %**	IS:2720 (Part-XL) – 1977
6.	IS Classification	**CH**	
7.	pH	9.7	IS: 2720 (part-26) – 1987
8.	Electric Conductivity	0.9 mS/cm	IS 14767- 2000
9.	Maximum Dry Density	16.8 kN/m³	IS: 2720(part 7) -1980
10.	Optimum Moisture Content	14.4 %	IS: 2720(part 7) -1980
11.	Unconfined Compression Strength	34.13 kN/m²	IS: 2720 (Part 10) – 1991

A. *Plasticity Characteristics*

1) *Liquid Limit*

The variation of liquid limit with $CaCl_2$ (Stabilizing Agent) Concentration is shown in Figure 5. From the graph, it can be observed that the liquid limit decreases across all trials. The primary reason for the drop in liquid limit is the replacement of monovalent ions (like Na^+) typically found in expansive soils with the divalent Calcium ions (Ca^{2+}) from the stabilizing agent. This compresses the water layer around clays, making the soil stiffer and less able to hold water before turning fluid.

2) *Plasticity Index*

The variation of Plasticity Index with Stabilizing Agent concentration is shown in Figure 6. From the results, it can be observed that electrokinetic treatment significantly improved the expansive soil properties, particularly by reducing the plasticity index through a modest plastic limit increase alongside a sharp liquid limit drop. Plasticity index plummeted primarily due to a reduction in liquid limit resulting from suppressed double-layer water adsorption following divalent/trivalent cation replacement. The Plasticity Index drop signifies lower moisture sensitivity and swell potential.

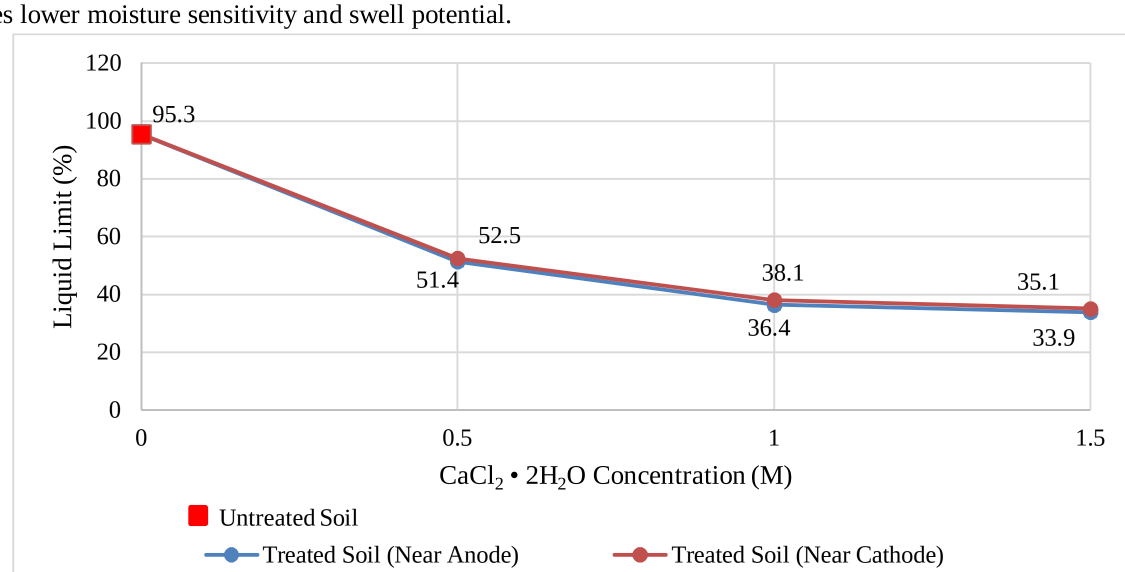

Fig. 5. Variation of Liquid Limit with Stabilizing Agent concentration at Anode and Cathode

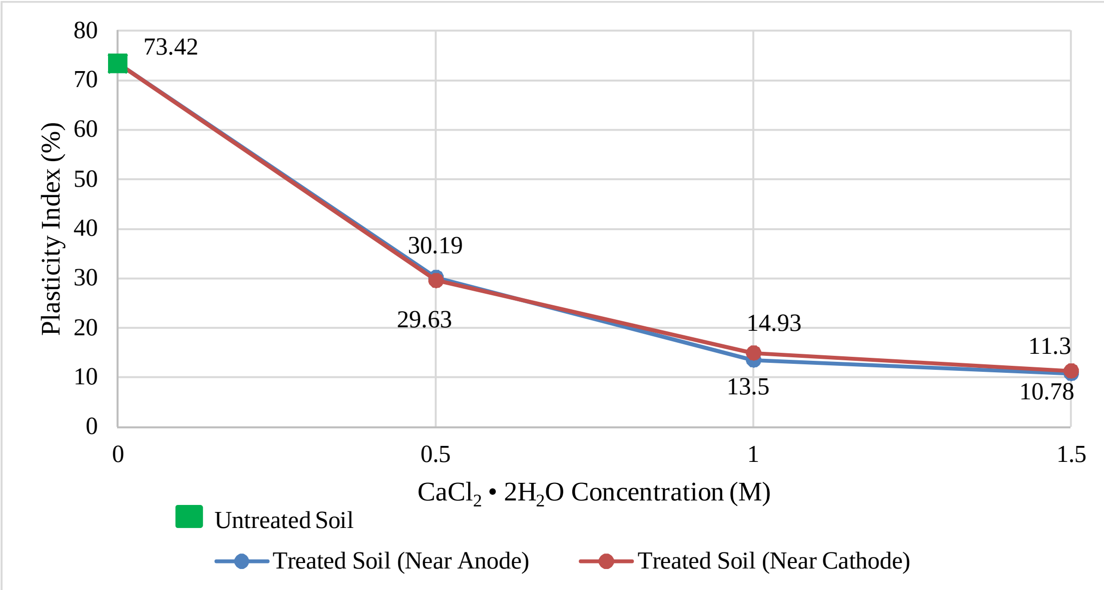

Fig. 6. Variation of Plasticity Index with Stabilizing Agent concentration at Anode and Cathode

B. Compaction Characteristics

Figures 7 and 8 depicts the variation of Maximum Dry Density and Optimum Moisture Content with Stabilizing Agent concentration. From the graph, it can be observed that the MDD increased while OMC decreased with calcium chloride concentration increment up to 1.0 M. Beyond this level, a reduction in MDD and a slight increase in OMC occurred at 1.5 M concentration, indicating possible ion saturation.

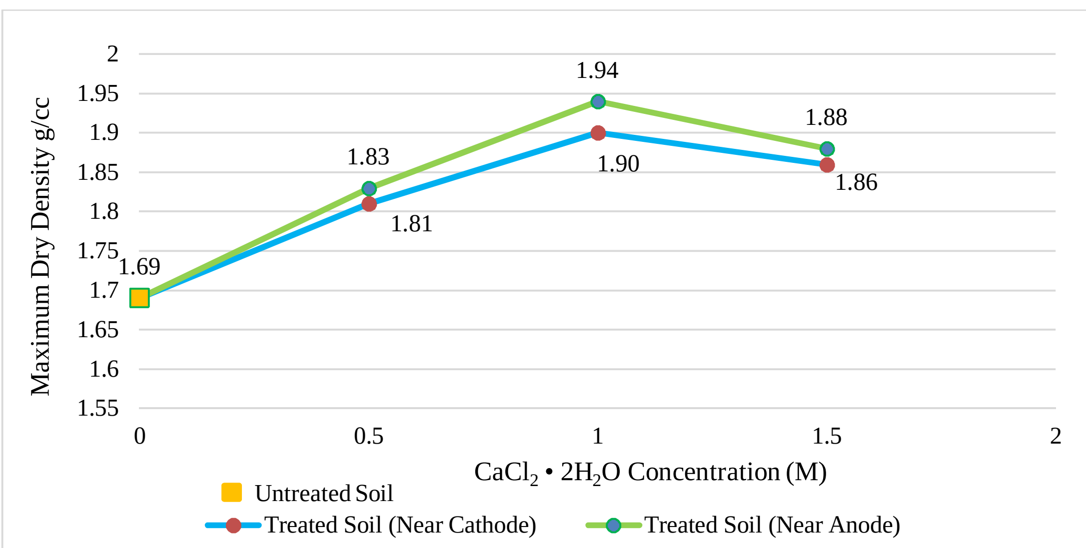

Fig. 7. Variation of Maximum Dry Density with Stabilizing Agent concentration at Anode and Cathode

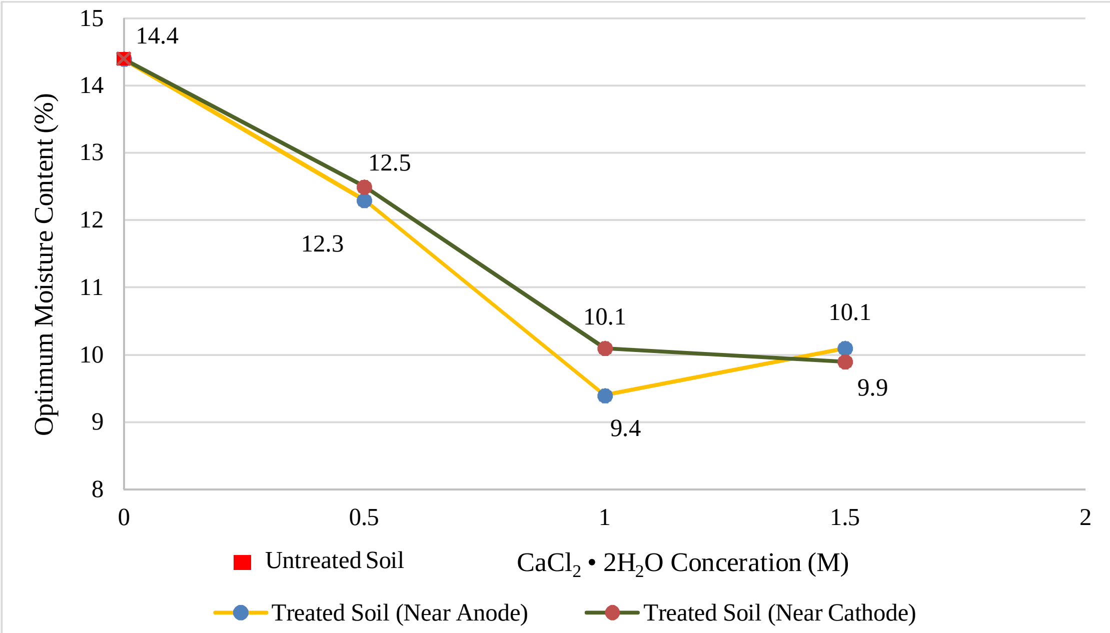

Fig. 8. Variation of Optimum Moisture Content with Stabilizing Agent concentration at Anode and Cathode

C. Unconfined Compressive Strength

The variation of UCC with Stabilizing Agent concentration is plotted in Figure 9. From the figure, it can be observed that the maximum Unconfined Compressive Strength (UCC) is obtained at 1.0 M, and the electrokinetic method improves soil strength in the stabilization process.

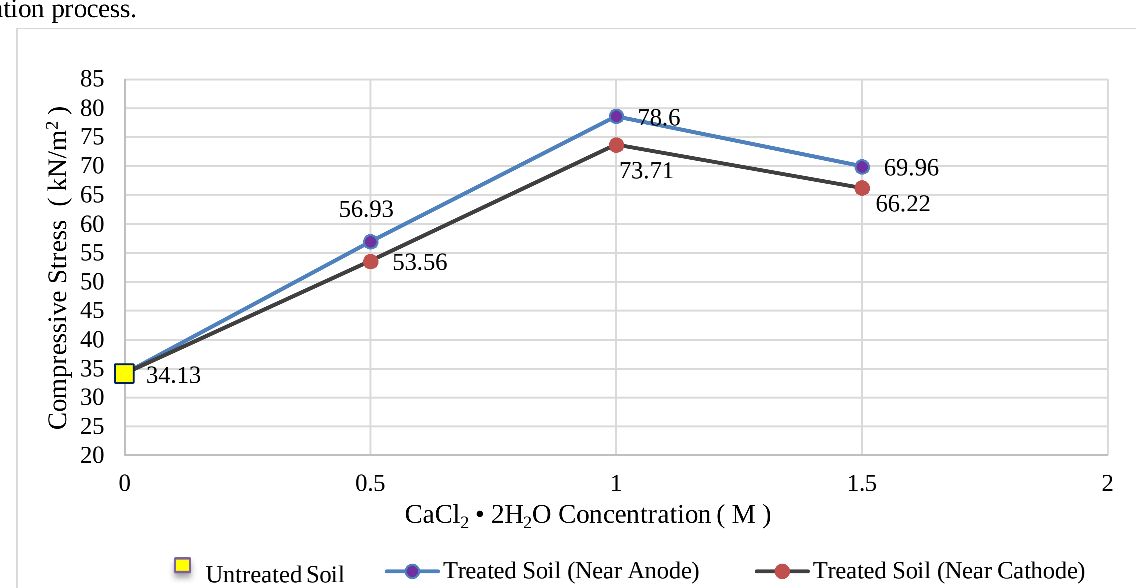

Fig. 9. Variation of UCC with Stabilizing Agent concentration at Anode and Cathode

D. Free Swell Index

The variation of FSI with Stabilizing Agent concentration is shown in Figure 10. From the results, it can be observed that the Free Swell Index decreases with the concentration of $CaCl_2$

This demonstrates the effectiveness of electrokinetic Method where, Direct current drives electromigration of Ca^{2+} ions from the anode compartment into the soil toward the cathode, while electroosmosis moves pore water and ions similarly. Aluminium electrodes dissolve at the anode, releasing Al^{3+} ions that migrate into the soil; these multivalent cations (Ca^{2+} and Al^{3+}) displace monovalent ions like Na^{+} on clay surfaces via cation exchange.

This exchange reduces the thickness of the diffuse double layer around expansive clay particles (e.g., Montmorillonite), reducing the soil's ability to absorb water and swell.

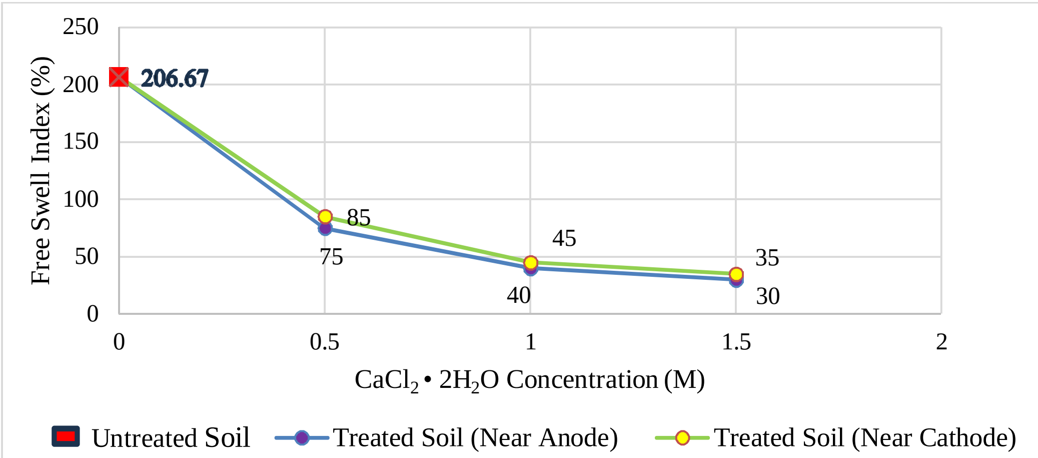

Fig. 10. Variation of Free Swell Index with Stabilizing Agent concentration at Anode and Cathode

E. Soil pH

The Variation of pH value for untreated soil and treated soil is shown in Table 4 and presented in Figure 11. It can be observed that Untreated soil is alkaline nature with pH of 9.7, typical for expansive clays like montmorillonite. At Anode pH drops from 8.51 (0.5 M) to 6.31 (1.5 M), whereas at the cathode, pH rises from 10.2 (0.5 M) to 12.34 (1.5 M).

TABLE IV
pH OF UNTREATED AND TREATED SOILS

Type	pH value	
Untreated Soil	9.7	
Treated Soil	At Anode	At Cathode
0.5 M $CaCl_2$	8.51	10.2
1.0 M $CaCl_2$	7.46	10.86
1.5 M $CaCl_2$	6.31	12.34

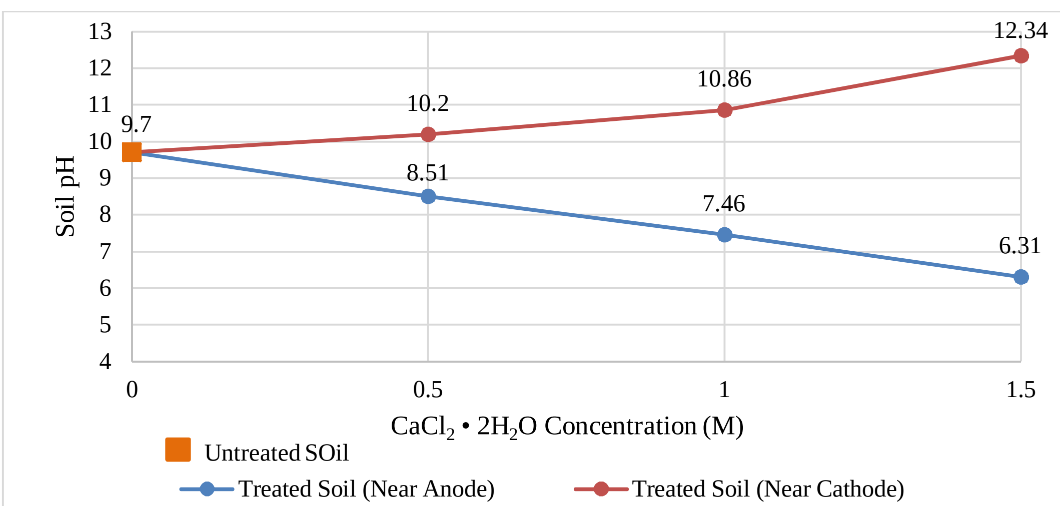

Fig. 11. Variation of pH with Stabilizing Agent concentration at Anode and Cathode

VI. CONCLUSIONS

The following conclusions are drawn based on the test results.

1) The native soil is Highly compressible clay with LL of 95.3 % and PI of 73.42 and an FSI exceeding 206 %, indicating high expansive nature and may not be suitable for engineering applications as the compressive strength (34 kPa) is low.
2) EKM is chosen for improving the strength of the selected expansive soil and swelling nature.
3) EKM was implemented in model box using Aluminium electrodes and $CaCl_2$ (Dihydrated) as stabilizing agent.
4) Model test studies were conducted at various concentrations (0.5M, 1.0M, and 1.5M) of Stabilizing Agent to observe its influence on Plasticity characteristics, Compaction characteristics, Free Swell Index and UCC of soil.
5) The studies demonstrate the variation of Plasticity characteristics, Compaction characteristics, Free Swell Index and UCC with the varying concentrations of $CaCl_2$.
6) The Liquid Limit reduced from 95.3 % to 33.9 %, and the Plastic limit increased from 20.96 % to 23.15 %.
7) The OMC decreased from 14.4 % to 9.9%, and MDD increased from 16.8 kN/m3 to 19.4 kN/m3.
8) Free Swell Index is reduced from 206% for untreated soils to 35% for soil treated with 1.5M of Calcium Chloride.
9) The Unconfined Compressive Strength (UCC) of soil improved from 34.13 kN/m2 to 78.6 kN/m2 at 1.0M concentration of Calcium chloride.
10) pH value for untreated soil is 9.7, which is a typical value for expansive clays. pH drops from 8.51 to 6.31 at the anode, and rises from 10.2 to 12.34 at the cathode, indicating a reduction in Diffusion Double Layer thickness and improving the strength of the soil.

It can be concluded that the Electrokinetic Method of stabilization is a viable, robust method for improving the geotechnical properties of soil. It can be used as remediation of deficiencies underneath building foundations, roads, railways or pipelines. This technique involves an approach with minimum disturbance to the surface while treating subsurface contaminants and improving the engineering characteristics of subsurface soils.

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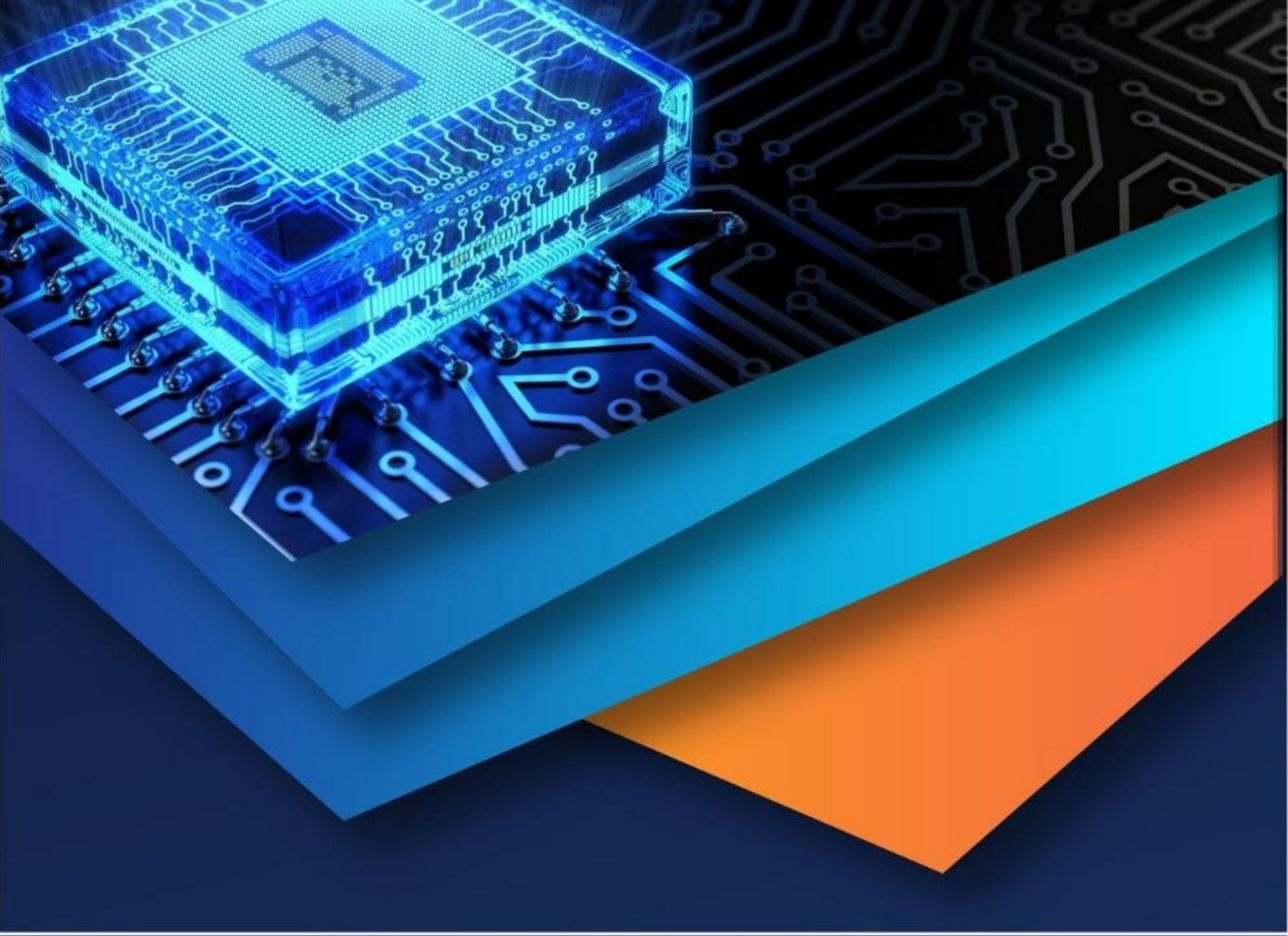

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