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INVESTIGATING THE EFFECTIVENESS OF ELECTRO-OSMOTIC TREATMENT OF PROBLEMATIC SOILS

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Abstract

The efficiency of electro-osmotic treatment is controlled by the electrical resistance of the system. Due to the application of an electric field, hydrated positively charged ions are attracted to the negative electrode (cathode). Those ions drag the hydrated water molecules towards the cathode, creating a flow of water. In this study, an expansive soil with a high swelling potential was compacted in an innovative wooden container and electro-osmosis treatments under different voltage gradients of 0.46 V/cm, 0.92 V/cm, and 1.84 V/cm for periods of 1 day, 2 days, 7 days, and 28 days. The results showed the improvement of soil around anode, where the swelling potential reduced by up to 83%, the pH reduced by up to 2.8, and the unconfined compressive strength increased by up to 400% in the best considered test. An electric field of 24 V, equivalent to the voltage gradient of 0.92 V/cm, applied for 7 days was considered as the optimum testing case to reduce the swelling potential. Chemical tests on samples taken from near anode and the anode showed a decrease of pH due to the electro-osmosis application. However, pH of the samples taken from near cathode increased. It was observed that the reduction of swelling potential of the highly expansive soil was attributed to the reduction of cathode ions. The

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stabilized soil specimens were characterized with scanning electron microscopy (SEM) and compressive strength testing which significantly improved the soil's consolidation properties, reducing settlement and increasing shear strength. The present paper shows that, from a practical point of view, the electro-osmosis method has superior performance compared to other methods, making it a viable option for soil dewatering and stabilization.

Introduction

Expansive soil commonly referred to as shrink–swell soil as a significant geotechnical challenge due to their inherent properties of swelling, upon wetting and shrinking upon drying is regarded as problematic. These soils primarily composed of clay mineral exhibit substantial volume change leading to differential settlement, heaving, and cracking which may undermine the long-term performance of structures which are built on them. These cyclic swells and shrinking necessitate innovative and effective soil stabilization techniques. However, expansive soils can be treated using electro-osmosis technique, which is a new and effective treatment method. The normally used stabilizers include Ordinary Portland Cement (OPC) and lime. In cement stabilized soils, the stabilization mechanisms are associated with hydration and pozzolanic reactions (Zeng et al. 2021). When lime is mixed with clayey soils, the clay particles become closer and the soil is stabilized through flocculation and pozzolanic reactions (Tohidvand et al. 2022). A major issue with conventional soil stabilizers (i.e., OPC and lime) is that their production processes are energy intensive and emit a large quantity of CO_2 (Liu, and Zhang, 2020). For instance, approximately one ton of CO_2 is emitted for the production of one ton of cement (Maleki et al. 2023). Furthermore, the raw materials readily available for cement production are being over-consumed. Therefore, civil engineering industry is always searching for new, viable sustainable alternatives to replace Portland cement and lime as soil stabilizers. Electro-osmosis is an established method of treating soft soils whereby a direct current (DC) is applied by electrodes. Electro-osmosis has also been extensively studied for its use in clay remediation. According to Bhattacharya, Basack, (2011), electro-osmotic treatment has been extensively tested and has been proven to have clear benefits to dewatering clay soils. With the application of an electric field, contaminants in clay Soil can be forced to migrate towards one of the electrodes, where they can be removed more efficiently. When electroosmosis occurs, water in the soil will flow from anode to cathode, inducing a negative pore pressure which will result in faster consolidation and increase in the shear strength of the soil (Micic et al., 2001). The phenomenon is developed for the fact that

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clay particles have negative surfaces which attracts the cations that are surrounded by water molecules. Once a current applied to the system, the cations start moving towards the cathode with the surrounded water molecules (Asadi et al., 2013). The application of electro-osmosis involves the installation of electrodes into the soil typically using a series of electrodes. The electrodes are connected to a power source, which applies an electric potential difference across the soil. When an electric potential difference is applied across the soil, water molecules in the soil are polarized with the negative end of the water molecules being attracted to the negative electrode (Zhang and Hu 2021). This movement of water molecules increases the soils density and reduces its porosity, resulting in an improvement in shear strength. The duration and intensity of the applied voltage depend on the specific project requirements and the properties of the soil. If drainage is provided at the cathode, and no water is permitted to enter at the positive electrode (anode), negative pore water pressure develops and dewatering of the Soil occurs, resulting in higher shear strength and lower compressibility. A study by Zhang et al. (2015) demonstrated that piles and anchors could be used as electrodes for the electrochemical improvement of soils. Yang et al. (2019) indicated that the change of applied voltage until a specific value could enhance the efficiency of electrochemical improvement of clays, while additional changes in voltage (more than the optimal value) have no significant effect on the electrochemical process.

Previously applied studies involving small-scale physical modeling tests using a soil box element test by (Al-Shammiri and Al-Mamgameri, 2016; Ling et al. 2017; Estabragh et al. 2014; Mahalleh et al. 2021; and Xue et al. 2017), large scale field tests (Burnotte et al. 2004; Lee 2015; (Zhuang and Wang, 2017) and numerical methods (Bader 2005; Yuan and Hicks 2015). These researches are made up of mostly fine-grained soils (including silts and clays), an average shear strength increase of 500–600% were achieved in the tests. However, the tests showed non-homogeneous strength distributions over the specimen and increase in shear strength was limited near the anode or cathode. In another research conducted by Alshawabkeh and Sheahan (2003), the un-drained shear strength of soil was increased by inter-particle cementation caused by the electrochemical injection of phosphate into the soil under the direct current (DC) field. The increase in shear strength of soil near the cathode can be related to the precipitation of phosphate in the soil. Otsuki et al. (2007) applied the electrochemical technique to inject Mg $(CH_3COO)_2$, $MgSO_4$, $Mg(NO_3)_2$, $ZnSO_4$, and $AgNO_3$ as anolyte solutions and NaOH and Na_2CO_3 as catholyte solutions into the kaolinic soil. The results showed that the shear strength was increased up to 300 kPa, but the region of improvement was still limited to near the cathode. The increase in shear strength of soil near the cathode could also be related to the precipitation of phosphate in the soil.

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Sample preparation and experimental procedure

The soil used in the testing program was native clay soil of Unwana. The soil can be classified as the clay with low plasticity (CL) according to the Unified Classification System (USCS). Drinking water was used for conducting the tests and it had a pH of 7.76, Cl content of 1.7 meq/L and Ca–Mg content of 9.1 meq/L. A specific amount of air-dried soil was mixed with water to achieve a water content of 5% above the liquid limit. The soil was mixed by hand steer for about 1 h until a smooth condition was achieved. This mixture was kept in a plastic bowl with closed lid for about 10 days for uniform distribution of water content. The strength of the prepared soil was measured by using shear vane apparatus (ASTM D4648-00, 2000) in random points of the soil. The prepared soil sample was placed in the main cell and a saturated geo-membrane was placed on top of the soil to create a horizontal flow condition. The level of water was kept the same in the anode and cathode reservoirs at two sides of soil in the main cell. Then a surcharge pressure of 22 kPa was applied to the soil via the loading plate. The settlement of the sample was monitored using a dial gauge. The consolidation settlement stopped after about five days. The samples used for consolidation tests were prepared with depths equal to 0.02 m. All samples were prepared with a dry density equal to 80% of the maximum dry density of clays. Before applying an electric field to the samples, a pressure equal to 100 kPa was applied to them, and samples were allowed to consolidate under this preloading condition. Effects of the electro-osmosis consolidation procedure on the strength of the used clays were also investigated using some samples with a height of 0.125 m (and diameter of 0.05 m), where unconfined compression tests were applied to them. Consistency between consolidation and unconfined compression tests was ensured using samples with the same volumetric strains for unconfined and electro-osmosis consolidation tests. This stage of test will be referred to as preloading consolidation. When this stage was completed a number of samples were taken along the soil for determining the water content. The osmosis consolidation was carried out after the preloading consolidation stage by setting the hydraulic gradient between two reservoirs to zero. The osmotic consolidation was enforced by applying a D.C. current through the soil. The vertical deformation was measured by monitoring the readings of the dial gauge and the volume of the sample was calculated by measuring from the volume of outflow of water from the cathode reservoir during the test. The total time for consolidation stage was about 10 days for different voltages. After the test, the un-drained shear strength was measured using shear vane at the anode, middle, and the cathode. The samples were taken for determination of water content and its Atterberg limits.

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Application of Scanning Electron Microscope (SEM)

Scanning Electron Microscope (SEM): Scanning Electron Microscope (SEM) is a microscope that forms images by using electrons rather than using light. SEM analysis gives valuable information about the microstructure of soils and change in microstructure for chemically treated soils. In this study, SEM analysis was performed at Civil Engineering Laboratory, Akanu Ibiam Federal Polytechnic Unwana, Ebonyi State, Nigeria and during analysis QUANTA 400F Field Emission Scanning Microscope was used. It is a high-resolution electron microscope with a resolution of 1.2 nm. Before the analysis all the samples were dried at 45°C as the water vapour harms the microscope. Then the samples were exposed to vacuum and covered with gold and palladium as the soil samples are insolvent. To see the effect of swell-shrink cycles on microstructure, samples were analysed both right after compaction and after being exposed to 5 swell-shrink cycles except for the 0.46 V/cm treated sample. The aim of analysing 0.46 V/cm treated sample after first condition (dry state of first cycle) was to determine the reason for high swelling amount in the first cycle.

Electro-osmotic soil experimental box

As large-scale field tests are expensive and time-consuming, this approach has been employed less than other ones in research projects, while physical modeling and element tests have been frequently used to study electro osmotic soil improvement methods. Electro-osmosis was performed by using an electro-osmotic soil box made of plexiglas (0.28 m diameter and 0.33 m height), bounded by a top and bottom plexiglas plate (Fig. 1). Plexiglas was used because of its electrical and hydraulic impermeability. The top is open for easy pouring and removing of soil samples and for connecting the tubular electrodes (anode and cathode), pressure probes for pressure consolidation, and drained tubes for consolidation**.** This study carried out electro-osmosis soil improvement in collaboration with geotechnical structural elements such as anchors, nails, and piles in the city of Unwana in Afikpo Local Government of Ebonyi State, Nigeria.





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Figure 1 Electro-osmotic/ Electro-migration experimental study

Electro-migration

Electro-migration is then carried out to enable flow of ions into the sample due to the presence of induced electric current. In this process, the negatively charged ions will migrate towards the anode while the positively charged ions will migrate towards the cathode. The rate of electro-migration depends on the mobility of involved ions. In addition, the migration of ions toward the electrodes is proportional to the concentration of ions in water and to the electric field intensity (Kim et al., 2005). Most common applications of electro-migration are to remediate soil from chemical contamination (Chen, and Wang, 2018). Based on the considerations followed by previous researchers, an apparatus was designed and fabricated for this work, similar to the one used by Rittirong et al. (2008) and Mohamedelhassan and Shang (2001). The apparatus consists of main cell, loading frame and D.C. power supply as shown in Fig. 1. The main section of the apparatus is the cell that consists of a rectangular tank that holds the soil sample. It was made of plexiglass plates with 2 cm thickness. Two electrodes, namely anode and cathode, were added on the two sides of the main cell and were connected to the cell as shown in Fig. 1. The reservoir was filled with wet soil sample and two electrodes made of conductive copper (anode and cathode) were vertically placed adjacent to each other in the reservoir and in contact with soil in the cell. A number of voltage probes were installed at the top of the cell at distances of 5 and 8 cm from the anode. Ameter was used to measure the voltage in certain time intervals during the progress of the test. The power supplier of D.C. current consists of a generator that produces various ranges of voltage and is connected to the EVD through the connections.

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Table 1: Moisture Content Results

Description	Oven dry		2hrs		4hrs		6hrs	
Can number	A1(g)	B2(g)	A1(g)	B2(g)	A1(g)	B2(g)	A1(g)	B2(g)
Weight of empty can	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Weight of empty can + wet sand	33.1	25.2	24.5	30.0	31.0	32.5	29.0	25.0
Weight of empty can + dry sand	26.5	21.9	20.8	25.0	25.8	27.6	24.8	21.8
Weight of moisture content	6.6	3.3	3.7	5.0	5.2	4.9	4.2	3.2
Weight of dry sand	16.2	11.6	10.5	14.7	15.5	17.3	14.5	11.5
Moisture content (%)	29.63	28.45	35.24	34.01	33.53	28.32	28.97	27.83
Average moisture content (%)	29.04		34.63		30.93		28.40	

Table 1 shows the result for the natural moisture content of the soil. The moisture content of the soil was determined to be 29.04% at 110˚C (230˚F) oven dry temperature, 34.63% at 2 hours, at 30.93% at 4 hours, 28.40% at 6 hours which depicts that at 6 hours which is very close to the natural. At 2 hours interval we had a moisture content of 34.63% which is far from the oven dry method. At 4 hours we had a moisture content of 30.93 which is a bit closer to the oven dry method. At 6 hours we had a moisture content of 28.40% which is very close to the oven dry method.

Sieve Analysis/Particle Size Distribution

Table 2: For Sieve Analysis Results of the soil.

Sieve No	Sieve Diameter (mm)	Weight Retained (g)	Cum Weight Retained	(%) weight retained	(%) Passing
4	4.75	20.3	20.3	4.06	95.94
10	2	54.3	74.6	14.92	85.08
20	0.85	74.8	149.4	29.88	70.12
40	0.425	103.2	252.6	50.52	49.48
80	0.212	100.8	353.4	70.68	29.32
100	0.15	73.1	426.5	85.3	14.7
200	0.075	38	464.5	92.9	7.1
Pan	-	28	492.5	98.5	1.5
Wt of mass (g)				500	

Source: field survey

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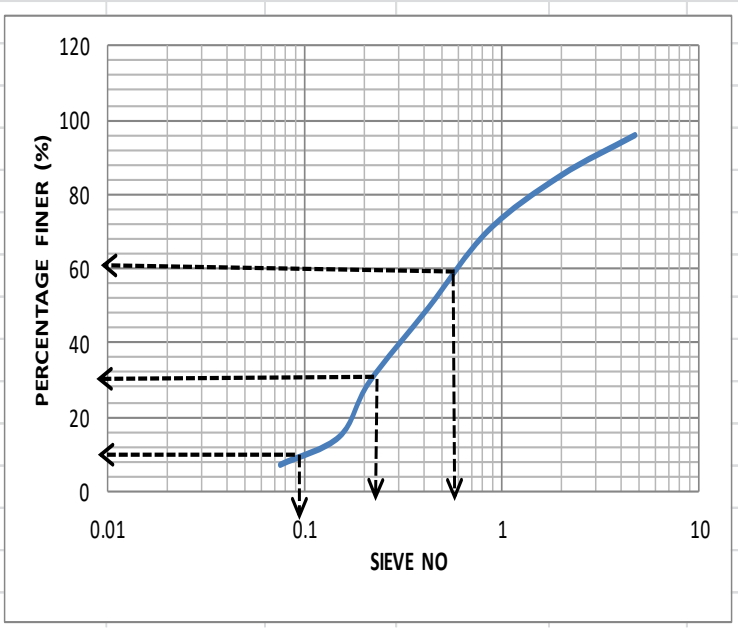

Figure 1: Sieve analysis graph

Particle size distribution of the soil

Table 2 and figure 1depicts the result for the particle size distribution of the soil. From the particle size distribution test result, it was discovered that for the soil sample, the percentage error was obtained as 1.5% coefficient of curvature (Cc) was 1.03, coefficient of uniformity (Cu) was 6.21 with a D60 of 0.59, D10 of 0.095, D30 of 0.24. With Cu > 6 and Cc 1 and 3, and USCS group symbol of GW the soil is classified as well-graded sand. This is an indication that the soil has low percentage finer and is a well-graded soil.

Atterberg Limit Test

Table 3: **Atterberg Limit Test**

ATTERBERG LIMIT TEST

	LIQUID LIMIT LL				PLASTIC LIMIT PL	
Number of blows	12	23	35	42		
Can number	C3	A4	C2	K5	K3	A1
Weight of can (g)	9.5	9.5	9.5	9.5	9.5	9.5
Weight of can + wet Sample (g)	21.3	21.3	22.1	21.6	14.6	14.4
weight of can + dry Sample (g)	16.7	16.8	17.5	17.4	12.9	13
	4.6	4.5	4.6	4.2	1.7	1.4
Weight of water (g)	7.2	7.3	8	7.9	3.4	3.2
Moisture Content (%)	64.4	62.1	57.5	53.2	50	43.4
Liquid Limit LL	60.8		Plastic Limit		46.7	
Plasticity index PI	14.1					

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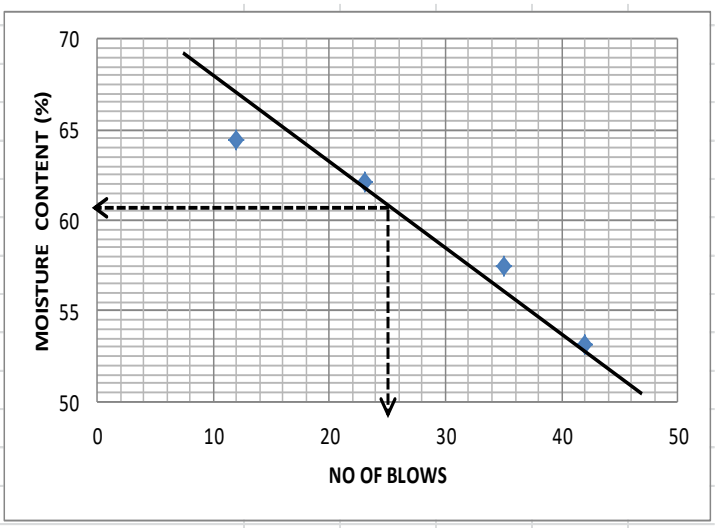

Fig 3: Atterberge limit graph

Table 3 and figure 3 show the results of Atterberge limit for the soil

The liquid limit (LL) and plastic limit (PL) of the soil (Atterberg limits) were obtained on the samples that were extracted from the soil in the apparatus after the test. The changes in the values of Atterberg limits in the cathode for different voltages show that they are changed from their initial values and these variations are dependent on the applied voltage and distance from the anode. The atterberge limit test results show that the method significantly altered the soil's water retaining capacity characteristics. The plastic limit increase shows an improvement in the soil's workability and stability while the plasticity Index reduction indicates a reduction in the soil's plasticity and improved stability.

Table 4: **Results for Consolidation Test**

CONSOLIDATION TEST

S/N	Time (minutes)	5KN/M2	10KN/M2	20KN/M2	SQUARE ROOT OF TIME
1.	0	32	52	72	0
2.	0.25	40	54	74	0.5
3.	1	41	55	75	1
4.	2	41	56	76	1.41
5.	4	42	56	78	2
6.	8	43	57	78	2.83
7.	15	45	57	80	3.87
8.	30	45	58	82	5.5
9.	60	45	59	82	7.75
10.	120	46	60	83	10.95
11.	240	47	61	85	15.5
12.	480	48	61	85	21.9
13.	1440	49	63	88	37.95

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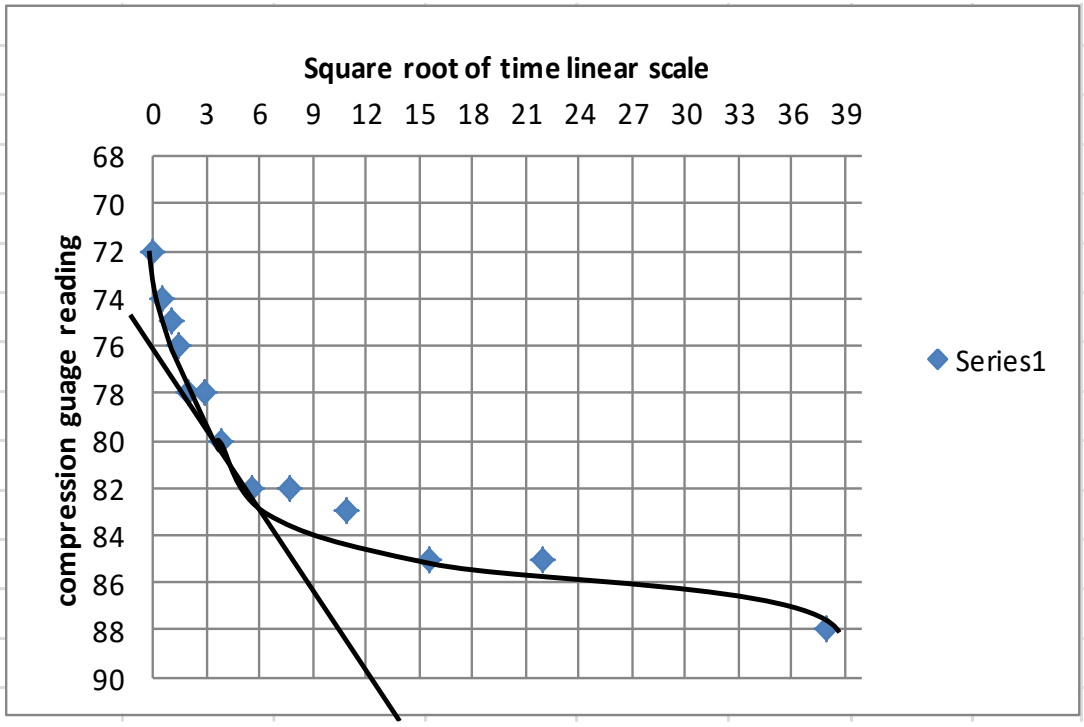

Figure 4: Consolidation graph.

Table 4 and figure 4 show the result of consolidation

After the test, the undrained shear strengths were measured at three points in the soil (anode, middle and cathode) using a shear vane (ASTM D4648-00, 2000). The results show the strength increased in comparison with the original value (2kPa) and it had different values along the length of the sample, suggesting enhanced soil stability and load-bearing capacity. This shows that the electroosmosis significantly improved the soil's consolidation properties. The data indicates a notable reduction in settlement and an increase in the soil's shear strength. Therefore, the values of strength are dependent on the applied voltage and distance from anode. In general, electrolysis reactions at the anode and cathode are generated during electroosmosis.

Electric Conductivity

The voltage gradient of 0.46v/cm, 0.92 v/cm and 1.84v/cm profiles at 15, 24, and 45V for soil at different times (1, 2, 7 and 28 days) were measured through the probes located at the top of the sample. The settlement of the soil was determined based on measurement of the volume of discharge water from the cathode. The variations of settlement with treatment time show that after 7days the total settlements are11and13mm for 24 and 45V respectively. It can be observed from this figure that the majority of settlement occurred

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during the first four days of treatment and after that the settlement attained a constant value. The settlement resulting from preloading is negligible in comparison with those of electro-osmotic settlements with 24 and 45V. The results of variations of electric conductivity with time for water in anode and cathode reservoirs for different applied voltages show that the value of EC was greater in the cathode reservoir than anode and it increased with time. It reached a constant value after 32h for 45V and about 20h for 24V. After 56h, the values of EC for 24V were 32 and 88.1ds/min anode and cathode respectively. The increase in the value of EC was dependent on the applied voltage; the values of EC in the cathode reservoir were 88 and 95ds/m for 25 and 45V respectively.

Chemical Condition

The changes in the values of pH for water in the electrode reservoir with time show that the initial value of pH (7.6) is increased in cathode and decreased in anode. The results of pH show that the rate of changes in the variations of pH depends on the value of applied voltage; higher applied voltages resulted in higher rates of pH variations in both electrode reservoirs. Reduction in the applied voltage resulted in fewer ions being produced by electrolysis. This led to migration of cations creating the acid front continuously moving towards the cathode resulting in the decrease of pH in the water in the cathode reservoir after 2 days of the electroosmotic process.

Hence, the pH value drops near the anode and increases near the cathode due to electrolysis, which in turn causes acidic and alkaline conditions to develop near the anode and the cathode, respectively.

Analysis of Scanning Electron Microscope (SEM)

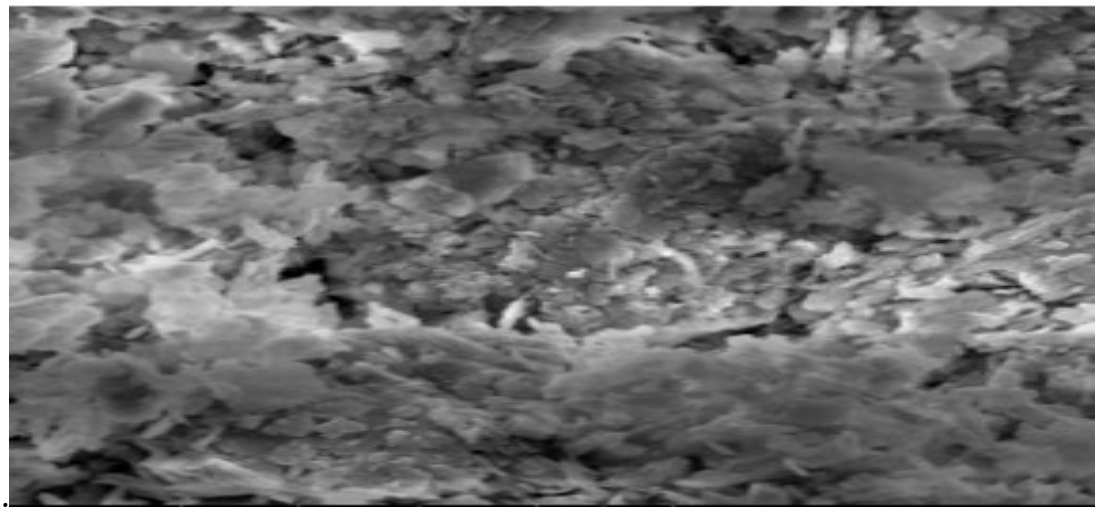

Fig 2a SEM image of sample after treatment (**Magnification factor = 10000**)

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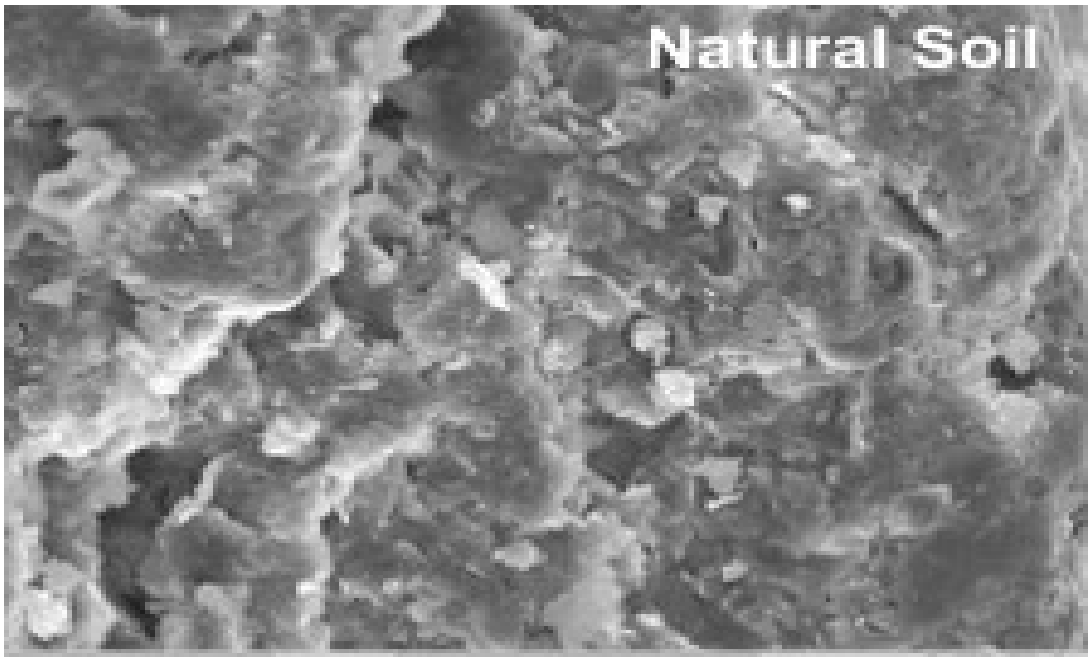

Fig 2b SEM image of natural soil sample (**Magnification factor = 10000**)

The SEM images reveal significant changes in the soil's microstructure after the electroosmosis treatment.

Soil Fabric: the treated soil exhibits a more compact and oriented fabric, indicating improved particle arrangement and void ratio.

Pore Size distribution: The pore size distribution shows a notable reduction in larger pores, suggesting improved soil desification and reduced permeability.

Particle Interactions: The SEM images indicate increased particle interactions and bonding, likely due to the electroosmotic flow and reduced moisture content. These changes contribute to improved soil stability, strength, and reduced compressibility.

CONCLUSION AND RECOMMENDATION

Electro-osmotic dewatering of expansive soils is an innovative and promising technique that has the potential to improve the performance of soils. The study successfully demonstrated the potential of electro-osmotic dewatering technique as an effective method for improving the properties of problematic soils. The experimental results suggest that the technique can effectively reduce water content, increase strength and stiffness, and improve the overall stability of expansive soil. Based on the achieved results, the electro-osmosis procedure can be efficiently used to modify the consolidation and strength properties of the high plastic clays, reducing the risk of settlement related

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issues. However, there are still several aspects of the technique that require further investigation. Based on the findings of this study, it is recommended that the electro-osmotic dewatering technique be further investigated on different soil types and optimize the treatment process.

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