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RESEARCH ARTICLE

The Electrokinetic Stabilization (EKS) Green Approach Towards Improving the Geotechnical Properties of the Gulf Sabkha Soil at Rabigh, Saudi Arabia

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Abstract

Objectives: Sabkha soil is widely formed in the Arabian Gulf in the Kingdom of Saudia Arabia, particularly along the coastline. Over the past 25 years, numerous studies have been conducted to understand and characterize sabkha soil and increase its strength and durability. To enhance the geotechnical properties of Sabkha soil using an environmentally friendly electrokinetic stabilization method. From a geotechnical perspective, the construction process heavily depends on improving weak soil strength, durability, and treatment cost. The presence of water, high salinity, low shear strength, and low specific gravity are the soft geotechnical features that need to be enhanced before any construction on sabkha soil. **Methods/Analysis:** The electrokinetic stabilization method was applied to extract salty particles and enhance the geotechnical properties of sabkha soil. The voltage gradient of 40 V was applied for 1, 3, and 7 days using stainless steel electrodes. **Findings:** The result showed an outstanding improvement of sabkha soil geotechnical properties where the shear strength was increased from 116 to 165, 230, and 360 kPa for Rabigh I (RI), 122 to 155, 254, and 371 kPa for Rabigh II (RII), and for Rabigh III (RIII), the shear strength was improved up to 405 kPa. The moisture content decreased from 34.5 to 16.8% for RI, 35.2 to 15.9% for RII, and 37.5 to 14.7% for RIII. **Novelty and applications:** Experimental results demonstrated that all parameters were improved massively by increasing the voltage gradient and operational time. This technique is highly recommended to strengthen weak soil and improve geotechnical properties.

Keywords: Sabkha soil; geotechnical properties; electrokinetic stabilization

1 Introduction

Soil plays a crucial role in infrastructure and construction projects, including buildings, roads, dams, and other structural design improvements. Due to the growing devaluation of construction land, ground augmentation is rapidly expanding globally. Many kinds of soil are used in construction projects but using soft soil (sabkha soil) has been problematic because it is exceptionally soft, unconsolidated, has weak shear strength, presence of water, high salinity, high specific gravity, and liquid limits. The construction sector is under immense pressure to create Saudi Arabia's essential infrastructure because of the country's rapidly expanding population and industrialization[1]. Most of the primary infrastructure is located along the Gulf coastline on sabkha soil (weak soil). Numerous residential and industrial developments are being built along the coastal area in line with the extensive urban planning and utilization of open spaces[2]. Due to the unstable soil, rising water tables, and high salinity of the water in sabkha locations, several technical issues have been encountered. In general, sabkha sediments have low dry densities and high void ratios. Many structures built on sabkha soils have apparent damage because of severe excessive settlements[3,4]. The demand for the infrastructure and construction of new buildings is growing as the population and industrialization are increasing rapidly in Saudia Arabia. The kingdom focuses some significant economic and social activities on the coastal areas, which consist of problematic sabkha soil. Thus, road and high-rise construction on the coast is a big challenge for construction engineers[5].

Sabkha is an Arabic word meaning a flat depression, usually close to the water and covered with a salt crust, and it's also known as saline soil and evaporated soil. Sabkha soil is salt encrusted, comprises many organic materials, and can be easily found in arid climatic countries, including India, Australia, the United States, Saudia Arabia, and some parts of Northern and Southern Africa. In Saudia Arabia, it is located along the coastline of the Kingdom of Saudia Arabia. Sabkha soil has weak and unique engineering properties, loose particles, permeable, porous, low bearing capacity, low shear strength, and sandy to coarse texture. The upper surface of Sabkha soil is hydroponic, which is muddy and wet during the humid period, as seen in Figure 1. The water table is close to the surface, ranging from 0.30 m to 1.15 m[6–8]. The natural characteristics of Sabkha soil make it unstable. As such, any construction on it may easily lead to collapse, a severe and unacceptable risk. The characterization, including physical and mechanical properties, must be adequately stabilized before being used as a foundation or other construction materials[9].

Fig 1. Detailed distribution of sabkha soil in Saudia Arabia[10]

The construction industry faces enormous pressure due to the rapidly growing population and industrialization. As such, building the necessary infrastructure in Saudia Arabia is essential. Most of the construction projects are concentrated along the coastal areas, comprised of weak soil, where the construction engineers face challenges during and after construction. Mostly, sabkha soil is found in coastal areas and is considered problematic in the construction industry due to its nature[11]. Sand deposits mixed with silt and clay particles make Sabkha soil widely distributed around the globe, including Saudia Arabia, where two basic types of sabkha soil are deposited. The first type in the coastal area is muddy Sabkha, found along the sea, while the second type is sandy Sabkha, mostly found inland[11–13]. The Sabkha of Eastern Saudi Arabia occupies roughly 15% of a coastal strip (40 km wide by 350 km long) that extends approximately from Saffaniyah in the north to Salwa (border with Qatar) in the south. A detailed distribution of sabkha soil in Saudia Arabia is shown in Figure 1 [10]. Most eastern Saudia Arabian cities lie within coastal plains. There are huge developments, including roads, residential areas, industries, and recreational areas near these sabkha-covered coastal plains [14–17].

To overcome these Sabkha soil challenges, it is essential to improve its engineering properties using stabilization techniques. Several field stabilization techniques improve weak soil properties, including vibro-flotation, cement stabilization, geotextile stabilization, stone column, dynamic compaction, chemical stabilization, and electrokinetic stabilization techniques. According to previous researchers, several stabilization techniques are used with various parameters to achieve Sabkha soil stabilization in Saudia Arabia. The electrokinetic stabilization technique is considered to be relatively cheaper than other existing techniques [18]. An innovative method especially advised for bolstering weak soil is electrokinetic stabilization [19,20].

The EK method uses electrodes to apply direct current, which causes charged particles to move. Hydrogen ions (H+) and hydroxide ions migrate across the soil because of the electric field's movement, which causes the pH of the soil to change. During the direct current, the charge ions and non-ionic species migrate toward the opposite charge electrode [21–25]. A low direct current (DC) or (pulsed electric field) is linked via electrodes injected vertically into the soil. Electroosmosis, electromigration, and electrophoresis occur, and the ions move toward electrodes [26–28]. The EKR cell designed for this research is made up of transparent acrylic plates with a rectangle shape with dimensions of 30 cm in length, width, and height of 10 cm, as can be seen in Figure 2 and Figure 3. EK is one of the best techniques which offer high efficiency and time effectiveness in strengthening low-permeability soils. Additionally, it provides low operational costs with the potential capability of improvement, [11,12,29]. The current study aims to improve Sabkha's soil geotechnical properties, which was carried out at Rabigh, Saudi Arabia.

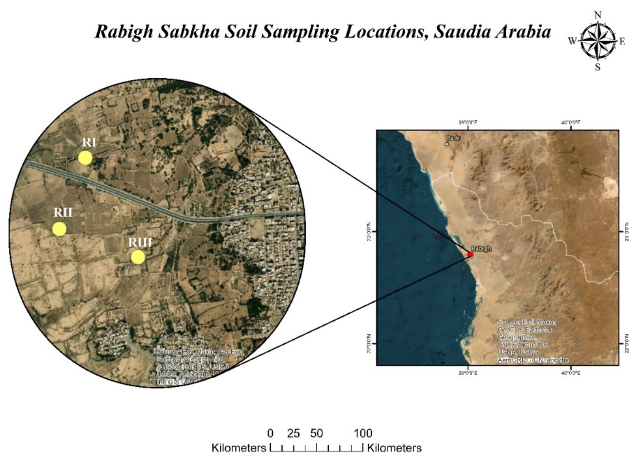

Fig 2. Rabigh Sabkha soil sampling locations

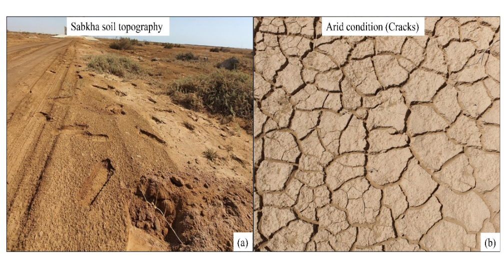

Fig 3. (a) The landscape of Sabkha soil, (b) Sabkha surface soil cracks

2 Material and methods

2.1 Area description and Soil sampling

Rabigh is in the historic Hejazi region, approximately 208 kilometers northwest in the Makkah Governorate of the Kingdom of Saudi Arabia. The sampling site's coordinates are 22°57'57.94"N, 38°55'28.11"E for Rabigh I (RI), 22°45'41.57"N, 38°58'58.27"E for Rabigh II (RII), and 22°37'54.52"N, 39°5'33.65"E for Rabigh III (RIII), respectively, with altitudes varying from 13 m above mean sea level as shown in Table 1. The coastline of Rabigh is made up of sand beaches, tidal zones, dunes, salt flats, marshes, coral reefs, lagoons, and terrigenous materials. Most of the soil in the coastal regions is sabkha, which is regarded as difficult for construction. The Global Positioning System (GPS) Model Garmin — GPS Map 64x made it easier to pinpoint the sampling site's location as can be seen in Figure 2. These sites were chosen based on soil observation, including pH, color, plasticity, and low shear strength. Infrequent land activities take place on the sampling sites. By visual identification, it was observed that sabkha soil was reddish brown, very soft, and contained clay particles, as can be seen in Figure 3(**a**) and due to arid conditions, the surface soil has been cracked, as can be seen in Figure 3(**b**). The specimens were taken from three different places in the surroundings of Rabigh city at 20, 40, and 60 cm, respectively, using a digging shovel, spade, and rake. To avoid contamination, storing the soil sample after it had been taken in a clean, dry container was crucial. The pH was measured on-site, and the samples were carefully transferred to the laboratory using polythene bags to avoid any characterization loss. The Sabkha soil specimens were prepared for detecting geotechnical properties such as moisture content, liquid limit, specific gravity, and unconfined compressive strength. The samples were examined at Mohammed Omar Jazzar Consulting Engineers Co. laboratory, Riyadh, Saudia Arabia, as seen in Figure 4(**a**) and Figure 4(**b**).

Table 1. Sabkha soil sampling locations coordinate

S/N	Location	Coordinate
1	Rabigh sabkha soil Sample I (RI)	22°47'24″N, 39°01'13″E
2	Rabigh sabkha soil Sample II (RII)	22°47'22″N, 39°59'31″E
3	Rabigh sabkha Soil Sample III (RIII)	22°48'43″N, 39°04'38″E

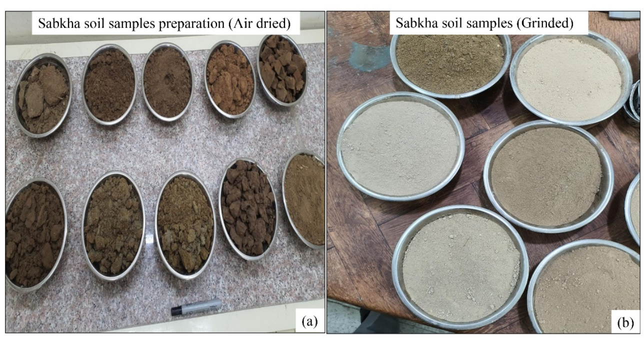

Fig 4. (a) Sabkha soil sample preparation at the laboratory, (b) grinded specimen

2.2 Electrokinetic stabilization treatment

The electrokinetic experimentation was meticulously executed with the overarching objective of augmenting the inherent attributes of the Sabkha soil matrix. The design of the electrokinetic (EK) cell was a result of a thorough assessment of the distinctive soil characteristics, culminating in the strategic determination of EK cell dimensions in terms of height, length, and structural integrity, which were meticulously selected based on a comprehensive analysis of the preliminary dataset. The EK cell comprised meticulously fabricated acrylic plastic sheets with discerningly placed apertures adorning all faces, facilitating the directed migration of contaminants towards the cathode and anode regions, as visually depicted in Figure 5(**a**) and Figure 5(**b**). Within the core of the EK cell, a pair of stainless-steel plates were adeptly positioned within the central enclosure, effectively serving as conduits to channel the requisite electric current into the soil matrix. The electric current's dynamic orchestration and precision control were rendered possible using a judiciously selected electric power supply system. Specifically, an electric potential of 40 V was meticulously administered to the EK cell, thereby subjecting the soil matrix to an array of operational time frames encompassing distinct phases, namely, one, three, and seven days in a continuous and unrelenting fashion. This chronicle of applied potential was scrupulously delineated following the particular temporal windows indicated earlier. After the prescribed electrokinetic treatment protocol, the Sabkha soil was systematically and judiciously extracted from the confines of the EK cell and subjected to a meticulous preparation process in anticipation of a battery of geotechnical property assessments. These assessments encompassed a comprehensive evaluation of fundamental attributes, including but not limited to moisture content, unconfined compressive strength, liquid limit, and specific gravity, all of which collectively served as proxies for characterizing the soil's mechanical behavior and physical attributes. The ensuing evaluation phase entailed a meticulous and exhaustive comparison between the pre and post-electrokinetic stabilization states, conducted phase-wise. This detailed analysis incontrovertibly highlighted an exceptional and noteworthy amelioration across both temporal phases, thereby affirming the efficacy and discernible success of the applied electrokinetic stabilization strategy in enhancing the geotechnical characteristics of the Sabkha soil matrix.

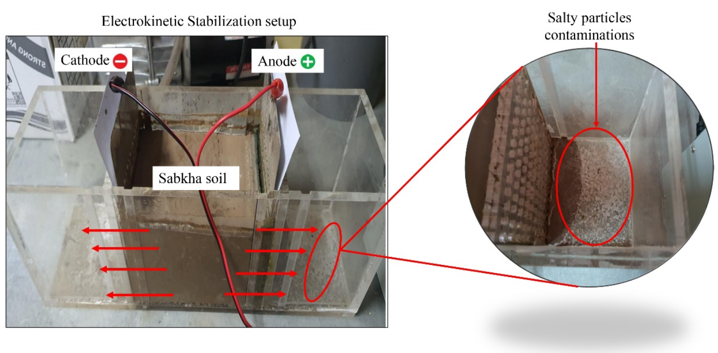

Fig 5. (a) The electrokinetic stabilization setup, (b) The contamination movement towards the anode and cathode

2.3 Geotechnical properties parameters (pre-EKS)

Investigations on the untreated soil were carried out to carefully to analyse the geotechnical characteristics of Sabkha soil. This made it possible to identify the inherent qualities of the Sabkha soil in its pure, natural state, free from any manipulations or treatments. The goal was to have a thorough grasp of the characteristics and behaviour of the soil. The tests on the geotechnical qualities were conducted in accordance with British standards to ensure precision and uniformity. To ensure that uniform procedures are used, these standards act as benchmarks and guides for conducting geotechnical testing. These accepted standards can be used to compare and interpret test results in a reliable manner, giving future study or application outcomes a uniform foundation.

2.3.1 Moisture content

The assessment of water content is of the utmost importance and a necessary component in geotechnical analysis. The quantification of moisture content in the current context was subjected to rigorous review while complying with the established procedures outlined in the British Standard BS 1377: Part 2: 1990. This procedure for measuring moisture content comprised a methodically planned desiccation regimen in which the specimens were put to the rigors of carefully monitored oven drying. The samples must be carefully placed inside a perfectly calibrated desiccation chamber that is kept at an ideal temperature of 105°C to 110°C for a period ranging from 16 to 24 hours. This meticulously organized process leads to a thorough evaluation of the moisture content in the tested materials.

2.3.2 Shear strength

The field vane shear technique was used to analyze shear strength parameters on- and off-site. The field vane shear equipment was used to analyze shear strength throughout the sampling phase. The shear strength examination was conducted at Mohammad Omar Jazzar Consulting Engineer laboratory in the Kingdom of Saudi Arabia, each of the nine chosen sites following the British Standard (BS 1377-7:1990). *Ex-situ* shear strength measurements were made in the lab for pre- and post-electrokinetic stabilization scenarios. The field vane shear apparatus was also used to assess the shear strength of sabkha soil samples positioned at various depths inside the electrokinetic (EK) cell.

2.3.3 Liquid Limit

The cone penetration method, a widely used geotechnical investigative technique, was flawlessly carried out within the restricted confines of the laboratory environment. The exacting adherence to the guidelines in the British Standard (BS 1377: Part 2: 1990) highlighted the methodological rigor involved. The core of this strategy was its rigorous application to an empirical investigation of the liquid limit properties built into Sabkha soil. Three distinctive specimens were thoughtfully retrieved from each unique site of interest, displaying a well-thought-out sampling method. This methodological rigor ensured that the cross-sectional description of the soil's inherent properties was statistically sound, raising the legitimacy of the subsequent analyses.

2.3.4 Specific gravity

The specific gravity parameter is crucial in construction engineering, significantly influencing several essential material properties. In complex calculations involving soil density, void ratio, and saturation, among other essential characteristics intrinsic to soil behavior, this metric which symbolizes the balance between the density of a substance and that of water, is of utmost significance. At the Mohammad Omar Jazzar Consulting Engineer Co. laboratory in Saudi Arabia, a meticulously applied procedure was strictly aligned with the exacting standards of British Standards (BS 1377-2:1990) at a standard temperature of 21°C. The "pycnometer method" is a carefully planned series of techniques that includes calculating the exact masses of a full pycnometer, the total amount of dried soil, and an aggregate abundance of the pycnometer, soil, and water. The culmination of these complex processes is the computation of specific gravity, a metric crucial for understanding the inborn properties of the investigated soil.

3 Results and Discussions

An extensive range of analyses were carried out on samples of untreated and treated soil as part of the systematic examination of geotechnical properties. This included a thorough collection of early evaluations that thoughtfully included crucial factors like moisture content, liquid limit, specific gravity, and unconfined compressive strength. These analyses collectively revealed the natural qualities of the Sabkha soil under investigation. After conducting a thorough exploration examination, an intricate electrokinetic stabilization (EKS) process was meticulously used, methodically unfolding in two distinct phases. Each phase was distinguished by carefully choosing operating parameters, such as calibrated voltage gradients, placed electrodes, and planned operation times. Compared to the Sabkha soil matrix that had not received any EKS treatment, the results showed a considerable improvement in the geotechnical properties.

3.1 Geotechnical properties for untreated soil

A comprehensive and systematic investigation was conducted to analyze the intrinsic geotechnical attributes of the Sabkha terrain, focusing exclusively on the unaltered and untreated soil matrix. The ensuing results, meticulously gleaned from this meticulous examination, played an instrumental role in elucidating and delineating the foundational characteristics that epitomize the unadulterated state of Sabkha soil, devoid of any artificial manipulations or interventions. In pursuit of uncompromised precision and accuracy, the battery of geotechnical property tests was scrupulously executed strictly with the established standards outlined by the British Standard (BS), ensuring a definitive adherence to internationally recognized protocols. The meticulous adoption of these standards as procedural benchmarks underscored the unwavering commitment to methodological consistency, enabling precise and reproducible results as can be seen in Table 2. By imbuing the experimental framework with a semblance of uniformity, these standardized procedures serve as pivotal guides and facilitate robust comparisons and interpretations of the ensuing test outcomes. Engenders a dependable and consistent foundation upon which future investigations, studies, or practical applications can be predicated, thus fortifying the reliability and applicability of the accrued knowledge in Sabkha geotechnical properties.

Table 2. The geotechnical properties of untreated sabkha soil

Properties	Followed Standard	R-I	R-II	R-III	Reference	
Moisture content (%)	BS 1377: Part 7: 1990	34.5	32.5	37.1	08 - 84	(30), (7), (31)
Shear strength (kPa)	BS 1377 7:(1990)	116	122	135	37 - 165	(32)
Liquid Limit (%)	BS 1377: Part 3: 1990	70.2	76.9	80.1	22 - 80	(15), (7), (17)
Specific gravity	BS 1377: Part 2-7: 1990	2.679	2.688	2.702	2.51 - 2.82	(30), (32), (33)

3.1.1 Moisture content (pre-EK)

The Saudi Arabian Sabkha soils have diverse moisture content depending on seasonal changes and location. Sabkha soils in Saudi Arabia typically have low moisture content, and the soil is frequently dry. However, the moisture content might rise during the rainy season, while the water content in the coastal region is high because of the high-water table. The salt concentration in Sabkha is high; As a result, the soil becomes less permeable. When evaluating the suitability of Sabkha soil for various purposes, including agriculture and construction, it is crucial to consider its moisture content because it might impact the soil's strength, compressibility, and other geotechnical features. The preliminary results provide essential new information about the unique Rabigh I (RI) sabkha soil variant's moisture content, which is 34.5%. As shown in Figure 6, the Rabigh III (RIII) sabkha soil revealed an observed moisture content of 37.1%, while the Rabigh II (RII) soil type displayed a recorded moisture content of 32.5%. These findings significantly impact understanding of the hydrological characteristics unique to the Sabkha environment. It is essential to highlight that earlier studies have shown the wide range of natural moisture content displayed by Saudi Arabia's Sabkha soils, ranging from 8 to 84% (7,30,31). This significant fluctuation highlights the intricate interplay of meteorological factors, sediment type, and hydrological processes influencing Sabkha ecosystems' moisture cycles. Compared to the existing literature, the current findings aid in a more thorough contextualization of the observed moisture content trends in the Rabigh region, permitting a more in-depth comprehension of the complex moisture-regulating mechanisms at work. The understanding of Sabkha soil hydrology is expected to improve with further research into the components impacting the recorded moisture content levels, enhancing the geotechnical and environmental discourse.

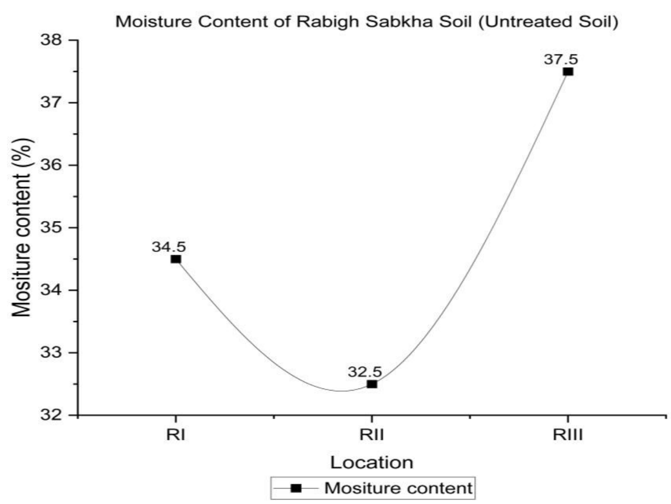

Fig 6. The moisture content of Rabigh Sabkha untreated soil

3.1.2 Shear strength (pre-EK)

These results offer essential details about the durability and stability of sabkha soils in the research area. In areas where sabkha soils are common, understanding these soils' mechanical characteristics is essential for various uses, including building and infrastructure development. Interesting results were found in the study's preliminary findings. The average shear strength for Rabigh I sabkha soil was determined to be 116 kilopascals (kPa). This value climbed somewhat for Rabigh II, reaching 122 kPa. Rabigh III sabkha sample had the maximum shear strength, measured 135 kPa. The previous researcher indicated that the average shear strength for untreated sabkha soil ranges from 37 to 165 kPa (32).

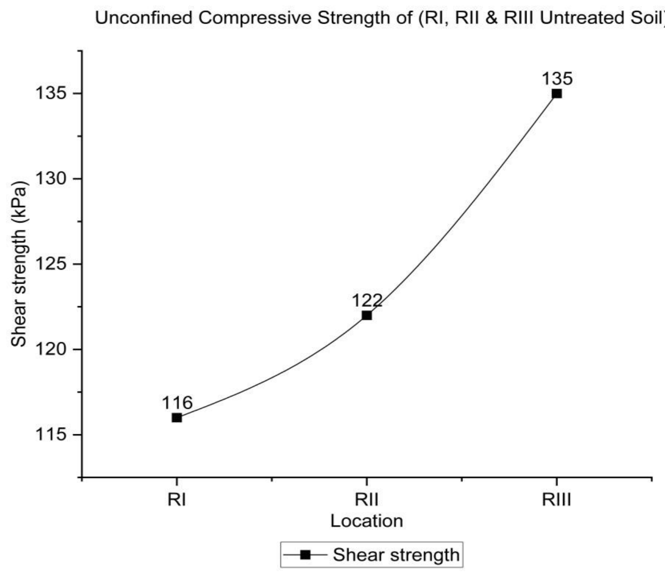

Fig 7. Shear strength of Rabigh Sabkha untreated soil 3.3.3 Liquid Limit (Pre-EK)

3.1.3 Liquid Limit (Pre-EK)

Following the preliminary outcomes derived from this rigorous examination, the calculated mean liquid limit for the untreated Sabkha soil analyzed at 70.2% for Region I (RI), 76.9% for Region II (RII), and 80.1% for Region III (RIII), respectively. These numerical manifestations distinctly demarcate the transitional juncture at which the soil undergoes a phase shift from its plastic state to a fluidic state, contingent upon the exacting testing conditions employed. It is noteworthy to underscore that the liquid limit attribute of the Sabkha soil substrate exhibits an inherent variability, oscillating between a lower threshold of 22% and an upper threshold hovering around 80%, as substantiated by multiple references [7,15,17]. The observations gleaned from this investigative endeavor resonate harmoniously with the previously documented range documented within the annals of existing literature. The determination of liquid limit values ascertained through this precisely orchestrated inquiry seamlessly dovetails into the existing corpus of knowledge and research germane to the distinctive realm of Sabkha soil typology. The present findings collectively enrich and bolster the compendium of information about this intriguing geologic substrate, thereby perpetuating the trajectory of scientific understanding in this domain.

3.1.4 Specific gravity (pre-EK)

The preliminary results of this thorough study revealed specific gravity values of RI were 2.679, RII was 2.688, and 2.762 for R-III Rabigh sabkha soil. An informed contextual foundation for these recently discovered insights is provided by carefully aligning these findings with earlier academic investigations, which had identified a specific gravity range spanning from 2.51 to 2.82 for the Sabkha soil context. These discoveries not only improve our fundamental understanding of the specific gravity of Sabkha soil but also show promise for the field of geotechnical exploration as a whole, leading to a thorough comprehension of the complex mechanisms driving soil mechanics [30,32,33].

3.2 Geotechnical properties for treated soil (post-EK)

The geotechnical analysis of Rabigh I, II, and III treated sabkha soil followed an electrokinetic stabilization procedure involving controlled periods of 1, 3, and 7 days with a 40-volt electric potential applied. The study carefully examined crucial parameters, including specific gravity, liquid limit, unconfined compressive strength, and moisture content, which are critical for understanding soil behavior, stability, and durability. Evaluation of post-electrokinetic stabilization outcomes highlighted significant improvements, particularly in phase III with a 7-days of operation, surpassing the effects observed in phase I with 1 day and phase II with 3-days of treatment. This underscores the substantial impact of prolonged electric potential application on enhancing geotechnical properties was remarked. Notable enhancements were observed in moisture content, unconfined compressive strength, liquid limit, and specific gravity, collectively indicating a tangible progression toward improved geotechnical properties and adaptability as tabulated in Table 3. These findings culminate in a comprehensive understanding of where electrokinetic stabilization orchestrates a transformative shift in the intricate geotechnical nature of sabkha soil. This orchestrated enhancement manifests as an integrated symphony of improved attributes, amplifying the soil's structural integrity and overall behavioral capacity.

Table 3. The current results comparison with previous literature

Properties	Current Improvement (%)			Previous Improvement	Researchers
	R-I	R-II	R-III		
Moisture content (%)	78%	81%	83%	22%	(34)
Shear strength (kPa)	210%	204%	237%	275%	(34), (35)
Liquid Limit (%)	32%	33%	38%	20%	(35)
Specific gravity	2.60%	2.68%	2.70%	3.05%	(33)

3.2.1 Moisture content (post-EK)

The water content for treated sabkha soil was determined by the same procedure as in phase I. The water concentration was reduced due to the voltage gradient, and the soil was observed to be hot and dried along both sides of the electrodes after applying the voltage gradient of 40 V for the duration of 1, 3, and 7 days constantly. According to British Standard, the soil was removed carefully from the EK cell and kept in an oven at 90 to 110°C for 16 to 24 hours. In phase I, 40 V was applied for the operational period of 1 day; in phase II, the duration was three days; in phase III, the same voltage was applied for seven days. The moisture content for Rabigh I sabkha soil decreased from 34.5% to 30.4% in phase I, whereas, in phase II, it decreased to 23.6%, while an excellent improvement was observed in phase III, where the water content was decreased to 16.8%. Rabigh II sabkha soil moisture content was reduced from 32.5% to 27.9% in Phase I and 20.1% in Phase II, and the moisture content was recorded at 15.9% in Phase III. Rabigh III sabkha soil moisture content was also decreased, whereas in phase I, it was reduced to 31.8%; in phase II, it was recorded at 22.3%, and it was reduced from 37.5% to 14.7% in phase III, as can be seen in Figure 9. Whereas, according to the previous researcher, the moisture content was decreased to 22% by adding cement to sabkha soil for 90 days of treatment [34].

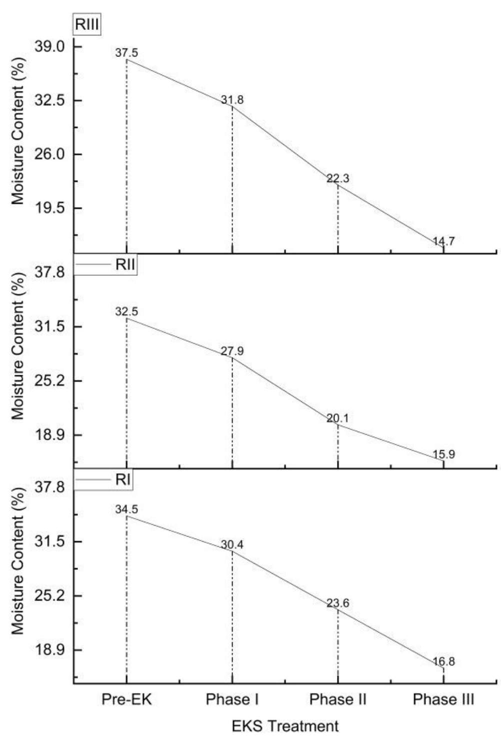

Fig 8. The moisture content of Rabigh sabkha soil (pre-and post-EKS)

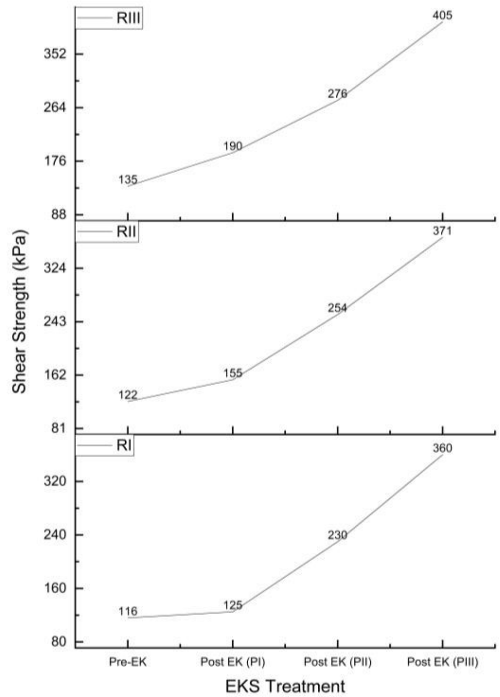

Fig 9. The shear strength (kPa) for Rabigh Sabkha soil (pre-and post-EK)

3.2.2 Shear Strength (Post-EK)

Shear strength is considered one of the key elements in construction of road and buildings on soil, it has been used to calculate the bearing capacity and design retaining walls, slopes, embankments, cement, and bricks, and indirectly used to grow plants to make building materials. Therefore, it's essential to treat the soil properly before constructing it. Sabkha's expensive soil is weak soil for construction purposes. The initial strength was examined from 116 to 135 kPa for different sites. For Rabigh sabkha soil (RI), with the applied electric gradient of 40 V in different phases, the shear strength was enhanced from 116 to 125 kPa in phase I and 230 kPa in phase II, while an outstanding improvement was observed in phase III, where the shear strength was examined up to 360 kPa. For Rabigh sabkha soil sample II, the shear strength was increased from 122 to 155 kPa in phase I, up to 254 kPa in phase II, while it was increased to 371 kPa in phase III. For Rabigh sabkha soil sample III, the shear strength was enhanced to 190 kPa, and 276 kPa in phase II, and a remarkable improvement was recorded in phase III, where the shear strength was increased from 135 to 405 kPa with applied the voltage of 40 V for the operational period of 7 days as can be seen in Figure 10. Previous researchers' results concluded that adding 10% of cement increased the sabkha soil strength to 275 kPa [34] and 322 kPa [35].

3.2.3 Liquid Limit (Post-EK)

The liquid limit of sabkha soil was determined for treated soil, where the results showed an outstanding improvement in all phases with a voltage gradient of 40 V for phase I, one-day treatment, three days in phase II, and seven days in phase III, respectively. The liquid limit for Rabiah I decreased from 70.2 % to 57 in Phase I and 51 % in Phase II. Similarly, it dropped to 47.2 % in phase III. Rabigh II sabkha soil experimental determination was also reduced from 76.9 % to 60.5 % in Phase I and 30.5 % in Phase II, while in Phase III, it dropped to 18.7%. Rabigh III sabkha specimen was also treated with the electrokinetic stabilization method; the water content for RI was recorded at 80.1 % for the untreated sample, with a voltage gradient of 40 V for the operational period of 1 day, it was reduced to 30.4% in phase I, and it was reduced to 26.2 % in phase II and final phase the water content was recorded about 19.4 %, which is considered a tremendous improvement from a geotechnical perspective as shown in Figure 11. Some previous researchers' experiments indicated that the liquid limit of sabkha soil decreased to 20% after adding cement and lime [33].

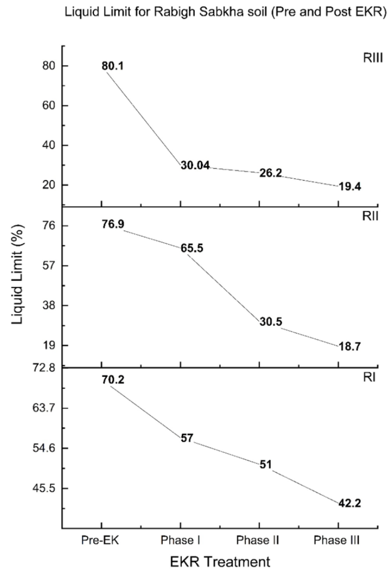

Fig 10. The liquid limit for Rabigh Sabkha soil (pre-and post-EK)

3.2.4 Specific Gravity (Post-EK)

The specific gravity was determined for treated sabkha soil after applying the voltage gradient of 40 V for the constant duration of 1, 3, and 7 days. The results showed the specific gravity for Rabigh I (R1) increased from 2.67 to 2.686 with a duration of 1 day, and it was increased to 2.702 with a period of 3 days. An excellent improvement was recorded after seven days of operation, where the plastic limit was increased from 2.679 to 2.730. Similarly, the specific gravity for Rabigh II (RII) sabkha soil was increased from 2.688 to 2.701 in phase I, with a duration of 1 day with an applied voltage of 40 V; in phase II, it was expanded to 2.715 with an operational period of 3 days, and similarly, in phase II, an outstanding improvement was observed where the specific gravity was increased to 2.726 with an active period of 7 days constantly with an applied voltage of 40V. Rabigh III (RIII) sabkha soil specific gravity was observed at 2.702, where it was increased to 2.17 in phase I, 2.722 in phase II, while in phase III, as can be seen in Figure 11, the specific gravity was raised to 2.730 with an operational period of 7 days with 40 Voltage gradient. By cement stabilization, the specific gravity of sabkha soil was increased to 3.05 [33].

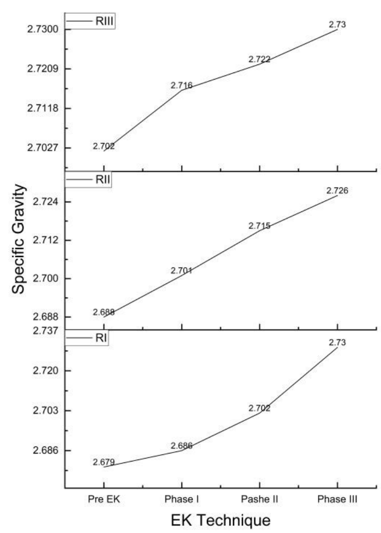

Fig 11. The specific gravity of Rabigh Sabkha soil (pre-and post-EK)

4 Conclusion

This study enhanced sabkha soil geotechnical properties using the electrokinetic stabilization (EKS) method. The initial research determined the original characterization of sabkha soil, and it was concluded that it is unsuitable for any construction without proper treatment. The enhanced description of sabkha soil includes moisture content, unconfined compressive strength, liquid limit, and specific gravity. Applying the Direct Current of 40 V in phases I, III, and III with the help of stainless steel showed an outstanding result; in phase III, excellent enhancement was observed compared to phases I and II. This technique is highly applicable for weak soil to strengthen its properties. The sabkha soil can be further used for any construction after using the ex-site EKS method on a large scale, and increasing its parameters can lead to better results. The following conclusions were drawn based on this study's interpretations.

Through the application of the electrokinetic stabilization (EKS) technique, a notable development in the civil engineering discipline, this study seeks to improve the geotechnical properties of sabkha soil. The initial stage of this inquiry entailed a thorough assessment of the sabkha soil's innate characteristics, which, following closer examination, demonstrated that it was unsuitable for construction projects without the necessary assistance. The enlarged illustration of sabkha soil included significant elements such as moisture content, unconfined compressive strength, liquid limit, and specific gravity. By introducing stainless steel electrodes, it was possible to apply a Direct Current of 40 V over three separate phases, I, II, and III, with excellent results. The phase III application stood out since it significantly improved over stages I and II's developments. This method displays a high degree of applicability for enhancing the characteristics of weak soil, assisting in the structural reinforcing of that soil. Sabkha soil could be used for construction once the *ex-situ* EKS process is successfully applied on a broader scale. Deliberately increasing the relevant parameters also can produce even better results. The culmination of this study's findings leads to the following conclusions supporting the interpretations drawn from this scholarly investigation.

Sabkha soil qualities are changed using electrokinetic stabilization, which manipulates ions by electrical potential. Water content is decreased as anions migrate toward the anode, and cations migrate toward the cathode. This treatment's strengthening and stabilizing effects make the soil acceptable for construction. Due to varying soil compositions, regional variances exist. Electrokinetic therapy affects the liquid limit because it alters the pore fluid chemistry and surface charge. Flexibility is increased by divalent cation migration while decreased by anions. The intricate connection between soil behavior and treatment is made clear by this approach.

5 Future Recommendations

Sabkha soil poses a substantial construction challenge due to its weak shear strength and limited load-bearing capacity. The Electrokinetic Stabilization (EKS) method offers a promising solution by adjusting operational factors like high voltage gradients, electrolyte having good conductor of electricity and treatment duration to enhance its mechanical properties promptly. EKS stands out as an inventive geotechnical technique that overcomes conventional limitations. When applied *ex-situ*, it circumvents complex soil geometries and eliminates the need for disruptive excavation, aligning with sustainability principles. Its adaptability for delicate ecosystems makes it an environmentally conscious choice, reducing ecological impact without dangerous chemicals or heavy machinery. Addressing the soil's inherent heavy metal content is crucial, necessitating targeted extraction alongside mechanical enhancement to protect human health and the environment. In essence, EKS is a feasible solution for sabkha soil challenges, offering potential for significant engineering improvement. Its versatility, support for sustainability, and role in managing heavy metal contamination enhance its importance in environmental protection and restoration.

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