

TRANSFORMATIVE EFFECTS OF SALINITY ON SEBKHA SOIL PROPERTIES: UNVEILING STRENGTH, STRUCTURE, AND STABILITY THROUGH ADVANCED REMEDIATION STRATEGIES



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Abstract: This study investigates the effects of varying salinity levels on sebkha soils, focusing on their physical, mechanical, and chemical properties. Soil samples were collected from Tin silt sebkha in Ain M'lila across three different seasons, resulting in high salinity soil (HSS), medium salinity soil (MSS), and low salinity soil (LSS). The grain size distribution curves reveal that 70% of grains in both HSS and LSS have diameters less than 60 μm , with LSS containing 19% more particles smaller than 20 μm compared to HSS. Unconfined compressive strength (UCS) measurements show a significant decrease from 1100 kPa in LSS to 200 kPa in HSS, with corresponding peak strains increasing from 2.3% to 4.7%. Chemical analysis indicates that pH decreases from 8.17 in LSS to 6.79 in HSS, reflecting increased soil acidity with higher salinity. SEM images demonstrate that higher salinity results in a denser soil structure due to salt cementation, whereas lower salinity soils exhibit more micropores. The study highlights the need for comprehensive models integrating these properties to enhance predictive capabilities and inform effective soil management. Future research should explore remediation strategies using additives to improve soil strength and stability, addressing the challenges posed by salt dissolution and soil degradation.

Keywords: salinity, sebkha soil, grain size distribution, unconfined compressive strength, soil pH, SEM analysis, soil remediation, predictive modeling.

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Introduction

Problematic soils are globally prevalent and pose considerable challenges to civil engineering infrastructures, often leading to costly damage and structural failures [1, 2]. Among these, collapsible soils are particularly notorious due to their sudden loss of strength upon wetting. Houston et al. [3] identified collapsible soils as one of the most problematic geomaterials in the field of geotechnical engineering, and the study of their behavior is essential for designing foundations and other civil structures. Sabkha soils, a specific type of unsaturated collapsible soil, are particularly troublesome in arid and semi-arid regions [4-7]. Their high soluble salt content and low clay fraction promote the formation of a macroporous structure, where soil particles are loosely bonded [8]. Under dry conditions, the salt phases act as a cementing agent, stiffening the soil structure. However, exposure to water triggers the dissolution of these crystalline phases, destabilizing the bonds and drastically reducing the soil's strength, which can lead to catastrophic settlement or collapse [8].

In recent decades, researchers have increasingly focused on understanding the complex behavior of saline soils, given their widespread occurrence in coastal and desert regions. Ying et al. [9] observed that compaction properties remain relatively unaffected by varying salinities, primarily due to the low clay content, which limits the influence of salinity on the diffuse double layer. However, Li et al. [10] demonstrated that the higher the chloride content is, the more likely the agglomerates are to appear in the soil, altering its microstructure. Hafhouf et al. [11] further highlighted the vulnerability of sabkha soils to drying-wetting cycles, showing that

prolonged leaching significantly reduces soil salinity from 16.3 dS.m⁻¹ to 3.8 dS.m⁻¹, with the corresponding soil strength decreasing by almost 50%, from 325 kPa to 175 kPa. Similarly, Modmoltin et al. [12] found that soil salts could mitigate some of the negative effects of organic matter on treated soils, while Li et al. [13] demonstrated that chloride salts weaken the mechanical properties, such as unconfined compressive strength, even if compaction remains largely unaffected. Moreover, Xing et al. [14] identified that chloride ions (Cl⁻) have the most detrimental impact on the strength properties of saline soils, followed by magnesium (Mg²⁺) and sulfate (SO₄²⁻), indicating that the chemical composition of salinity plays a pivotal role in determining soil behavior.

Despite these efforts, there remains a notable divergence of opinions in the scientific community regarding the effects of salinity, especially in relation to soil strength. Some studies report a stabilizing effect of certain salts, while others emphasize their destructive impact on soil cohesion and mechanical integrity [15-17]. These discrepancies are largely attributed to the complex interplay between different types of salts, which is often not fully accounted for in studies focusing on a single ion [18]. Furthermore, the role of microstructure is increasingly recognized as a critical determinant of macroscopic behavior. Foncea et al. [19] emphasized the influence of natural soil structure, classifying soils into macroporous and microporous categories, each with distinct permeability and strength characteristics. This highlights the need for a more integrated approach, combining both chemical and structural analyses, to fully capture the effects of salinity on soil performance [20].

The primary objective of this study is to address these gaps by investigating the combined effect of chloride and sulfate salts on the physical, chemical, and mechanical properties of saline soils. The research aims to provide a more comprehensive understanding of how varying salt concentrations affect soil behavior under different environmental conditions, particularly in relation to its strength, compaction, and permeability. Furthermore, advanced microstructural analysis using Scanning Electron Microscopy (SEM) will be employed to elucidate the interaction between salt phases and soil particles, linking microscopic changes to macroscopic behavior. By bridging the gap between microstructural and macrostructural analyses, this study seeks to offer new insights into the mechanisms governing the behavior of saline soils, particularly in complex environments where multiple salts interact. These findings will have practical implications for geotechnical design, offering strategies for mitigating the risks associated with saline and collapsible soils in infrastructure projects.

Materials and Methods

Soil samples were collected from the Tin silt sebkha in Ain M'lila using a hydraulic excavator, at a depth of 1 to 2 meters below the surface. This sampling was conducted during three distinct seasons: summer, spring, and winter, resulting in three different salinity levels: highly saline soil (HSS), moderately saline soil (MSS), and slightly saline soil (LSS). The classification of these salt-affected soils follows the guidelines established by the US Salinity Laboratory Staff [21]. After collection, the samples were air-dried, gently crushed using a plastic hammer to avoid contamination, and then sieved through a 2 mm mesh to remove larger particles.

Ying et al. [9] demonstrated that the salinity levels have an insignificant effect on the Atterberg limits of soils with low clay content. As a result, only the geotechnical characteristics of HSS are presented in Table 1, since variations in salinity did not significantly alter these properties for the other samples. The highly saline soil (HSS) was classified as Lean Clay (CL) according to the Unified Soil Classification System (USCS). The chemical composition of HSS, shown in Table 2, reveals the dominance of chloride (Cl⁻) and sulfate (SO₄²⁻) ions, with concentrations of 3585 mg/l and 4704 mg/l respectively, indicating the presence of halite and gypsum phases. According to Loyer (1991), the soil's pH of 6.79 classifies it as a neutral chloride-sulfate soil.

Table 1. The geotechnical characteristics of HSS

Soil parameters	Methods	Values
Liquid limit LL		34.00
Plastic limit PL	(ASTM D4318-00, 2000)	17.300
Plasticity index PI		16.70
≤ 2 mm fraction (%)	(NF P94-056, 1996)	98
≤ 80 μm fraction (%)		68
≤ 2 μm fraction (%)	(NF P94-057, 1992)	3
USCS	(ASTM D2487-00, 2000)	CL

Regarding soil compaction characteristics, such as optimal dry density (δ_{opt}) and optimal water content (w_{opt}), it was observed that the salinity levels had a negligible impact, a finding consistent with that of Ying et al. [9]. Therefore, all three soil types—HSS, MSS, and LSS—were compacted at their respective optimum water contents, which remained constant across varying salinity levels. This consistency suggests that, despite significant chemical differences, the mechanical response of the soil to compaction is not strongly influenced by salinity within the studied range.

Table 2. The chemical composition of the soluble salt content of HSS

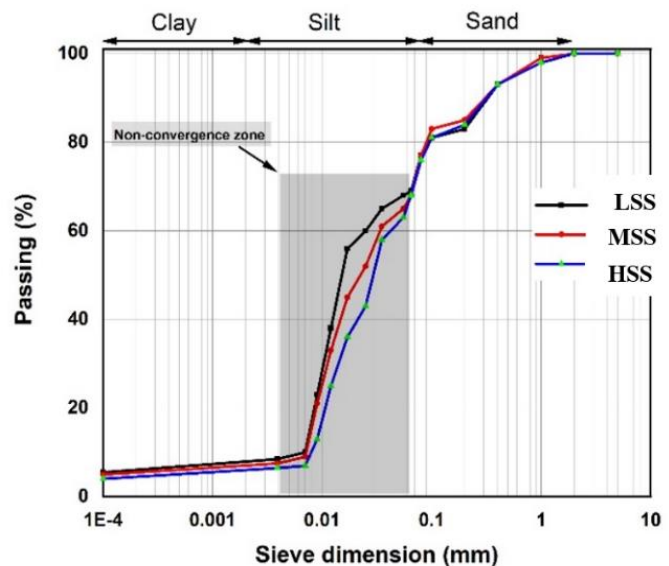
ECe (dS.m ⁻¹)	Salinity (g.l ⁻¹)	pH	Soluble salt content (mg. l ⁻¹)						
			Na ²⁺	K ²⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
23.2	14.84	6.79	2323	50	391.2	156.5	10	3585	4704

Results and Discussion

Granulometry

Figure 1 demonstrates the grain size distribution curves (GSDC) of sebkha soil across varying salinity levels, revealing the significant influence of salinity on particle size distribution, particularly within the silt grain range. The non-convergent trend between slightly saline soil (LSS) and highly saline soil (HSS) underscores the complex interplay between soil salinity and granulometry. For both LSS and HSS, approximately 70% of the particles exhibit diameters smaller than 60 μm, yet when examining finer fractions, the divergence becomes more apparent. For LSS, 57% of the grains fall below 20 μm in diameter, whereas for HSS, only 38% do, representing a 19% increase in fine particles for LSS compared to HSS.

This variation can be explained by the presence of soluble salts such as halite (NaCl) and gypsum (CaSO₄·2H₂O) in HSS [22]. These salts act as cementing agents between soil particles, especially within the silt fraction, due to the larger specific surface area of silt particles relative to sand grains [23]. The specific surface area is a critical factor in geotechnical engineering, as it dictates the degree of interaction between particles and binding agents. In dry conditions, halite and gypsum form strong crystalline bonds that stabilize larger aggregates, effectively reducing the proportion of fine particles. However, upon exposure to moisture,

**Fig. 1.** The grain size distribution curves of the three sabkha soils

the dissolution of these salts weakens the interparticle bonds, leading to the disintegration of aggregates and an increase in the proportion of finer particles [24].

The impact of salinity on particle size distribution is closely linked to the microstructural properties of the soil. Silt particles, with their higher specific surface area, are more susceptible to salt cementation compared to coarser sand grains. This interaction leads to the formation of larger aggregates in saline environments, but when subjected to wetting-drying cycles, the breakdown of these aggregates results in a shift towards finer particle fractions. Such behavior is consistent with findings by Li et al. [13], who observed that increased chloride salt concentrations induce crystallization and flocculation, thereby increasing the proportion of particles greater than 2 μm . This suggests that chloride salts play a fundamental role in modifying soil structure through the crystallization of salt phases, leading to temporary stabilization that is disrupted during dissolution processes.

Furthermore, the differential behavior between HSS and LSS can be attributed to the chemical composition of the soils. HSS contains a higher concentration of soluble salts, which enhances the cementing effect between soil particles. These salts form a rigid matrix that holds the particles together, leading to larger aggregates and a reduced proportion of fine particles in dry conditions. Conversely, LSS, with a lower concentration of salts, exhibits less aggregation, resulting in a higher proportion of fine particles. The dissolution of salts in HSS causes the breakdown of these aggregates, thereby increasing the fraction of fine particles under moist conditions. This process is particularly relevant in sebkha soils, which experience fluctuating moisture levels due to environmental conditions, leading to cycles of salt precipitation and dissolution that significantly alter soil structure.

The presence of gypsum and halite in sebkha soils, especially in the silt fraction, is further supported by their high solubility in water, making them highly susceptible to dissolution. When exposed to moisture, these salts dissolve, weakening the soil's structural integrity and leading to a loss of cohesion between particles. This results in an increase in the proportion of finer particles, as previously cemented aggregates disintegrate. This behavior is critical for understanding the geotechnical performance of saline soils, particularly in regions where seasonal variations in moisture can lead to dramatic changes in soil stability.

Additionally, the limited clay content in the tested sebkha soil explains why the effect of salinity on the clay fraction is minimal. Clay particles, known for their plasticity and water retention capabilities, typically respond to salinity through changes in the diffuse double layer and interparticle forces. However, due to the low clay fraction, these effects are negligible in the current study, and the influence of salinity is predominantly observed in the silt fraction. Ying et al. [9] also noted that for soils with a low clay fraction, salinity has little to no effect on the Atterberg limits, further supporting the hypothesis that the observed behavior is primarily driven by interactions between soluble salts and silt particles.

In conclusion, the grain size distribution of sebkha soils is strongly influenced by salinity levels, with significant differences observed between LSS and HSS [25]. The cementing effect of soluble salts such as halite and gypsum plays a crucial role in stabilizing soil aggregates, particularly in the silt fraction, while the dissolution of these salts during wetting cycles leads to the disintegration of aggregates and an increase in fine particles [26].

Stress-strain curves of unconfined strength tests

The stress-strain curves presented in Figure 2 illustrate the results of unconfined compressive strength (UCS) tests for sebkha soils with varying salinity levels. The stress-strain behavior of these soils is influenced significantly by salinity, with a marked decrease in peak strength prior to failure across all samples. A key observation is that soils with higher salinity exhibit a more pronounced ductile behavior, meaning that peak strength is attained at larger axial strains as salinity increases. This relationship is crucial in understanding the mechanical performance of saline soils in geotechnical applications.

In saline soils with higher salt content, such as halite (NaCl) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), the solid salt phases within the soil skeleton begin to dissolve under certain moisture conditions. Halite, being highly soluble, dissolves rapidly upon contact with water, transforming solid particles into fluid phases [27]. This dissolution leads to a loss of cohesion between soil particles, thereby disrupting the soil structure and resulting in a softer, more ductile response under loading. The mechanical disturbance caused by the dissolution of these salt phases explains the reduction in strength and the shift toward greater ductility, as the soil becomes less capable of resisting deformation [4].

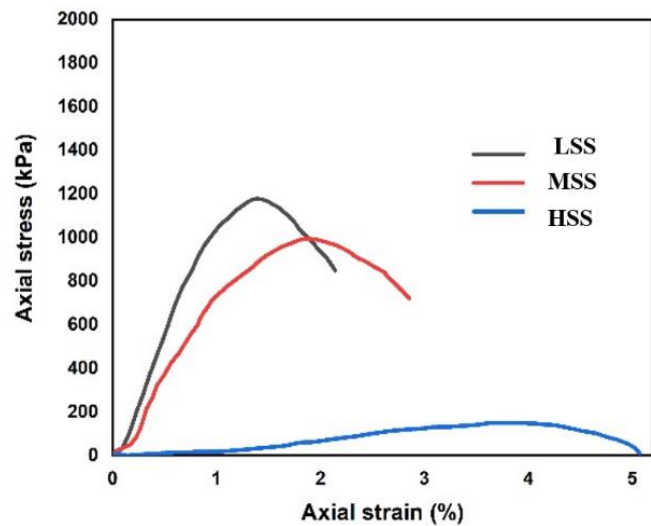


Fig. 2. The stress-strain curves of compacted three sabkha soils

In contrast, gypsum is less soluble compared to halite, which slows its dissolution process. However, even partial dissolution of gypsum can still contribute to the weakening of the soil matrix. The combined presence of these salts leads to a progressive softening of the soil, with increasing salinity exacerbating the degradation of the soil's structural integrity. As a result, the soil's capacity to bear loads decreases, which is evident from the stress-strain curves.

For the slightly saline soil (LSS), the dissolution phases are almost negligible due to the lower salt content. The low solubility of salts in LSS ensures that the soil structure remains largely intact, leading to a stiffer response during loading. This is reflected in the stress-strain curve, where the LSS displays a prominent peak at failure, indicating that the soil retains much of its original strength until a distinct failure point is reached. The pronounced peak in the blue plot (Fig. 2) represents this stiff behavior, as LSS maintains its cohesion and strength over a broader range of axial strain before failing suddenly, which is characteristic of more brittle materials.

The transition from stiff, brittle behavior in low-salinity soils to soft, ductile behavior in high-salinity soils can be attributed to the complex interplay between the dissolution of soluble salts and the resulting changes in the soil microstructure. As the salinity increases, the soil undergoes a shift in mechanical behavior from brittle failure, where the soil fractures and fails abruptly, to ductile deformation, where the soil continues to deform beyond the peak load without sudden failure. This behavior is indicative of the weakening bonds between particles, caused by the dissolution of salts [4].

The progressive ductile response with increasing salinity highlights the need for careful consideration of salinity in geotechnical design, particularly in regions with saline soils like sebkha environments. The softening of the soil structure due to salt dissolution can lead to significant settlement and deformation in engineering structures, particularly when subjected to loading over time. Therefore, understanding the stress-strain behavior of saline soils is essential for predicting their performance under real-world conditions, especially in areas where moisture fluctuations can exacerbate the dissolution of salts.

Unconfined compressive strength

Figure 3 illustrates the relationship between peak strength, axial strain, and salinity levels for sebkha soil samples subjected to unconfined compressive strength (UCS) testing. The peak strength (UCS) represents the maximum stress the soil can withstand before failure, while the slope of the stress-strain curve before failure indicates soil stiffness. Both the UCS and stiffness exhibit a decreasing trend with increasing salinity levels, highlighting the detrimental effect of salt content on the mechanical properties of sebkha soils.

For example, the UCS is only 200 kPa for highly saline soil (HSS), while it increases to 580 kPa for

moderately saline soil (MSS) and reaches 1100 kPa for low salinity soil (LSS). These results suggest that salinity significantly weakens the soil structure, particularly in soils with high soluble salt content, such as halite and gypsum. The dissolution of these salts under certain moisture conditions compromises the integrity of the soil matrix, leading to a notable reduction in strength.

In contrast, the axial strain at failure exhibits the opposite trend. The strain at failure (ϵ) is much larger for HSS ($\epsilon = 4.7\%$) and MSS ($\epsilon = 4.2\%$) compared to LSS ($\epsilon = 2.3\%$). This inverse relationship between salinity and strain indicates that higher salt concentrations result in more ductile behavior, where the soil deforms more before reaching its failure point. The high ductility of HSS and MSS can be attributed to the dissolution of halite and gypsum, which causes the soil structure to soften and undergo greater deformation before failure. In LSS, however, the lower salt content limits the dissolution processes, resulting in a stiffer and more brittle response under loading.

The variations in UCS and strain between MSS and LSS are more pronounced than those between HSS and MSS, indicating that the reduction in salinity from 8.30 dS.m⁻¹ to 2.55 dS.m⁻¹ has a more substantial effect on the soil's strength and stiffness compared to the reduction from 23.2 dS.m⁻¹ to 8.30 dS.m⁻¹. This finding can be explained by the relative solubility of the salts involved. In highly saline soils, halite is the dominant phase due to its high solubility, and it dissolves more readily when exposed to water. In contrast, in MSS, gypsum becomes the predominant phase, which is less soluble and has a more significant impact on the soil's mechanical properties.

The presence of gypsum in MSS plays a critical role in both strength and stiffness. While halite dissolves rapidly, leading to a softer soil structure, gypsum's slower dissolution process allows it to maintain some cohesion and strength within the soil matrix. However, when MSS is exposed to leaching, the gradual dissolution of gypsum can lead to a significant reduction in soil resistance. This makes MSS highly susceptible to strength loss during wetting-drying cycles, posing a potential risk for civil engineering works in saline environments. In this context, field conditions involving MSS warrant closer attention due to the greater risk of structural degradation over time.

In summary, the UCS and stiffness of sebkha soils increase as salinity decreases, with LSS demonstrating the highest strength and lowest strain at failure. Conversely, the ductility of the soil increases with salinity, as evidenced by the larger strains at failure for HSS and MSS. The sharp reduction in strength and stiffness between MSS and LSS highlights the critical role of gypsum in soil behavior, particularly in environments where salinity levels fluctuate. Given these findings, MSS soils in particular should be carefully monitored and managed in geotechnical applications to prevent excessive weakening under environmental stressors such as leaching.

Chemical Analysis

Seasonal climatic conditions play a critical role in influencing soil salinity through mechanisms such as capillary action and evaporation. The solubility of different salt phases in the soil is contingent on the salt type and its degree of crystallization, as well as the inherent structure of the soil (Foncea et al.[19]). In the case of the sebkha soil under study, chloride salts are predominant. Chlorides are highly soluble, which means they

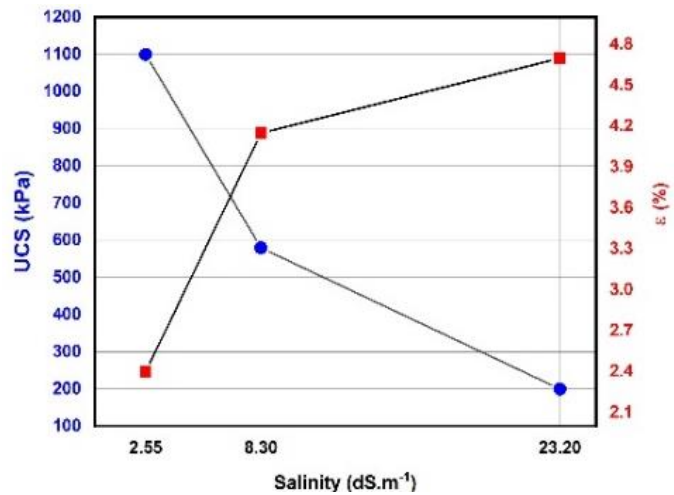


Fig. 3. The peak strength and axial deformation of compacted three sabkha soils

readily dissolve in moisture and migrate to the soil surface via capillary forces and evaporation. This process leads to a reduction in soil salinity as the chloride content diminishes over time.

In contrast, gypsum, which is also present in the soil, exhibits a lower solubility rate compared to chloride [28]. Gypsum's dissolution is less pronounced under the same conditions, leading to a slower decrease in soil salinity. This differential solubility influences the overall chemical composition and pH of the soil, as reflected in the chemical analysis results [29].

Table 3 provides an overview of pH variations across different salinity levels. It is observed that as soil salinity increases, there is a corresponding decrease in pH, indicating an increase in soil acidity. This trend is attributed to the high concentration of chloride ions in the soil, which contributes to a more acidic environment. Specifically, the soil at the highest salinity level (HSS, CE = 23.2 dS.m⁻¹) shows a significant drop in pH, reflecting the strong acidic influence of chloride salts.

Table 3. The chemical analysis of compacted three sabkha soils

CE (dS.m ⁻¹)	pH	Salt content (g.l ⁻¹)
23.20 (HSS)	6.79	14.24
8.30 (MSS)	8.03	5.31
2.55 (LSS)	8.17	1.29

Conversely, when salinity decreases from 23.2 dS.m⁻¹ to 2.55 dS.m⁻¹, there is a notable increase in pH from 6.79 to 8.17, resulting in a more neutral environment. This shift is indicative of the reduced impact of acidic chloride salts and the relative dominance of less acidic phases, such as gypsum, which contributes to the neutralization of soil acidity. The variation in pH values underscores the dynamic interplay between different salt phases and their impact on soil chemistry.

The impact of salinity on pH is more pronounced when transitioning from high salinity levels (e.g., 23.2 dS.m⁻¹) to lower levels (e.g., 8.30 dS.m⁻¹), reflecting a more significant change in soil acidity. In contrast, the pH variations between lower salinity levels (e.g., 8.30 dS.m⁻¹ to 2.55 dS.m⁻¹) are less dramatic, suggesting that the soil's chemical environment stabilizes as salinity decreases.

This chemical behavior has practical implications for managing saline soils in agricultural and civil engineering contexts. High salinity levels can lead to increased soil acidity, which may adversely affect plant growth and soil stability. Conversely, lower salinity levels are associated with a more neutral pH, which can be more conducive to plant growth and soil health.

Microstructural Analysis (SEM)

Figure 4 provides insights into the microstructural characteristics of sabkha soil samples analyzed via Scanning Electron Microscopy (SEM). The observations reveal significant differences in the soil microstructure corresponding to various salinity levels.

High Salinity Soil (HSS)

In Figure 4 (a), the SEM images of HSS illustrate the presence of well-defined crystalline salt phases. The soil's chemical composition, predominantly chlorine-sulfate, confirms that halite (NaCl) and gypsum (CaSO₄·2H₂O) are the main compounds. Halite typically appears as white, platelet-like crystals, whereas gypsum exhibits a more random and varied morphology. These salt crystals contribute to a denser soil structure through their cementing action. The halite and gypsum crystals act as binding agents, creating a cohesive matrix of soil particles. The interlocking of these crystals with soil particles forms a robust network that enhances the soil's initial strength and stiffness. However, the stability of this structure is contingent upon the salt phases remaining intact.

Low Salinity Soil (LSS)

In contrast, the SEM images of LSS reveal a different microstructural arrangement. The lower salt content in LSS results in a less dense structure with more noticeable micropores between the soil aggregates. This porous texture is likely due to the reduced presence of soluble salts like halite and gypsum, leading to fewer cementing agents within the soil matrix. Additionally, the lower clay content in LSS may contribute to the more pronounced appearance of micropores, as the reduced clay fraction limits the overall cohesion and binding capacity of the soil [25].

The effect of salinity on soil microstructure is evident in the observed changes. Higher salt content results in a denser and more cohesive soil structure due to the cementing effect of halite and gypsum [25]. However, when the soil is exposed to water, the solubility of these salts comes into play. Halite, being highly soluble, dissolves readily upon moisture exposure, which disrupts the cementing bonds and weakens the soil structure. Gypsum, while less soluble, still contributes to structural changes over time. The leaching process, wherein salts are washed out from the soil surface, creates additional micropores and alters the particle arrangement, resulting in a more porous and less cohesive structure.

The dissolution of salts through leaching significantly impacts the soil's mechanical properties. As the cementing salts are removed, the previously bound soil particles are left with reduced cohesion, leading to a decrease in soil strength and stiffness. This shift in the microstructural arrangement highlights the importance of considering salinity and its impact on soil behavior in practical applications [30].

Conclusion

The investigation into the effects of salinity on sebkha soils has yielded significant insights into their physical, mechanical, and chemical properties. The study reveals the following key findings:

- **Grain Size Distribution:** Higher salinity levels lead to a greater proportion of finer particles, with 70% of grains having diameters less than 60 μm . Specifically, low salinity soil (LSS) contains 19% more particles smaller than 20 μm compared to high salinity soil (HSS). This shift is attributed to the dissolution of larger aggregates in high salinity conditions, which increases the proportion of finer particles.
- **Stress-Strain Behavior:** Increased salinity results in more pronounced ductility and reduced peak strength. The unconfined compressive strength (UCS) decreases from 1100 kPa in LSS to 200 kPa in

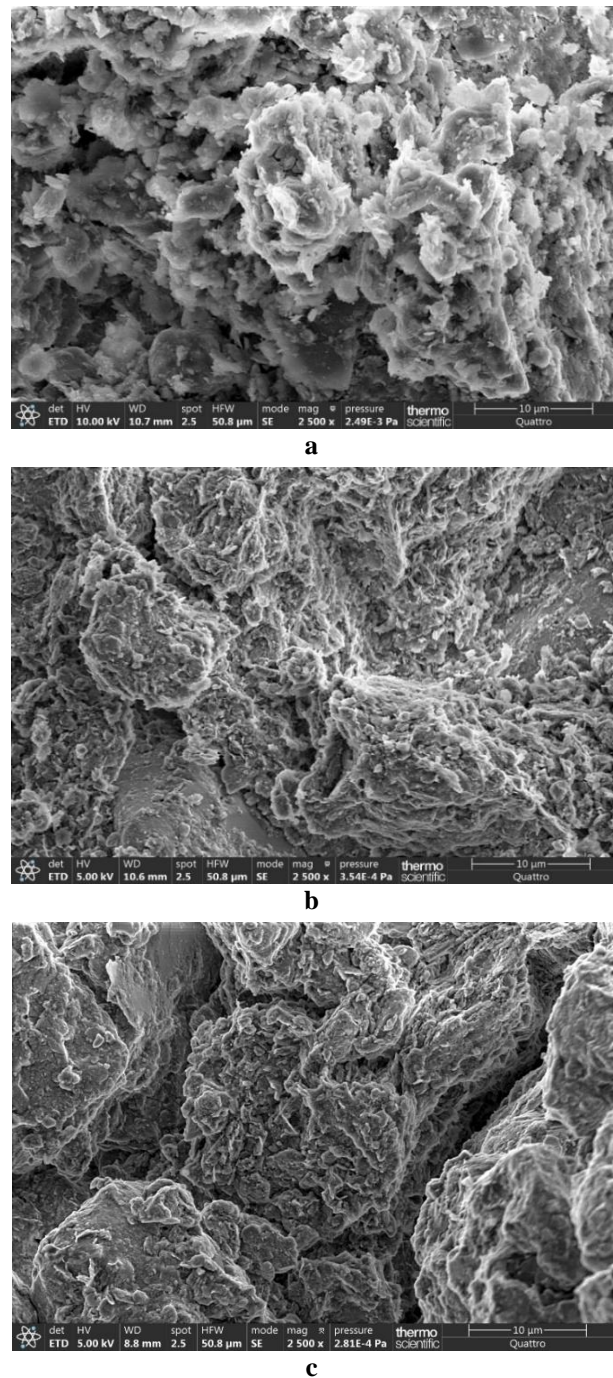


Fig. 4. SEM of compacted three sabkha soils: a - HSS, b - MSS, c - LSS

HSS, while the peak strain at failure increases from 2.3% to 4.7%. This trend indicates that higher salinity softens the soil structure due to the dissolution of salt phases, disrupting soil cohesion.

- **Unconfined Compressive Strength (UCS):** UCS decreases with increasing salinity, with values of 200 kPa for HSS, 580 kPa for medium salinity soil (MSS), and 1100 kPa for LSS. The maximum strain at failure also varies, showing higher strain in higher salinity soils. This reflects the impact of gypsum and halite on soil strength, with gypsum having a significant effect when salinity levels decrease.
- **Chemical Analysis:** The pH of the soil decreases with increasing salinity, indicating greater acidity. The pH shifts from 8.17 in LSS to 6.79 in HSS, highlighting the influence of chloride concentrations. The transition from high to low salinity also shows a shift towards a neutral pH environment.
- **Microstructural Analysis (SEM):** Higher salinity soils exhibit a denser microstructure due to salt cementation. In contrast, lower salinity soils have a more porous structure with increased microporosity. The dissolution of salts under higher salinity leads to structural rearrangements, affecting soil strength and stability.

Future research should focus on developing comprehensive models that integrate the chemical, physical, and mechanical properties of saline soils. These models would enhance predictive capabilities, aiding in the design of effective soil management strategies. Additionally, understanding the effects of salinity on soil properties can inform remediation and stabilization techniques. Investigating methods to stabilize or improve saline soils with additives or treatments that counteract the negative impacts of salt dissolution could significantly enhance soil strength, cohesion, leading to more robust and sustainable management practices.

Conflict of Interest

The authors declare no conflicts of interest.

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