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An investigation into the effects of salt water on geotechnical properties, compressive and shear strength characteristics of fine-grained soil

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Abstract

This study examines the effect of water salinity levels on the mechanical geotechnical properties of clay-rich soil. Laboratory tests were conducted on a set of soil samples with varying salinity levels, including unconfined compressive strength (UCS), Atterberg limits, oedometer, and direct shear tests. The conducted test results are further used to evaluate alterations in soil properties resulting from exposure to sodium chloride (NaCl) concentrations ranging from 0 mM (pure water) to 600 mM (seawater). The findings show a progressive decrease in liquid limit, plastic limit, and plasticity index with increasing salt concentration, indicating reduced water affinity and significant physicochemical alterations to the soil structure. These trends are consistent across all experimental observations and have been confirmed by zeta potential measurements and mineralogical analyses using X-ray diffraction (XRD). However, maximum dry density increased in parallel with a decrease in optimum moisture content. The increase in salinity led to a decrease in compressive strength, indicating a weakening of the soil structure. The shear strength parameters (cohesion and Internal friction angles) experience a decrease due to the presence of saline water. Therefore, soils with high salinity will also exhibit lower shear strengths. The results of this study provide reliable information to support road construction activities in coastal environments.

1. Introduction

The impact of saline water on coastal and arid areas will significantly alter soil behavior, thereby affecting its ability to support geotechnical structures [1-5]. In these areas, soil is exposed to unique physicochemical conditions caused by the presence of saline water, either through infiltration, marine intrusion (a typical occurrence along the coast), capillary rise, or salinization due to climate change via excessive evaporation in arid locations [6]. As sea levels rise, droughts become more frequent, and groundwater is overused, saline water continues to invade both the surface and subsurface soils, resulting in severe alteration of soil geotechnical properties [3,6,7]. This situation has now been classified as an important problem for geotechnical engineers, as changes in salinity affect soil structure, soil mechanics, soil strength, and the ability of soils to support structures [4,8]. Fine-grained soils, especially clay, exhibit extreme sensitivity to chemical variations due to their large specific surface area and many charged surfaces; additionally, a diffuse double layer

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associated with their particle surfaces responds to dissolved ions in water [4, 6,9]. The presence of salt(s), particularly sodium chloride, can modify the physicochemical equilibrium between soil particles, potentially leading to increased flocculation, dispersion, and thickening or reduction in thickness of the diffuse double-layer (increasing and decreasing in thickness, respectively) and changes to the internal microstructure of the soil [9]. Each of these processes will directly affect the Atterberg limits, as well as the compressibility of the soil under load (unconfined compressive strength and shear conditions) [7,10]. There are a variety of studies conducted on the interactions between fine-grained soils and salt water available in the existing literature [11]; however, there appears to be significant variability in the conclusions drawn from these studies based on different soil types tested, dominant mineral content, different salt concentrations tested, and experimental protocols utilized [12]. Some researchers have reported that the addition of Na+ or Cl- ions reduces the double-layer thickness, promotes flocculation of clay particles [13], and consequently reduces plasticity [9]. Several researchers have reported that in some cases the liquid limit increases with lower salinity before decreasing at higher salinity and that this may occur as a result of a complex realignment of the internal microstructure of the soil. Mechanical testing for the soil strength, either compressive strength or shear parameters [10], has generally shown that elevated levels of salts result in a decrease in cohesion and the internal friction angle. As a consequence, there is a significant reduction in soil strength due to increasing salt concentrations; this is well documented by Van et al. [2] and Campbell et al. [3], with the greatest impact on smectite-dominated soils. Significant gaps remain in the scientific literature despite these important contributions to knowledge. Previous studies generally considered a limited range of salinity levels (much narrower than those observed in nature). So far, there are limited works that include all salinity values, from fresh water to equal to or greater than seawater (even though this salinity range would be representative of actual conditions). Moreover, the few existing studies investigate only a couple of geotechnical properties (e.g., Atterberg limits or compressive strength) and do not examine the variation in physicochemical properties associated with the mechanical variations measured experimentally. This led to a limited understanding of the effect of saline conditions on soils. This study employs a comprehensive methodology to address the identified gaps. Specifically, the research uses a very wide range of salinity levels (0 to 600 mM NaCl), spanning typical salinity levels found in estuarine, coastal, and marine environments. Moreover, the study employs all appropriate testing methods (Atterberg limits, unconfined compressive strength, oedometer tests, and direct shear tests) in order to comprehensively explore the influence of saltwater on the behavior of fine-grained soils.

2. Materials and methods

2.1. Materials

The tested materials were collected from a clay-loam (30% clay, 50% silt, and 20% very fine sand) soil source within the Adrar region. To obtain samples, ASTM D1587 (Standard for Soil Testing with Thin-Walled Core Method) outlines techniques for collecting samples using a thin-walled coring method in order to maintain the original soil structure. In the current study, the collected sample ranged from 0.80 to 1.20 m in depth. Upon retrieval, samples were immediately placed into airtight bags or pouches and lined with Aluminum foil to prevent the transfer of water between soil samples as well as to avoid oxidation of the clay particles (which would affect the mineralogical reactivity of the clays). In the laboratory, the samples were then immediately cut into smaller sections and dried at a controlled temperature of (20±1°C) for 72 hours, to minimize the impact of salt crystallization. To limit the influence of water content variations on the mechanical property test results, each sample was stored under similar humidity and saturation conditions prior to testing. This procedure ensured that the observed differences were primarily due to physicochemical effects arising from increased saltiness.

After this point, the samples were further separated by hand to reduce the mechanical force applied during handling individual clay layers. Following the drying procedure, samples were sifted through a 2 mm sieve to remove the larger fractions, retaining the fines for the following testing. The interactions between the clay soil and the ionic medium were tested with solutions of sodium chloride using the following molar concentrations: 0, 25, 50, 100, 200, 300, and 600 mM. These solutions were prepared dissolving increasing concentrations of salt with a minimum purity of 99.5% in distilled water. The sodium chloride mass per solution was measured on an analytical balance with 0.1 mg accuracy prior to mixing with a magnetic stirrer for 30 minutes to allow complete dissolution of the sodium chloride. The solutions were then tested for conductivity, pH, osmolarity, and temperature to confirm the ionic stability of the saline solution used to treat the soils [11]. The previously sieved soils were then soaked in these solutions for 72 hours in airtight containers. This time frame was selected to allow for the complete exchange of Na^+ cations with the interlayer sites of the clays while ensuring complete water saturation of the sample. The equilibrium was determined to have been achieved once the electrical conductivity of the solutions did not change after 48 hours, and was used as the basis for evaluating the effects of NaCl on the microstructural characteristics of the immersed soils. Measurements were taken under controlled conditions to minimize potential variance due to environmental factors, such as temperature and humidity, that could affect the accuracy of the results. Drying was intentionally performed at a low controlled temperature (20 ± 1°C) to minimize possible salt crystallization and microstructural disturbance associated with rapid evaporation. Nevertheless, localized salt precipitation during drying cannot be completely excluded and represents a potential limitation of the experimental protocol. Prior to the salinization treatment, all samples were statically compacted to achieve approximately identical initial dry densities, corresponding to an average initial void ratio of $e_0 = 0.76 \pm 0.03$.

2.2. Materials Analysis

The soil was characterized using elemental analysis, X-ray diffraction (XRD), and zeta potential, in order to better elucidate the physicochemical mechanisms governing hydromechanical behavior and to confirm the presence of active clay minerals, likely dominated by illite and smectite fractions, which are highly sensitive to the chemical composition of interstitial fluids and to diffuse double-layer interactions.

2.2.1. X-ray Diffraction

The soil was analyzed by XRD using the Empyrean diffractometer (Malvern Analytical). X-ray diffraction is used to determine the crystal structure of the minerals that make up the soil, whether they are of organic or inorganic origin. The XRD diffractogram shown in Figure 1 indicates that this soil has a silty-sandy texture with a clay matrix and a dominant quartz phase, as evidenced by a distinct peak at 26.6°, consistent with the high silt and fine sand content (70%). The presence of calcite (≈ 29.4°) indicates a carbonate-rich soil, typical of arid environments. Clay minerals, primarily kaolinite and likely illite, appear with less pronounced peaks, consistent with the moderate clay content (30%).

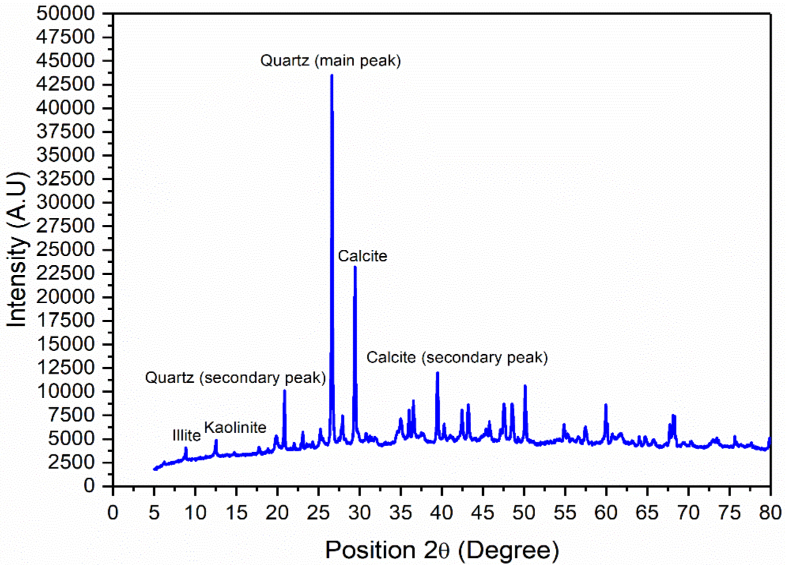

Fig. 1. Soil X-ray diffraction

2.2.2. Zeta Potential Measurement

The soil zeta potential was measured using a ZetaCAD and a ZetaCompact (manufactured by CAD, France) at different salinity levels. The ZetaCAD is a zeta potential analyzer equipped with Ag-AgCl electrodes and a cylindrical cell (2 cm inner diameter and 10 cm length). It measures the electrophoretic mobility of particles in a vertical plane (using a high-sensitivity digital camera) and calculates the zeta potential of these soil particles. The influence of salinity on the zeta potentials of soil particles is shown in Figure 2. As shown in the graph, soil particles are negatively charged at the experimental pH (6.5 ± 0.1). For all surfaces, the zeta potential becomes less negative as the ionic strength increases, due to the compression of the electrostatic double layer. These zeta potential values are subsequently used to calculate the repulsive electrostatic double-layer interaction energies between the fine particles constituting the soil.

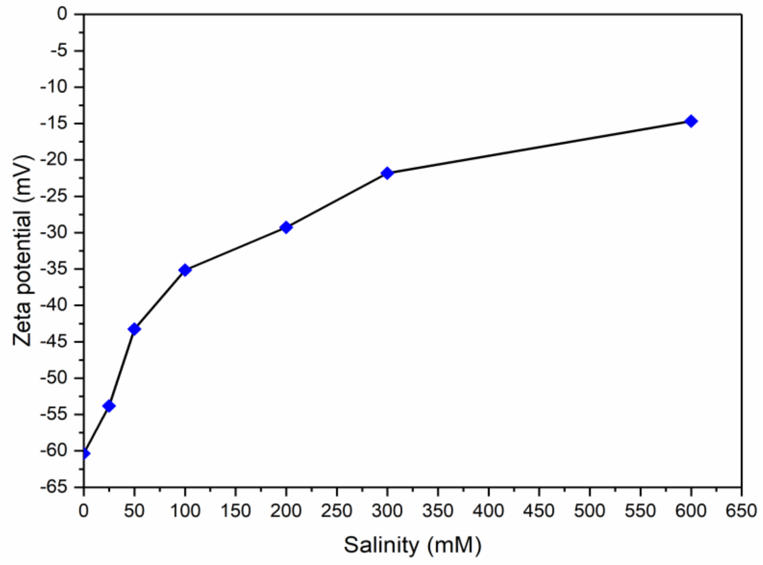

Fig. 2. Zeta potentials of soil particles as a function of salinity at a pH of 6.45 (± 0.1)

2.3. Methods

2.3.1. The Atterberg Limits

Atterberg limits were determined at different salinity levels to evaluate the changes in the states of plasticity and consistency of the material based on the presence of dissolved ionic species [2,6, 13]. ASTM D4318 was used to conduct Liquid Limit (LL) and Plastic Limit (PL) tests to obtain the Plasticity Index (PI), which is required to evaluate how salinity affects the material's behavior [3,7,14]. Three trials were conducted for each test to validate reproducibility; thus, the average value of the data obtained across repetitions is reported. For each experimental condition, the reported values correspond to the arithmetic means of three independent measurements. The coefficient of variation remained below 5% for most measured parameters, indicating satisfactory repeatability of the testing procedure. The observed variability did not affect the general trends discussed in this study.

2.3.2. California Bearing Ratio (CBR) Compaction Test

In this study, the CBR (California Bearing Ratio) tests were used to analyze the overall impacts of salinity on soil bearing capacity [6]. Controlled density and moisture conditions were maintained for the CBR tests. The original soil was used for sampling, and the resulting samples were homogenized with saline solutions corresponding to all salinity levels tested in this study. All series of test materials were compacted using the standard Proctor test method (ASTM D698), allowing for a direct comparison of the resulting material properties across all test conditions.

Each of the compacted samples was then saturated with the saline solution corresponding to each saline concentration investigation for a predetermined period, thereby providing the same mechanism of salt intrusion in an undisturbed environment that would occur under field conditions [3]. The CBR test was conducted in accordance with ASTM D1883 with a standardized penetration depth of 2.54 mm; this penetration depth has been documented to provide fair to good sensitivity to structural changes associated with ionic interactions [15]. The structure of this protocol aimed to describe the influence of physicochemical processes that contribute to penetration resistance and soil bearing capacity in saline environments [1].

2.3.3. Unconfined Compression Tests (UCTS)

According to ASTM D4767, unconfined compressive strength (UCS) testing of reworked cylinder-shaped specimens was conducted on soil stabilized under a range of saline solution concentrations [1,16-18]. The tested specimens were compacted in standard molds to achieve identical dimensions and dry density and maintain uniformity across all saline concentrations. The compacted specimens were cured under designated conditions in an ambient-controlled environmental chamber to achieve complete chemical equilibrium between the fine soil particles and the saline solutions; therefore, the internal microstructure of the soil represents the influence of ionic concentration [19]. Osmotic suction was neither directly measured nor controlled during the UCS tests; however, the specimens were tested after attaining chemical equilibrium; hence, osmotic pressure is assumed to be near equilibrium. The UCS tests of the cylindrical specimens were conducted at a constant strain rate until failure.

The maximum strength developed at each concentration was recorded for the purpose of comparative analysis on the effect of NaCl on apparent cohesion and total strength of the soil matrix. Pre-saturated samples were enclosed in stainless steel rings according to the standard specifications and then, under no vertical load, were monitored for their vertical swelling amplitude in a saline solution until a steady state was reached. The monitoring system used was a digital reader with a resolution of 0.002mm. After reaching a steady state, the coefficient Cg was calculated using the difference in sample height between the original and final positions. Soil compressibility and compressibility pressure (Pc) were determined using a one-dimensional oedometer test conducted in accordance with ASTM D2435/D2435M [12,21]. The procedure consisted of a sequence of incremental load stages followed by a period of gradual unloading. This sequence allowed for determining the compressibility index (Cc), the compressibility index (Cr), and the coefficient of consolidation. The purpose of this study was to determine how the soil consolidation process would change at different levels of salinity, given the effect ionic interactions would have on the soil's internal structure.

The hydromechanical behavior of the treated soil was evaluated through a series of complementary geotechnical tests. The degree of swelling was measured using a free-swelling oedometer. Pre-saturated samples were loaded directly into standard stainless-steel rings without vertical load. These samples were completely immersed in their corresponding saline solutions, and vertical swelling was recorded digitally to ±0.002 mm and continued until swelling stabilized. After achieving steady-state soil elevation, the coefficient of consolidation (Cg) was determined from the relative change in height between the initial and final states [20]. Subsequently, the soil's compressibility and corresponding compressibility pressure (Pc) were determined by conducting one-dimensional oedometer tests in accordance with ASTM D2435/D2435 M. The loadings for each test were adjusted at increasingly larger increments (12.5-25-50-100-200-400-800 kPa) [21]. Each loading was maintained until at least 95% of the primary consolidation had occurred, using the Taylor method to estimate when that point was reached. The plots of void ratio as a function of the logarithm of vertical loading provided the means to determine the pre-consolidation pressure (Pc) in accordance with the Casagrande method, as well as to estimate the compressibility index (Cc) by the slope of the normally consolidated portion of the void ratio versus the logarithm of the applied stress. Data acquisition used digital sensors with micrometer resolution to capture measurements and ensure data traceability. To assess the impact of NaCl in the soil on the shear strength of soil, direct shear box tests were performed to determine the cohesion (C) and internal friction angle (φ) for each sodium chloride concentration of the test soils. Shear strength was tested by subjecting each sample to multiple stages of normal stress in the shear box for each salt concentration. The shearing of the samples was performed at a constant rate according to ASTM Standard [16,22].

Each testing condition was replicated at least three times to verify the repeatability of the measured parameters. The reductions observed in cohesion and internal friction angle exhibited a consistent monotonic trend with increasing salinity. Subsequently, failure envelopes were determined to estimate Mohr-Coulomb parameters and systematically compare the effects of salinity on shear strength. The selected testing method is suitable for fine-grained soils, where the electrochemical properties of soil particles contribute significantly to the material cohesion [23,24]. This methodical approach would assess the cumulative effect of salinity on a suite of key geotechnical properties over a wide range of tested saline concentrations. Results from plasticity, compressive strength, consolidation, and shear testing are combined to provide a detailed understanding of the effect of NaCl on fine-grained soils and enable a complete comparison across the concentrations being studied. This methodology offers a suitable framework for accounting for the effect of saltwater on soils affected by marine intrusion during the site investigation phase of coastal structures and other infrastructure in coastal communities where salinization is a concern. The variability observed among replicate tests remained relatively small throughout the experimental program. Although error bars are not displayed for clarity, repeated measurements yielded consistent results, confirming the reliability of the observed salinity-dependent trends.

2.3.4. Soil Surface Charge and Electrical Double Layer

In an electrolytic solution, the distribution of ions around a charged particle is not uniform, giving rise to an electric double layer (Fig. 3). This simple representation of the interface between a charged particle and the ionic solution is provided by the Helmholtz model [25]. This model, shown in Figure 3, illustrates the distribution of ions at the interface, particularly in the region near the particle.

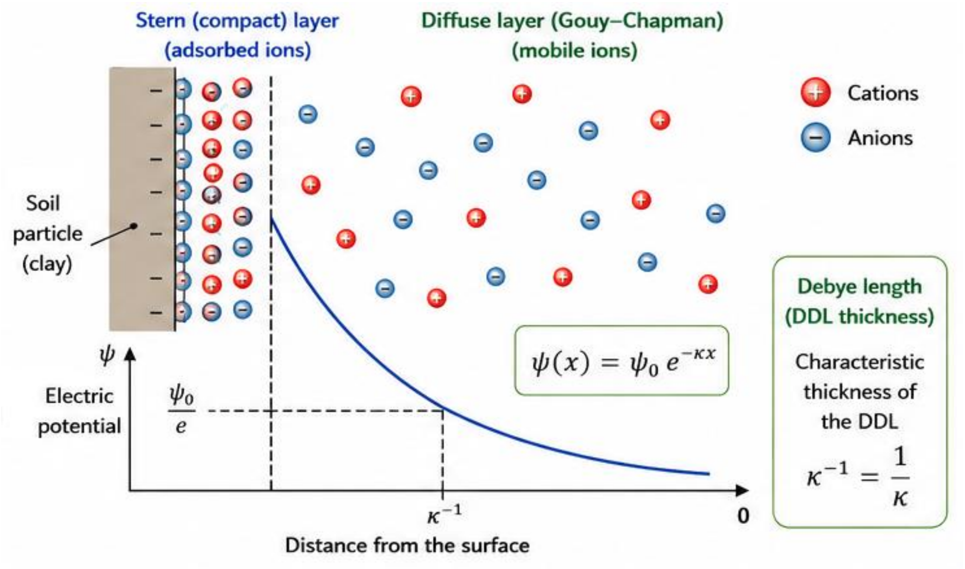

Fig. 3. Structure of the electrical double layer according to the Gouy-Chapman model

The potential difference between the solution and the particle is measured at the shear plane. This electric potential, called the zeta potential, is generally measured at the outer Helmholtz plane [25]. The thickness of the diffuse layer is represented by the Debye length (Eq. 1), k^{-1}, which depends on the chemistry of the solution. It is related to the ionic strength, I, by the following equation:

$$k^{-1} = \left(\frac{\varepsilon_0.\varepsilon_r.K_B.T}{2.e^2.N_A.I}\right)^{0.5} \tag{1}$$

Where ε_0, ε_r, e, N_A, K_B, T, and I are, respectively, the permittivity of free space (ε_0 = 8.854 × 10^{-12} F/m), the relative permittivity (ε_r = 78.4 for water at 20°C), the elementary charge, Avogadro's number N_A = 6.022×10^{23}, the Boltzmann constant (K_B = 1.38 × 10^{-23} J K^{-1}), absolute temperature (K), and the ionic strength. The latter is expressed as follows:

$$I = \frac{1}{2}\sum_{i} c_i \, . \, z_i^2 \qquad (2)$$

Where c_i and $\boldsymbol{z_i}$ are, respectively, the concentration of ions "$\boldsymbol{i}$" and the valence associated with those ions. The total concentration of the solution is the sum of the $\boldsymbol{c_i}$ values; it represents the salinity of the solution.

3. Results and Discussion

3.1. Effect on Consistency Limits

The relationship between salt concentration and the Atterberg limits for the soil in question (liquid limit "W_L"; Plastic limit "W_P"; Plasticity index "PI") has been illustrated in Figure 4. Results show that as salinity increases, soil consistency becomes highly sensitive to variations in salt concentration, as evidenced by changes in the physical and chemical interactions among fine particles and pore water. The increased salt concentration led to generally lower liquid limit values (W_L) across all samples; however, this trend became more pronounced with increasing salinity [1,3,10,13]. Overall, it appears that as the pore solution becomes more saturated with salts, a given soil transitions from a liquid state at lower amounts of water added (to produce a liquid mixture) compared to soil that has a less saline pore solution. The reduction in W_L values with increasing salinity can also be attributed to the compression of the diffuse double layer (DDL) surrounding clay mineral particles as ionic strength increases [3,9]. With an increase in dissolved ions, a portion of the negative charge on the clay sheet surface will be neutralized, reducing the thickness of the water film required for particle sliding and relative movement. For example, in saline environments, the transition to the liquid state occurs at a lower moisture level than in soils with lower salinity, indicating a reduction in the soil's water-attracting capacity.

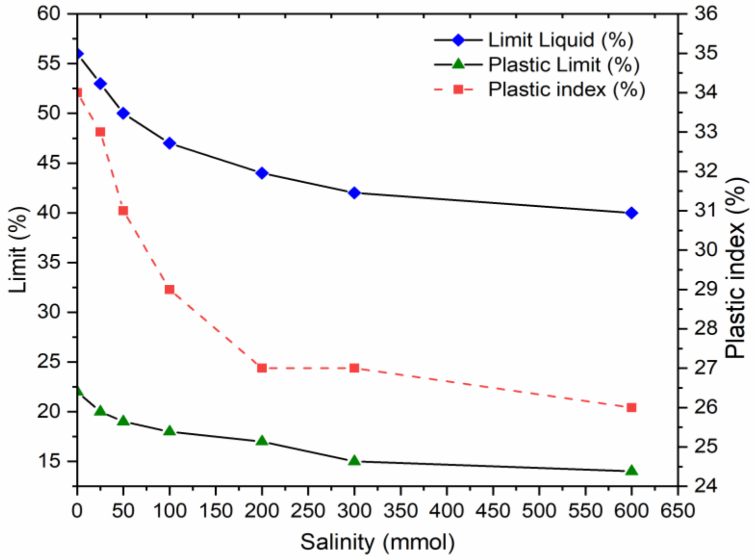

Fig. 4. Effect of salt water concentration on the liquid and plastic limits

The plasticity limit will also decrease, however, to a greater extent than the liquid limit; therefore, salinity affects the transition from the semi-solid to the plastic state less than the other two transitions. The decrease in the W_P limit results from a reduction in the amount of water associated with particles required to maintain minimal particle cohesion during soil shaping. Although W_P is less sensitive than W_L, the effects of salinity on soil fluidization mechanisms and the conditions that contribute to initial plasticity can be distinguished. With increasing salinity, the plasticity index (PI), defined as the difference between W_L and W_P, decreases substantially, and the range of plasticity within the soil becomes less pronounced [3]. Higher salinity conditions reduce plasticity due to aggregation and flocculation of the soil's fine particles. Electrostatic repulsions between particles are reduced, thereby enhancing their ability to aggregate and diminishing their capacity to accommodate large deformations due to fluid action. As soil moisture content varies, separation or fragmentation conditions will produce less pronounced plasticity than in the absence of salinity [6]. The relative consistency of fine soil is correlated with its PI levels and produces unpredictable outcomes with saline solutions compared to non-saline solutions. Furthermore, saline solutions alter soil properties, including its ability to retain moisture, and the behavior of fine soil by altering the nature of connections between individual fine soil particles. A reduction in soil plasticity is associated with enhanced physical and chemical stability [3]. A reduction in Atterberg limits indicates that the soil is less sensitive to water in saline environments; therefore, these materials are generally advantageous for construction projects, such as earthwork and subbase preparation. Furthermore, a decrease in the plasticity index may reduce soil deformation capacity and, thus, increase susceptibility to cracking under mechanical or hydraulic loads [7].

3.2. Variation of Compaction Characteristics with Salinity

Figure 5 shows that salinity clearly affects soil compaction parameters, including maximum dry density ($\gamma_{d,max}$) and optimum water content (w_{opt}). The results also indicate that although both parameters respond positively to increasing salt concentrations, they do so at different rates (opposite trends) depending on salinity level [10]. The overall trend shows an increase in $\gamma_{d,max}$ with increasing salinity, with the first phase characterized by little change in $\gamma_{d,max}$ at low salt concentrations. In other words, as the salinity increases, the solid particles are presented in a more ordered state when compacting. The compression of the diffuse double layer surrounding the clay particles is due to the increase in the number of ions in the soil (compared to that of pure water) [9]. With the increase in the number of ions in the pore solution, the electrostatic repulsive forces between clay particles decrease. This decrease causes the clay particles to be closer together, resulting in a more compact arrangement and denser packing. Also, as pore volume decreases, the soil's maximum dry density increases. At elevated salinity levels, the more stable structure of the solid skeleton accounts for the increase in $\gamma_{d,max}$, indicating that the soil's compaction capacity is greater when it contains salts. As salinity increases, optimum water content decreases nearly linearly.

The reduction in the amount of water required to achieve optimal soil compaction results from a decrease in the amount of water that can be adsorbed onto fine-particle surfaces in saline environments [10]. This occurs because the bound water layer around the grains decreases in thickness as the ionic strength of the pore solution increases, thereby reducing the water required to provide sufficient lubrication for the particles during compaction. The partial flocculation of particles due to dissolved salts creates a more open particle arrangement at the start of compaction, providing an opportunity for the particles to reorganize more easily and achieve their optimum state with less water, influenced by the applied compaction energy. In addition, the inverse relationship between $\gamma_{d,\,max,}$ and w_{opt} as a function of salinity indicates that the hydromechanical behavior of the soil has changed. A reduction in optimal water content with an increase in maximum dry density indicates a trend toward increased efficiency of compaction (Fig. 5). Furthermore, based on this fact, it can be inferred that the material's behavior is more dependent on the interactions between grains and water (physico-chemical) than on the energy applied during compaction [4].

The experimental results also show that not all geotechnical parameters exhibit the same sensitivity to salinity. Plasticity parameters exhibited very high sensitivity, as they depend directly on the physicochemical interactions between fine particles and water, as well as on the thickness of the diffuse double layer. In contrast, compaction characteristics showed relatively lower sensitivity, with dry density being primarily determined by particle rearrangement and geometric packing during compaction. Mechanical strength parameters such as uniaxial compressive strength (UCS), cohesion, angle of internal friction, and CBR exhibited moderate to high sensitivity, as they depend heavily on electrochemical interparticle bonds and microstructural integrity. The observed reduction in strength, therefore, reflects not only the effects of densification but also the progressive degradation of electrostatic attractive forces within the soil skeleton. Similar trends have been reported in previous studies of fine-grained saline soils, where salinity-induced flocculation resulted in denser but mechanically weaker structures due to reduced physicochemical cohesion. These comparisons confirm that saline environments induce coupled microstructural and mechanical alterations, with the relative influence of these alterations depending on the specific technical parameter under consideration. Thus, these data demonstrate that salinity affects soil structure; it modifies particle interactions and therefore directly affects implementation parameters [1]. Therefore, these data demonstrate that in saline environments, close control of the compaction water content is essential, as the optimal compaction water content decreases relative to similar content in non-saline environments [10]. Scientifically, these data demonstrate that to understand the results of Proctor tests and model fine soil behavior, it is necessary to include the physico-chemical effects associated with salinity [4].

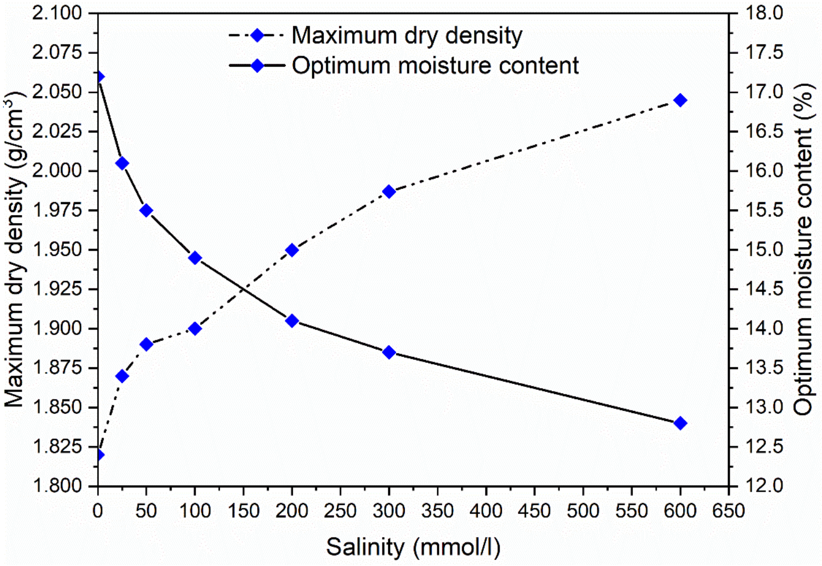

Fig. 5. Optimum Moisture Content and Maximum Dry Density versus salinity

Although salinity promotes denser particle packing and increases the $\gamma_{d,max}$ value, this densification does not necessarily imply an improvement in mechanical strength. The increase in dry density primarily reflects a geometric rearrangement of particles resulting from compression of the diffuse double layer. However, salt ions simultaneously reduce the electrostatic attractive forces and interparticle bonds that confer resistance to shear and penetration. Consequently, the soil becomes denser but mechanically weaker under loading conditions such as CBR penetration or shear stress. This apparent paradox highlights the distinction between compaction density and physicochemical cohesion in fine-grained saline soils.

3.3. California Bearing Ratio (CBR)

As illustrated in Figure 6, the CBR (California Bearing Ratio) of each tested soil sample varies with its corresponding salinity [10]. Progressive decreases in CBR with increasing salinity indicate a loss of bearing strength under saline conditions. When the soil has low salinity (0 to 25–50 mmol), there are still relatively high levels of CBR, indicating stable internal organization, as the particles remain tightly bonded to one another through cohesive forces, which provide enough resistance to maintain its structure and adequately resist penetration under applied loads (i.e., good bearing capacity) due to the moderate effects of dissolved ions. When salinity levels are intermediate (100-200 mmol), CBR values decrease. This effect can be attributed to the alteration in physicochemical properties associated with increased ion concentrations in pore water. The compression of the diffuse double layer surrounding fine aggregate particles, along with the effects of ion exchange and modifications in electrostatic forces, results in a decrease in the apparent cohesion of the soil and in the granular structure reorganizing toward a more degraded state, along with increased deformability of the material under loading [9]. CBR continues to decline at extreme salt levels (300 to 600 mM), though at a slower rate, suggesting that the material's degradation is becoming more stable. At this stage, the soil microstructure exhibits significant alteration: increased effective pore space, reduced inter-particle bond strength, and less responsive penetration resistance to further increases in salinity. The mechanical behavior of the soil will be more fragile, with reduced bearing capacity. Overall, the results suggest that increased salinity directly affects the CBR index, reducing bearing capacity. This trend is consistent with the microstructural mechanisms observed in saline environments, particularly the weakening of cohesive forces between fine particles and the gradual reorganization of the internal structure of the soil. The results indicate that salinity must be considered when designing pavements and geotechnical structures, particularly in saline environments or areas frequently exposed to salt-rich waters.

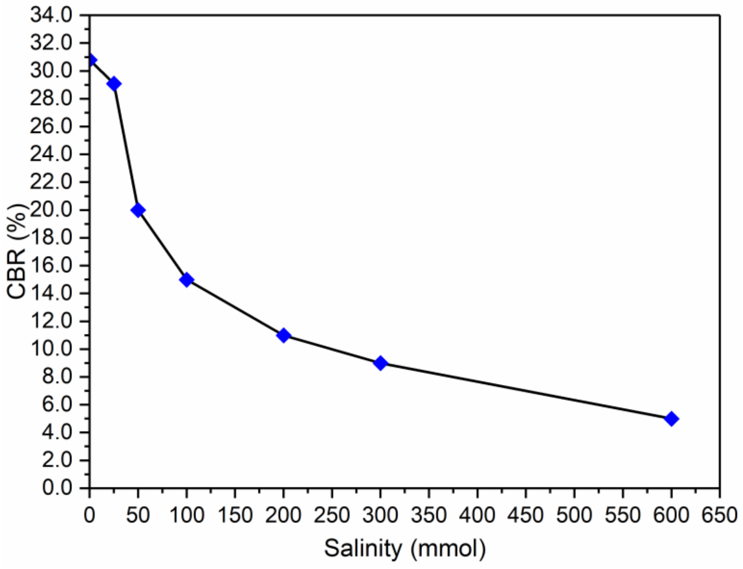

Fig. 6. Variation of CBR with Salinity

3.4. Unconfined Compressive Strength (UCS)

Variation of UCS (Unconfined Compressive Strength) with salinity (mmol) is depicted in Figure 7. UCS is strongly negatively correlated with salinity, indicating that the mechanical properties of the tested materials will continue to vary with the addition of soluble salts. Additionally, UCS was found to be consistent with a low salinity range (0-50 mmol) at approximately 210-180 kPa; therefore, it indicates a mild environmental condition that did not cause significant alterations to the material's internal structure. Minor differences in particle/particle interaction and matrix cohesion occurred, which enabled most of the high-strength properties of the materials to remain unchanged. At a medium salinity range (100-200 mmol), UCS decreased from 155 kPa to 135 kPa as salinity increased. This significant decrease in UCS can be attributed to an increase in the total ionic concentration in the pore solution, which disrupts the physicochemical balance of the material. In particular, the compression of the diffuse double layer around the solid particles, combined with ion exchange, reduces the cohesive forces between grains [5,9]. This reduction in cohesion yielded a decrease in the material's mechanical strength.

The UCS continues to decrease under high salinity (300 to 600 mmol). However, the rate of decrease becomes less evident, with a lesser slope. The strength ranges from 115 kPa to 95 kPa, indicating near-stabilization of the material against degradation. At this stage, the material's microstructure has already been extensively degraded: the effective porosity has increased, the physicochemical bonds within the material have been ruptured, and the overall load-bearing capacity of the material shows virtually no reaction to increasing salinity [26]. These observations provide strong evidence that salinity negatively affects the mechanical behavior of materials; specifically, that increases in salt concentration and the prior presence of salts in the material itself alter its microstructure, due to increased porosity, less organized matrix, and weakened solid-phase bonding between solid materials [5]. In addition, these changes will be reflected in measurable macroscopic changes in the material's compressive strength [18,26]. The results demonstrate the need to consider the effects of saline environments when working in aggressive environments.

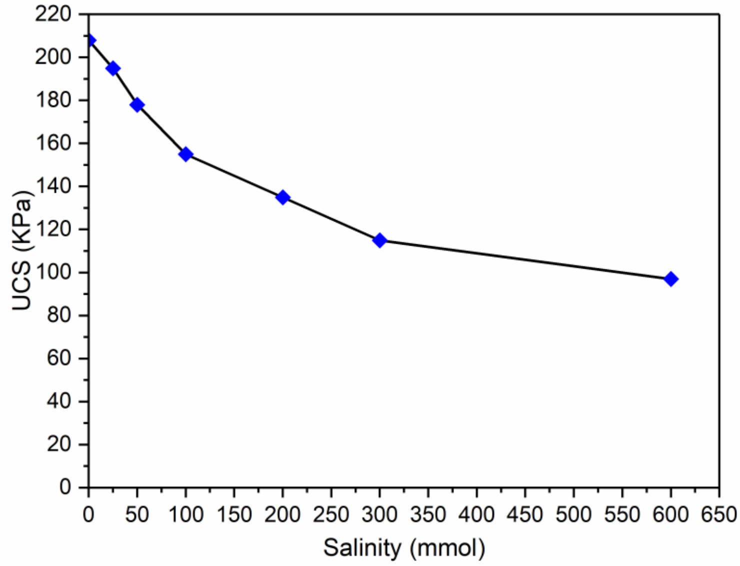

Fig. 7. Variation of unconfined compressive strength with salinity

In addition to microstructural changes, increased salinity also alters the osmotic component of total suction. The effective stress state can be influenced by osmotic suction according to the following formula:

$$\sigma' = \sigma - u_a - \pi \tag{3}$$

Where $\sigma^{'}$ is the effective stress, σ is the total stress, u_a pore air pressure, and π represents the osmotic pressure associated with dissolved ions in the pore fluid. Increasing salinity increases osmotic effects while simultaneously weakening electrostatic interparticle attractions, contributing to the observed reduction in UCS.

3.5. Effect of Salinity on Consolidation Characteristics of Soil

Figure 8 shows that the variation in salt concentrations within the pore solutions of the material studied have affected some of the most important features of the materials behavior when subjected to an external load (the index of virgin compression, the coefficient of compression and the coefficient of expansion) with all three variables showing a very clear correlation with each other and therefore demonstrate the significant change that the physico-chemical effects of higher saline pore solutions can produce in soils volume under one-dimensional loading [17]. These results illustrate a strong negative relationship between the virgin compression index and salinity, indicating a radical reduction in the material's deformability in an irreversibly compressed state at any given salt concentration.

The primary reason for the very low values of the virgin compression index (Cc) (Fig 8a) at high salinities can be attributed to an increase in ionic strength, which allows for effective ion-mutual cohesion between both the negatively charged sites on the surfaces of clay particles and the surrounding water in the diffuse double layer [9,16,21]. This will ultimately assist with enhancing the flocculation and/or agglomeration of the particles within the clay fraction(s) (finer). Therefore, as the material structure becomes increasingly rigid and stable, at a given applied vertical effective stress, there is less reduction in the void ratio under equivalent loads, leading to lower values of (Cc) than would normally occur [16]. Although both the pre-consolidation pressure (Pc) and the virgin compression index (Cc) decrease with increasing salinity, the rate at which the Pc value decreases is, in general, not as pronounced as for Cc. According to the collected data, there is a general reduction in soil compressibility across different loading methods (e.g., initial loading, consolidation, or rebounding) in saline environments [16]. This reduction in Pc (Fig. 8.c) illustrates that the flocculated structure induced by salt results in lower compressibility and greater resistance to volumetric deformation, due to the increased forces applied to the soil. As the load on the soil increases, the soil's response to changes in load is less pronounced, as evidenced by the reduction in the void ratio at a given load. The data suggest that increased salinity acts as a hardening agent in the soil, reducing its overall compressibility. There is a significant reduction in Cg with increasing salinity, demonstrating a substantial reduction in the soil's ability to recover its volume, whether after unloading or when saturated [17,21].

The reduction in Cg (Fig. 8 b) can be attributed to decreased water availability for adsorption onto fine soil particles in saline environments [16]. Additionally, due to compression of the diffuse double layer, the movement of water into the interlayer space between individual clay particles is restricted by the presence of salt. Therefore, shrink-swell processes are restricted [9]. More volumetric stability and less response to fluctuations in moisture content is indicated by soil's exhibiting a decrease of the Atterberg limits and plasticity index as well as from a geotechnical point of view, a decrease in primary settlement under static loads in saline environments as shown by a decrease in Cc and Pc; and a significant reduction in the incidence of swelling as evidenced by a decrease in Cg, which indicates increased stability and increased durability of structures; however, these beneficial effects are also influenced by the chemical stability of the environment [2]. Soil will reactivate compressibility and swelling mechanisms as progressive soil desalination reduces Cc, Pc, and Cg. In light of this, it is clear, from a scientific perspective, that Cc, Pc, and Cg do not represent constant properties inherent to the soil [21]. Their values depend on the physicochemical properties of the soil environment and should be considered when modeling the hydromechanical characteristics of fine-grained soils. The progressive flocculation induced by increasing salinity may also result in apparent over-consolidation. Indeed, particle aggregation and enhanced structural rigidity reduce compressibility and increase resistance to volumetric deformation, mimicking some features typically associated with over-consolidated fine-grained soils.

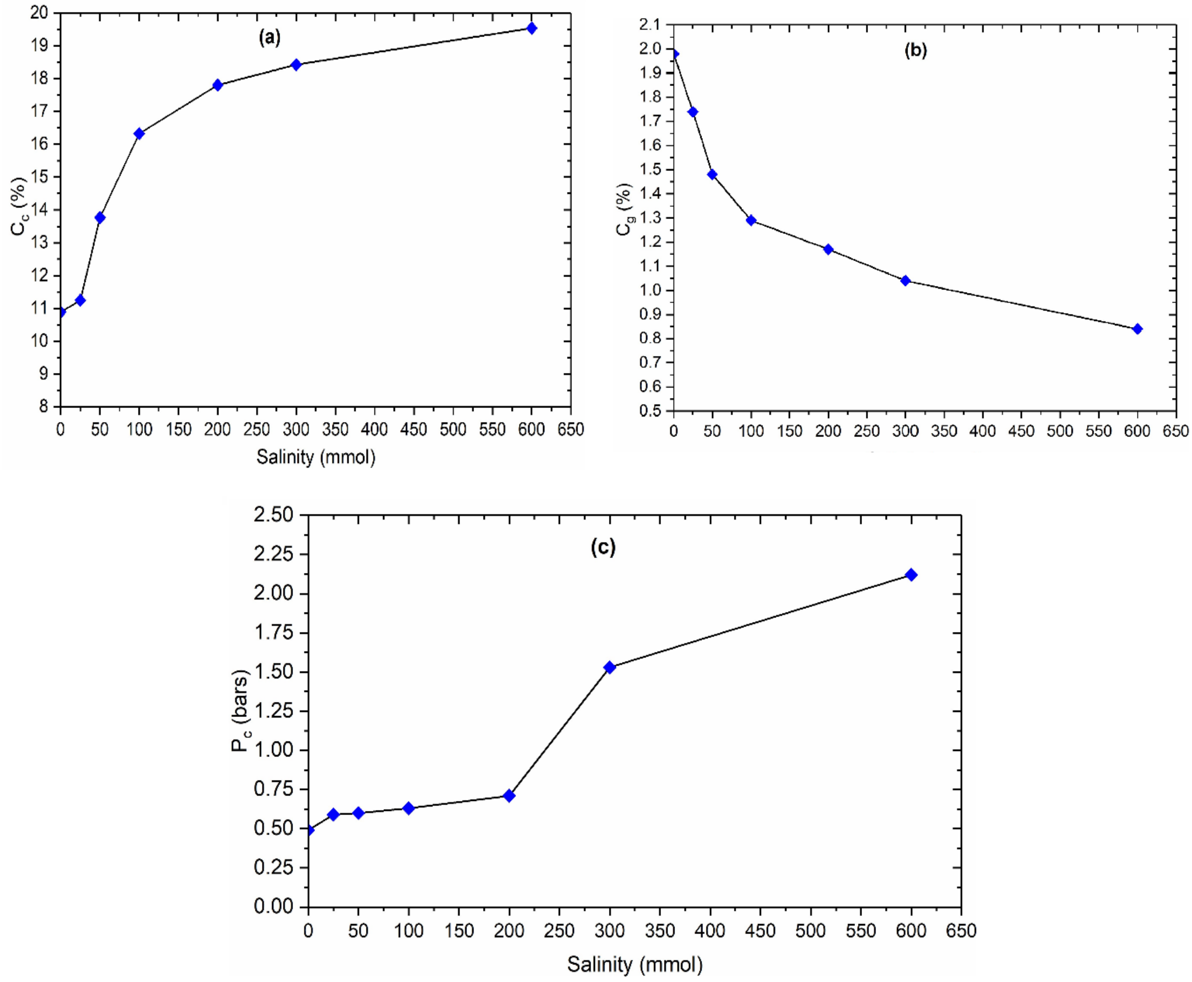

Fig. 8. Variation of oedometer parameters versus salinity: a) compression index Cc; b) coefficient of swelling Cg; and c) pre-consolidation pressure Pc

3.6. Shear Strength Parameters

Salinity has a major role in determining the soil shear strength parameters of the tested materials, as depicted in Figure 9. The angle of internal friction (φ) (Fig. 9a) and the cohesion (C) (Fig. 9b) of the soils progressively decrease with increasing salinity [19,26]. The results show a similar pattern to UCSs as salinity increases and indicate an overall degradation of the mechanical properties of the material. The angle of internal friction decreases almost continuously with increasing salinity, from an average of 29° at 0 salinity to approximately 14° at 600 mmol NaCl [8]. At low salinities (0-50 mmol), high φ values indicate good interlocking between grains and significant frictional resistance between grains. The granular structure remains intact and maintains a well-defined arrangement of the materials. At intermediate salinities (100 to 200 mmol), the ongoing decline in φ indicates that the effectiveness of inter-grain contacts continues to deteriorate. This evolution is attributed to changes in the physicochemical forces within the pore solution and also the disruption of the configuration of fine-grained materials, resulting in a decrease in the frictional component of overall resistance [26]. At salinities greater than 300 mmol, while φ continues to decrease slowly, this form of degradation indicates that an established microstructural state has been affected by high salinities, and these conditions are stabilized by prior exposure to similar salinity levels [4,26]. It is believed that, as a result of these unique physical characteristics, sliding resistance decreases, thereby affecting the stability of soils under shear loading.

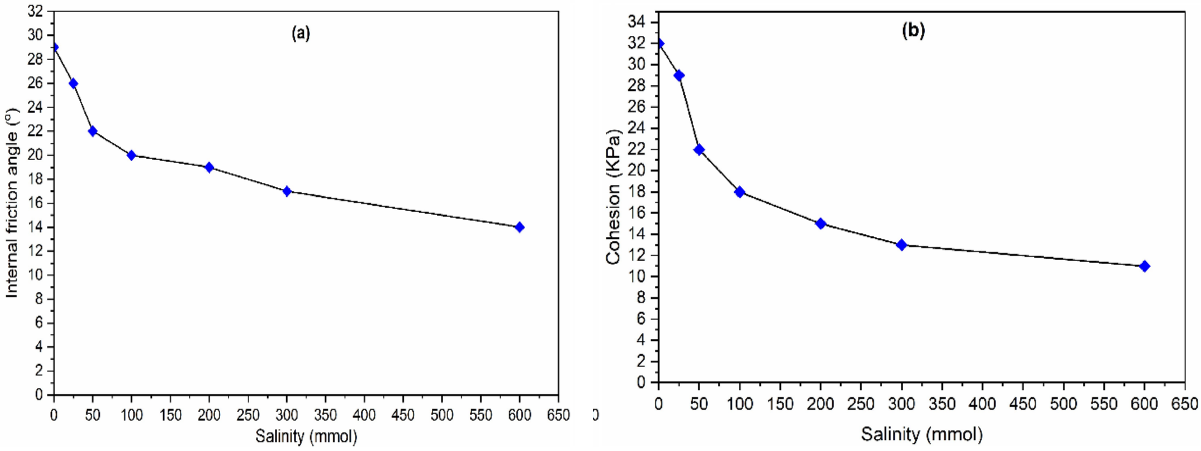

Fig. 9. Variation of shear strength parameters versus salinity: (a) Internal friction angle; and (b) Cohesion

Cohesion decreased from approximately 32 kPa at 0 mmol to approximately 11 kPa at 600 mmol, and while the angle of internal friction does not change very much at lower salinities (c values generally appear to be greater than 32 KPa as a result of increased apparent cohesion and due to both mechanical factors fine particles and electrostatic forces acting upon each particle, the same is not true for high salinity levels (lower apparent cohesion) due to the high concentration of ions found in the pore spaces of the soils at high salinity levels compressing the particle diffuse double layer [9]. This reduction in the thickness of the diffuse double layer directly reduces the intensity of electrostatic forces between clay particles and, consequently, the attractive forces between them. Partial neutralization of surface charges drastically decreases the interfacial cohesion and weakens the bond between components. At higher salinity levels, interfacial cohesion decreases and tends to stabilize at a constant value. This indicates that the overall soil structure is in an advanced state of degradation [26,27]. In addition, the remaining interfacial cohesive forces have also been reduced; therefore, there will be no further increases to interfacial cohesion resulting from continued salinization. The high sensitivity of the interfacial cohesive force to salinity suggests that the loss of soil strength is predominantly due to physicochemical mechanisms. There is a collateral trend in the reduction of φ and C, signifying that the overall shear strength has been reduced in the same manner [27]. The reduction in strength is affecting both the internal friction and cohesion components, thus subsequently altering the overall mechanical performance of the soil. Simultaneous reductions in both φ and C are common in fine-grain soils, especially in clay-rich soils, where physicochemical interactions are the primary influencing factors [26,27]. These changes are expressed at the macro level through significant reductions in shear parameters, which may reduce the stability of slopes and/or embankments; and/or shallow foundations in saline environments [8].

From a physicochemical perspective, the observed changes can also be explained by Gouy-Chapman's diffuse double-layer theory. Increased salinity reduces the Debye length, thereby compressing the diffuse double layer surrounding soil particles. This compression reduces electrostatic repulsion while promoting flocculation and particle aggregation. Consequently, the soil exhibits denser compaction but reduced electrochemical cohesion. Although quantitative estimates of the diffuse double-layer thickness were beyond the scope of this study, the experimental trends are consistent with classical models of the electrochemical behavior of soils. Overall, the experimental results indicate a very strong connection between the hydro-chemical-mechanical behavior of the fine-grained soil tested during saline conditions. The drop in plasticity index values of the Atterberg limits highlights the gradual compression of the diffuse double layer and the decline in the affinity between clay particles and the invading pore fluid. The drop in each property (UCS, CBR, cohesion, angle of friction) reflects interconnected events driven by the identical microstructural degradation mechanism induced by increased salinity. Conversely, the reduction in compressibility and swelling potential (flocculation) indicates that the density of the soil skeleton increases, as well as its fragility (less deformable, mechanically vulnerable). Therefore, the combined interpretation of plasticity, compaction, and consolidation, in addition to strength parameters, shows that salinity affects not only the density state of the soil but also the character of the inter-particle interactions that control the macro-engineering behavior of the soil.

3.7 Study Limitations

Although this study provides information on the influence of salinity on the geotechnical behavior of fine-grained soils, several limitations should be acknowledged. First, osmotic suction was not measured directly during the tests. Consequently, the contribution of osmotic effects was inferred from salinity variations and interpreted using established theoretical concepts rather than direct measurements. Second, the cation exchange capacity (CEC) of the soil under study was not determined. Since CEC strongly influences ion exchange mechanisms and electrochemical interactions between clay particles and the interstitial fluid, future studies should include CEC measurements to provide a more quantitative assessment of soil reactivity. Third, although XRD analysis and zeta potential measurements provide indirect indications of the compression of the diffuse double layer, no direct quantitative determination of its thickness was performed. Consequently, the proposed physicochemical interpretation remains partially qualitative. Future research combining suction measurements, CEC characterization, scanning electron microscopy, and advanced physicochemical analyses would contribute to a more comprehensive understanding of salinity-induced changes in soils.

4. Conclusion

This experimental study examines and highlights the influence of salt water on the geotechnical properties, compressive strength, and shear parameters of fine-grained soils. The results demonstrated that salinity significantly influences the stability of coastal structures. The conducted tests demonstrated that increasing salinity causes a progressive decrease in the Liquid Limit (W_L), Plastic Limit (W_P), and Plasticity Index (PI), reflecting a reduction in water affinity and the progressive compression of the diffuse double layer surrounding clay particles, which reduces the ability of fine-grained soils to hold moisture; as such, fine-grained soils are more open and less cohesive, with soil structure and, therefore, much more brittle and difficult to model. Also, fine-grained soils exhibit a decrease in Unconfined Compressive Strength with increasing saltwater content, indicating an overall reduction in Cohesion (or attraction) between soil particles. As such, the amount of saltwater will significantly impact the overall performance of fine-grained soils during their infrastructure application, especially when high concentrations of saltwater are used to model results, rendering them irrelevant to existing conditions. Furthermore, a noticeable decrease in shearing parameters, such as cohesion and the angle of internal friction, with increasing salinity suggests that the soil's internal structure has been compromised. The study shows that the cumulative effects of prolonged salinity exposure may become partially irreversible, depending on mineralogical composition, exposure duration, and hydro-chemical conditions, and that soil subjected to prolonged exposure to saline solutions will not regain its initial properties. This presents difficulties for the engineering field, given anticipated increases in sea level and saltwater intrusion. The information indicates that there is a considerable change in the mechanical properties at very moderate concentrations and should therefore be addressed in the design of infrastructure systems. Finally, it is concluded that salinity results in substantial alterations to the geotechnical characteristics of fine-grained soils and should therefore be included in geotechnical evaluations.

References

[1] Derdour, H. Angers, D.A. "Influence on salinity and other constituents on the mechanical behaviour of clay soils", Soil Technology, 5 (1), p. 39-46, 1992. https://doi.org/10.1016/0933-3630(92)90005-L

[2] Van Paassen, L.A. Gareau, L.F. "Effect of Pore Fluid Salinity on Compressibility and Shear Strength Development of Clayey Soils". In: Hack, R., Azzam, R., Charlier, R. (eds) Engineering Geology for Infrastructure Planning in Europe. Lecture Notes in Earth Sciences, 104., Springer, Berlin, Heidelberg, 2004. https://doi.org/10.1007/978-3-540-39918-6_39

[3] Campbell, N. Look, B and Atmadja, A. N. "An investigation into the effect of salt water on the geotechnical properties of a residual clay", Australian Geomechanics Journal. 44 (1), p. 19-28, 2009

[4] Ying, Z. Cui, Y-J. Benahmed, N. and Duc, M. "Salinity effect on the compaction behaviour, matric suction, stiffness and microstructure of a silty soil", Journal of Rock Mechanics and Geotechnical Engineering, 13 (4), p. 855-863, 2021. https://doi.org/10.1016/j.jrmge.2021.01.002.

[5] Pan, L. Liu, H. Qiu, W. et al. "Effects of Salinity and Curing Time on Compression Behavior of Fly Ash Stabilized Marine Clay" KSCE J Civ Eng, 27, p. 4141–4151, 2023. https://doi.org/10.1007/s12205-023-1674-8

[6] Abu zeid, M.M. Abd El-Aal, A.K. "Effect of salinity of groundwater on the geotechnical properties of some Egyptian clay", Egyptian Journal of Petroleum, 26 (3), p. 643-648, 2017. https://doi.org/10.1016/j.ejpe.2016.09.003.

[7] Yan, W.M. Chang, J. "Effect of pore water salinity on the coefficient of earth pressure at rest and friction angle of three selected fine-grained materials" Engineering Geology, 193, p.153-157. 2015. https://doi.org/10.1016/j.enggeo.2015.04.025.

[8] Geng, W. Han, W. Yin, J. et al. "Salinity effects on the strength and morphological indices of soft marine clay". Sci Rep. 12, 17563. 2022. https://doi.org/10.1038/s41598-022-22627-w

[9] Shen, J. Wang, Q. Chen, Y. Zhang, X. Han, Y. and Liu, Y. "Experimental investigation into the salinity effect on the physicomechanical properties of carbonate saline soil" Journal of Rock Mechanics and Geotechnical Engineering, 16 (5), p. 1883-1895. 2024. https://doi.org/10.1016/j.jrmge.2023.09.024.

[10] Li, M. Chai, S. Du, H. and Wang, C. "Effect of chlorine salt on the physical and mechanical properties of inshore saline soil treated with lime" Soils and Foundations. 56 (3), p. 327-335. 2016. https://doi.org/10.1016/j.sandf.2016.04.001.

[11] Deng, Y. Zhang, T. Cui, Y. Chen, Y. Deng, T. and Zhou, X. "Pore water salinity effect on the intrinsic compression behaviour of artificial soft soils", Applied Clay Science, 166, p. 299-306. 2018. https://doi.org/10.1016/j.clay.2018.09.027.

[12] Deng, Y.F. Yue, X.B. Cui, Y.J. Shao, G.H. Liu, S.Y. and Zhang, D.W. "Effect of pore water chemistry on the hydro-mechanical behaviour of Lianyungang soft marine clay" Applied Clay Science, 95, p. 167-175. 2014. https://doi.org/10.1016/j.clay.2014.04.007.

[13] Sridharan, A. EL-Shafei, A. and Miura, N. "Mechanisms Controlling the Undrained Strength Behavior of Remolded Ariake Marine Clays". Marine Georesources and Geotechnolog, 20, p. 21-50. 2002.

[14] Souileh, A. Mabrouk, A. Ouadif, L. and Hachmi, D. E. ''Analysis of the geotechnical and mineralogical characteristics of the Settat-Khouribga shale clay for potential civil engineering applications''. Research on Engineering Structures & Materials, 10, 4, p.1699–1716. 2024. https://jresm.org/article/resm2024-408ma0824rs/

[15] Taybi, A. Akacem, M. Moulay Omar, H. Bennacer, L. and Abdedaiem, L. ''Co-valorization of local materials tuff and red brick waste mixture for use in road construction''. Research on Engineering Structures & Materials, 12, 1, p. 535–547. 2025. https://jresm.org/article/resm2025-906ma0517rs/

[16] Mansouri, H. Jorkesh, Z. Ajalloeian, R. et al. "Investigating effects of water salinity on geotechnical properties of fine-grained soil and quartz in a sandstone case study: Ajichay project in northwest Iran". Bull Eng Geol Environ , 76, p. 1117–1128. 2017. https://doi.org/10.1007/s10064-016-0920-4

[17] Gaspar, T.A.V. Jacobsz, S.W. Heymann, G. Toll, D.G. Gens, A. and Osman, A.S. "The mechanical properties of a high plasticity expansive clay" Engineering Geology, 303, , 106647. 2022. https://doi.org/10.1016/j.enggeo.2022.106647.

[18] Li, H. and Yang, M. "Study on unconfined compressive strength and deformation characteristics of chlorine saline soil". Sci Rep. 14, 1478. 2024. https://doi.org/10.1038/s41598-023-50441-5

[19] Yin, J. Han, W-X. Xu, G-Z. Hu, M-M. and Miao, Y-H. "Effect of Salinity on Strength Behavior of Cement-treated Dredged Clay at High Initial Water Contents". KSCE Journal of Civil Engineering, 23 (10), p. 4288-4296, 2019. https://doi.org/10.1007/s12205-019-0695-9.

[20] Sarah, D. Hutasoit, L.M. Delinom, R.M. Sadisun, I.A. and Wirabuana, T. A. " Physical Study of the Effect of Groundwater Salinity on the Compressibility of the Semarang-emakAquitard, Java Island". Geosciences , 8,130. 2018. https://doi.org/10.3390/geosciences8040130

[21] Yin, J. Lu, Z. Geng, W. Han, W. and Hudu, A. A. "Effect of porewater salinity on compression behaviors and hydraulic conductivity of soft marine clay". Marine Georesources & Geotechnology, 40(7). p. 813–822. 2021. https://doi.org/10.1080/1064119X.2021.1941451

[22] Abdi, M. R. Ghalandarzadeh, A. and Chafi, L.S. "An investigation into the effects of lime on compressive and shear strength characteristics of fiber-reinforced clays" Journal of Rock Mechanics and Geotechnical Engineering, 13 (4). p. 885-898. 2021. https://doi.org/10.1016/j.jrmge.2020.11.008.

[23] Rouhanifar, M. Afrazi, M. Fakhimi, A. and Yazdani, M. ''Strength and deformation behaviour of sand-rubber mixture''. International Journal of Geotechnical Engineering, 15, 9, p.1078–1092. 2021. 10.1080/19386362.2020.1812193.

[24] Afrazi, M and Yazdani, M. ''Determination of the Effect of Soil Particle Size Distribution on the Shear Behavior of Sand''. Journal of Advanced Engineering and Computation, 5, 2, p.125–134. 2021. 10.25073/jaec.202152.331.

[25] Mahanta, K.K. Mishra, G.C. and Kansal, M.L. ''Estimation of the electric double layer thickness in the presence of two types of ions in soil water''. Applied Clay Science, 87, p.212–218. 2014. https://doi.org/10.1016/j.clay.2013.11.007.

[26] Yılmaz, B. and Türköz, M. "Determination of shear strength parameters of compacted high plasticity clay soils based on different laboratory tests". TUJE. 6(4). p. 313-319. 2022. 10.31127/tuje.1004043

[27] Qiu, K. Ding, L. Yu, W. Chen, K. Huang, S. and Gao, K. "Experimental Investigation of Shear Strength of Carbonate Saline Soil under Freeze-Thaw Cycles". Atmosphere. 13, 2063. 2022. https://doi.org/10.3390/atmos13122063