IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 49, No. 5, October, 2025, pp. 505-514
Journal homepage: http://iieta.org/journals/acsm

Synergistic Influence of Cement–Lime Stabilization on the Mechanical Properties and Mineralogical Changes of Sabkha Soils from Aïn M'lila

Meriem Kitchah[1*], Ouassila Bahloul[2], Assia Aidoud[3], Messaouda Bencheikh[3]

[1] Laboratory of Research Laboratory in Applied Hydraulics (LRHYA) and Civil Engineering Laboratory – Risks and Structures in Interactions (LGC-ROI), Department of Civil Engineering, Faculty of Technology, University of Batna 2 – Mostefa Ben Boulaïd, Batna 05000, Algeria
[2] Laboratory of Civil Engineering Laboratory – Risks and Structures in Interactions (LGC-ROI), Department of Civil Engineering, Faculty of Technology, University of Batna 2 – Mostefa Ben Boulaïd, Batna 05000, Algeria
[3] LGCH Laboratory, Department of Civil Engineering and Hydraulics, Faculty of Science and Technology, University 8 May 1945 Guelma, Guelma 24000, Algeria

Corresponding Author Email: o.bahloul@univ-batna2.dz

https://doi.org/10.18280/acsm.490506

Received: 20 August 2025
Revised: 14 October 2025
Accepted: 19 October 2025
Available online: 31 October 2025

Keywords:
sabkha soils, soil stabilization, collapse, CBR, UCS, XRD analysis, cement, lime

ABSTRACT

The sabkha soils of the Aïn M'lila region present major geotechnical challenges, including high salinity, significant gypsum and soluble salt contents, and low mechanical strength. To improve their geotechnical performance, this study evaluated the effectiveness of cement–lime stabilization at various mixing ratios. Mechanical tests, including compressibility, California bearing ratio (CBR), and unconfined compressive strength (UCS), were conducted to identify the optimal dosage. The 6/4% cement–lime mixture exhibited the best performance, showing a significant increase in bearing capacity and soil cohesion. Based on these results, an X-ray diffraction (XRD) analysis was carried out exclusively on this optimal mixture to examine the associated mineralogical transformations. The XRD results revealed a pronounced structural reorganization characterized by the formation of secondary carbonates and pozzolanic products (C-S-H and C-A-H), which contributed to matrix densification and improved mechanical resistance. Despite the persistence of certain evaporitic phases such as gypsum and halite, the 6/4% cement–lime mixture proved to be the most effective, confirming the suitability of this approach for the sustainable stabilization of sabkha soils.

1. INTRODUCTION

Sabkha soils represent a major geotechnical challenge in arid and semi-arid regions, particularly in North Africa and the Middle East, where climatic conditions are characterized by low rainfall and large seasonal temperature variations [1, 2]. Formed in topographic depressions subjected to intense evaporation, these soils exhibit high salinity, elevated gypsum and soluble salt contents, and a metastable structure that is highly sensitive to moisture fluctuations [3, 4]. The accumulation of salts in the upper horizons results from the upward capillary rise of groundwater followed by evaporation, leading to the formation of partially cemented saline crusts whose strength decreases significantly upon wetting due to salt dissolution and leaching [3, 5, 6].

In Algeria, sabkhas cover large areas, particularly in the High Plateaus and the North-East, where they constitute a major obstacle to infrastructure development [7, 8]. These soils generally consist of quartz sand and gypsums silt rich in sulfates, chlorides, and sodium, causing significant variations in density and consistency depending on moisture content. They are characterized by high compressibility and a strong collapse potential, resulting from a porous and weakly cemented structure [9]. Such chemical and structural properties explain their poor mechanical stability and high sensitivity to saturation, making pre-treatment essential before any construction work. Recent studies have highlighted the importance of addressing these challenges, emphasizing the assessment of foundation performance on collapsible soils [10] and the need for precise seismic characterization of both coastal and inland sabkhas [11].

To overcome these limitations, several researchers have investigated stabilization using hydraulic binders such as cement and lime, which are recognized for their technical efficiency and economic feasibility [12-20]. Cement quickly generates hydration products (C-S-H and C-A-H) that provide initial rigidity, while lime promotes flocculation of fine particles and triggers long-term pozzolanic reactions, enhancing soil cohesion and durability [14, 17, 18]. Recent research, such as that of Benrebouh et al. [18], examined the effect of sulfate-resistant cement on saline sabkha subgrade soils, including in the Aïn M'lila region, confirming the relevance of these binders in aggressive environments [18, 19].

Furthermore, the exploration of more environmentally friendly solutions, such as geopolymer treatment, is highlighted as a promising alternative to traditional binders for improving the bearing capacity of sabkha soils [21].

However, the effectiveness of combined cement–lime treatment applied to highly saline sabkha soils remains insufficiently studied, particularly concerning the interactions between chemical mechanisms and the reduction of collapse potential [4, 6].

In this context, the present study aims to evaluate the combined effect of cement and lime on the mechanical and chemical properties of sabkha soil from Aïn M'lila (North-Eastern Algeria). Compressibility, CBR, and unconfined compressive strength (UCS) tests were performed to determine the optimal formulation, followed by X-ray diffraction (XRD) analysis to interpret the mineralogical mechanisms responsible for the observed improvements.

2. MATERIALS AND METHODS

2.1 Sample preparation

The soil investigated was collected from the Aïn M'lila region, located in northeastern Algeria, near Lake Mzouri (Sabkha El Zemoul) along the national road NR3 (Figure 1). From a geotechnical standpoint, the soil exhibits a predominantly silty texture, consisting of 57% silt, 36% sand, and 3% clay (Figure 2), classifying it as low-plasticity clayey silt (CL) according to the unified soil classification system (USCS) [22] and as category A2 under the French Road Engineering Design Guide (GTR). The Atterberg limits indicate low plasticity (WL = 34.7%, PI = 16.92%), while the Standard Proctor test performed according to standard P94-050 [23] yielded a maximum dry density of 19.11 kN/m³ and an optimum moisture content of 11.40%.

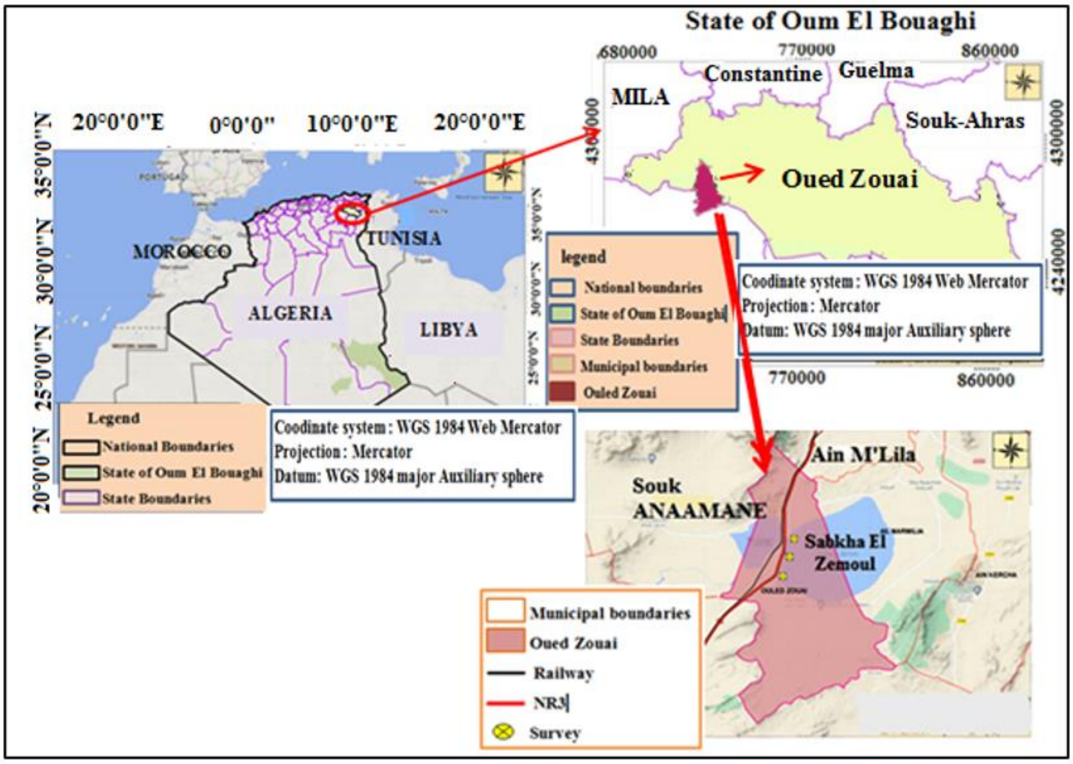

Figure 1. Location of the studied sabkha soil

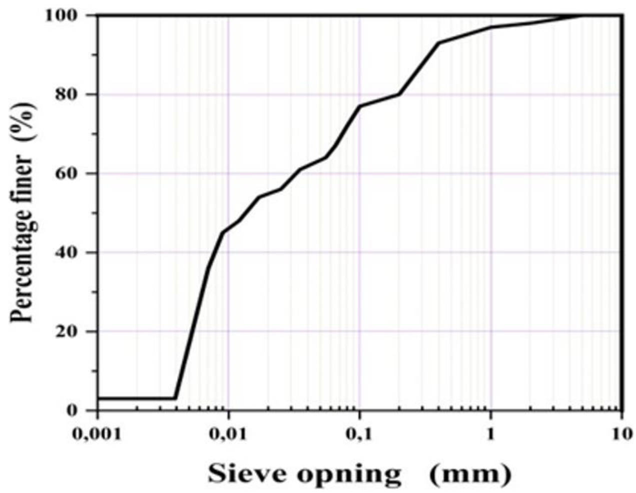

Figure 2. Particle size distribution curve of the studied sabkha soil

Figure 3. Sabkha soil from the Aïn M'lila region

Morphologically, the sabkha surface is characterized by the presence of saline crusts and visible salt crystals, formed through evaporation and upward capillary rise processes. These surface saline deposits, clearly observable in Figure 3, are indicative of intense evaporative activity and directly influence moisture distribution and suction behavior within the unsaturated zone.

The cement used in this study was a Portland composite cement (CPJ-CEM II/A 42.5) produced locally at the Aïn Touta plant (Batna, Algeria). The lime was sourced from the M'Sila region and corresponds to a high-purity hydrated lime ($CaO \approx 83\%$, $SiO_2 < 2\%$).

2.2 Test and procedure

Laboratory mechanical tests, including compressibility, unconfined compressive strength (UCS), and California bearing ratio (CBR), were performed on sabkha soil specimens. In this study, the collapse potential (CP) of the soil was determined using the double oedometer test proposed by Jennings and Knight [24], which compares the settlement of two identical specimens one tested in its natural state and the other pre-saturated or moistened.

The samples were prepared in molds measuring 60 mm in diameter and 20 mm in height, and then extracted using an oedometer ring of 50 mm × 19 mm through lateral trimming followed by ring insertion (Figure 4). The upper surface of each specimen was coated with a thin layer of petroleum jelly to prevent moisture loss during testing.

$$C_p\,(\%) = \left[\frac{\Delta_e}{1+e_0}\right] \times 100 \tag{1}$$

where,

- Cp = Collapse potential
- Δe = e1 − e2
- e1 = void ratio before flooding
- e2 = void ratio after flooding
- e0 = initial void ratio

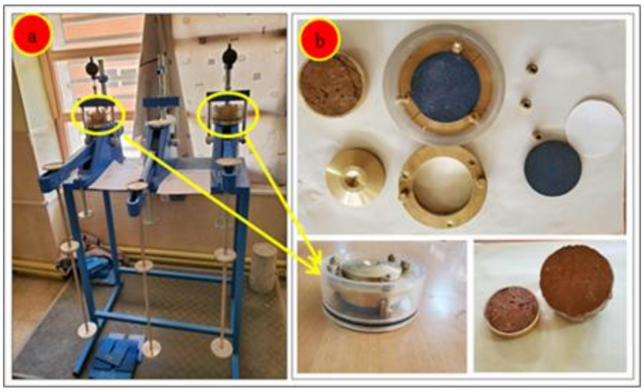

Figure 4. Compressibility test apparatus

The California bearing ratio (CBR) tests were performed in accordance with standard NF P94-078 [25]. The dry soil was mixed with the amount of water corresponding to the optimum moisture content obtained from the Proctor test. The samples were compacted in Proctor molds (152 mm × 127 mm) in three layers and then soaked for four days prior to testing. The CBR values were determined at penetrations of 2.5 mm and 5.0 mm under a loading rate of 1.27 mm/min (Figure 5).

Figure 5. CBR test apparatus

Figure 6. UCS test apparatus

The unconfined compressive strength (UCS) tests were conducted according to ASTM D2166 [26] and the procedure described by Kafodya and Okonta [27]. The dry soil was mixed with water at the optimum moisture content and sealed for two hours before molding. Cylindrical specimens (37.5 mm × 75 mm) were statically compacted in four layers at a rate of 1.27 mm/min, with surface scarification between layers to ensure proper bonding and homogeneity (Figure 6).

Chemical analyses were carried out to characterize the chemical condition of the sabkha soil by measuring pH, electrical conductivity (EC), gypsum content ($CaSO_4 \cdot 2H_2O$), and chloride content (NaCl). The experimental program, based on LCTP procedures and the Calcich–Frühling standard [23], focused on determining the insoluble fraction, sulfates, chlorides, and carbonates. Ground and sieved samples were subjected to acid digestion (10% HCl), followed by filtration, drying, and titration of the filtrate with silver nitrate (N/10) using potassium chromate as an indicator. The gypsum concentration was determined from the precipitate formed with barium chloride ($BaCl_2$). Salinity was assessed by measuring the electrical conductivity of a 1:5 soil-to-water extract at 25°C using an Inolab-Cond conductimeter, while pH was measured on a 1:2.5 extract, following standard procedures reported in the literature [28].

Finally, X-ray diffraction (XRD) analyses were performed on the cement–lime-treated sabkha soil samples to identify the mineralogical changes induced by stabilization. The measurements were conducted using a Rigaku MiniFlex 600 diffractometer (Kα wavelength = 1.5406 Å, voltage = 40 kV, current = 15 mA). The diffraction data were processed using HighScore Plus software, allowing the identification of dominant crystalline phases and evaluation of the efficiency of the chemical stabilization reactions.

3. RESULTS AND DISCUSSION

The chemical analysis of the Sabkha soil from Aïn M'lila (Table 1) highlights a high salinity level (EC = 16.33 mS/cm; salinity = 10.45 g/L) and a slightly basic pH (7.49), indicating a neutral to alkaline environment that favours carbonate precipitation. The high contents of soluble salts, particularly gypsum (6.07%) and chlorides (2.35%), confirm the evaporitic and gypsiferous nature of this material.

Table 1. Physical, chemical, and mechanical parameters of the sabkha soil Ain M'lila

Sabkha Soil			
Mechanical and Geotechnical Characteristics		**Chemical Characteristics**	
Optimal water content w_{opt} (%)	11,40	EC (mS/cm)	16,33
Dry density γ_d (kN/m^3)	19,11	Salinity (g.l^{-1})	10,451
Liquidity limit LL (%)	34,70	PH	7,49
Plasticity limit PL (%)	17,78	Gypsum rate	6,072
Plasticity Index PI (%)	16,92	Chloride level	2,352
Fine passers-by <80µ (%)	68	Soluble salt content in the 1/5 extract (mg. l-1)	
Fine passers-by ≤ 2mm	98	Na^+	2323
Percentage of gravel (%)	4	K^+	50
Percentage of sand (%)	36	Ca^{+2}	391,2
Percentage of silt (%)	57	Mg^{+2}	156,5
Percentage of clay (%)	3	HCO_3^-	10
Uniformity coefficient	9	Cl	3585
Curvature coefficient	0,51	SO_4^-	4704
Classification of Sabkha Soil Ain M'lila			
Classification GTR		A2	
Classification according to the Unified Soil Classification System (USCS)		CL (low plasticity clayey silt)	
Classification according to the US Salinity Laboratory (USSL)		saline-alkali soil	

The ionic analysis of the 1/5 extract reveals a predominance of sulfate (SO_4^{2-} = 4704 mg/L), chloride (Cl^- = 3585 mg/L), and sodium (Na^+= 2323 mg/L) ions, accompanied by calcium (Ca^{2+}= 391.2 mg/L), indicating a mixed chloride–sulfate salinity with sodium dominance. The high sodium adsorption ratio (SAR) further supports the classification of the material as a saline–alkaline soil according to the US Salinity laboratory (USSL) system [29].

These chemical properties increase the soil's sensitivity to moisture variations and explain its weak structural stability, thereby justifying the use of combined cement–lime treatment to improve cohesion and reduce the expansive behavior of the soil [30-33].

The pH and electrical conductivity (EC) are key indicators for assessing the stabilization of sabkha soils rich in soluble salts and sodium. The analysis of the different cement/lime dosages applied to the Aïn M'lila soil (Figure 7) shows a significant increase in pH, from 7.49 to values ranging between 12.3 and 12.6, due to the hydroxides released by cement and lime, which promote pozzolanic reactions [33-35].

In parallel, the EC increases from 16.33 mS/cm in the natural state to values between 24 and 29.2 mS/cm depending on the dosage, indicating a substantial release of polyvalent cations (Ca^{2+}, Mg^{2+}) that enhance soil flocculation and cohesion [3, 36, 37]. These variations confirm that maintaining a high pH and increasing electrical conductivity create an alkaline and ionically active environment, favorable to chemical stabilization and to the long-term durability of the material [38].

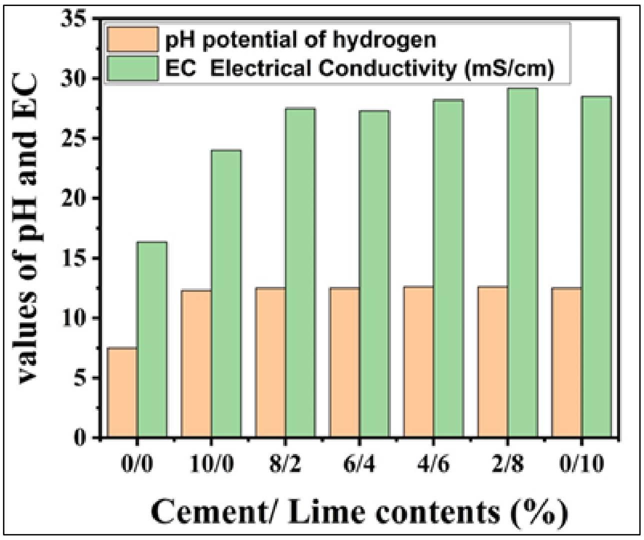

Figure 7. Electrical conductivity and potential of hydrogen of sabkha soil treated

3.1 Influence of cement/lime treatments on collapsibility

The study of the collapsibility of the sabkha soil treated with cement and lime aims to evaluate the effectiveness of the treatment in reducing both collapse potential and compressibility. Cement acts through the formation of cementitious products (C-S-H) that ensure a rigid bonding between particles, while lime promotes flocculation and structural stabilization. Their combination induces a microstructural reorganization that reduces voids and enhances mechanical strength.

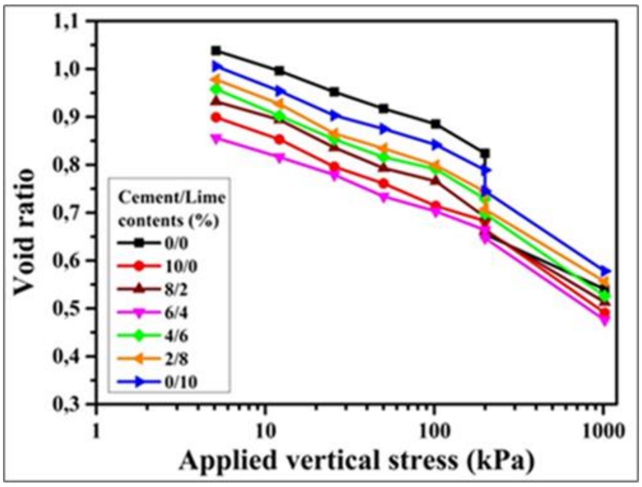

Figure 8. Evolution of the void ratio (e) as a function of the logarithm of vertical stress for different cement/lime dosages

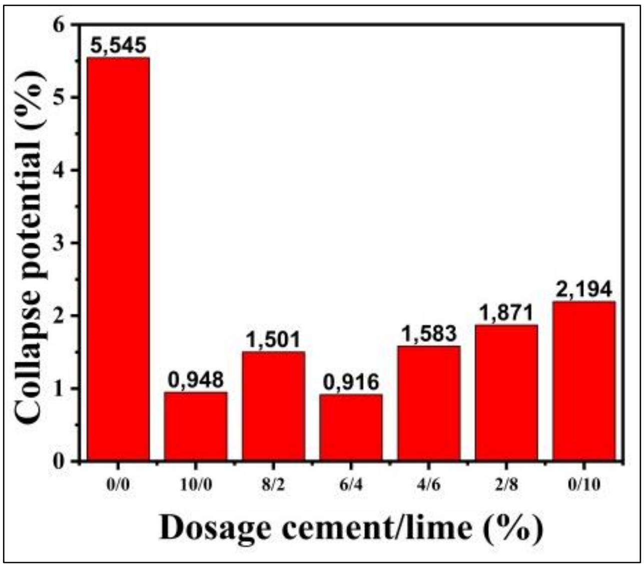

Figure 9. Influence of cement–lime dosage on the collapse potential of Aïn M'lila sabkha soil

The oedometer test results (Figure 8) show a clear improvement in the behaviour of the stabilized soil: the untreated soil (0/0) exhibits the highest void ratio and strong compressibility, confirming its highly deformable nature [39]. In contrast, mixtures with higher binder contents, particularly 10/0 and 6/4, display lower and less steep curves, indicating increased stiffness and a significant reduction in deformation [3].

Figure 9 illustrates the collapse potential as a function of the cement/lime dosage. The untreated soil (0/0) shows a very high collapse potential (5.6), typical of saline and porous soils [39]. The addition of hydraulic binders leads to a marked decrease in this potential, with the 6/4 mixture reaching a minimum value of around 0.9, classifying it among non-collapsible soils, while the 10/0 mixture also performs effectively. This reduction results from cementation and pozzolanic reactions forming products (C-S-H, C-A-H) that bind particles together and fill the voids, creating a rigid skeleton resistant to salt dissolution and to the breakdown of intergranular bonds under the effect of water [17, 32, 33, 40].

3.2 Influence of cement–lime stabilization on the soaked California bearing ratio (CBR) of sabkha soil

The CBR test results (Figure 10) show a significant improvement in the bearing capacity of the sabkha soil after stabilization. The natural soil exhibits an initial CBR value of 15.44%, indicating very low strength. The addition of cement alone (10/0) increased this value to 58.76%, corresponding to an improvement of +280.5%. The cement–lime mixture (6/4%) achieved the best performance, with a CBR value of 83.83%, representing an increase of +442.89% compared to the untreated soil. Mixtures with high lime content, such as 2/8 and 0/10, showed more modest improvements, with values of 25.21% and 21.76%, respectively, indicating the lower effectiveness of lime when used alone.

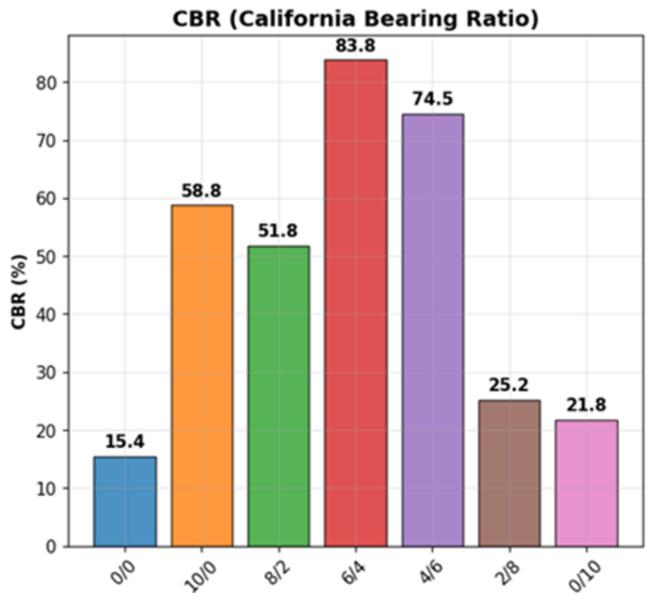

Figure 10. Effect of adding cement/lime on the CBR index

This trend confirms that the combined action of cement and lime, in a balanced proportion, promotes more complete pozzolanic and carbonation reactions, leading to improved cohesion and increased densification of the sabkha soil matrix [41].

3.3 Effect of cement–lime stabilization on the unconfined compressive strength of sabkha soil

The unconfined compressive strength (UCS) test results (Figure 11) show a significant increase in soil strength with both curing time and binder content. The natural sabkha soil (0/0) exhibits very low strength, reflecting its weak and unconsolidated structure. The addition of cement alone (10/0) leads to a rapid improvement, reaching approximately 1300 kPa after 90 days.

The cement–lime mixture (6/4%) demonstrates the best performance, with UCS values ranging between 1500 and 1600 kPa after 90 days, indicating a clear synergistic effect between cement hydration and the pozzolanic reactions of lime. This combination promotes the formation of C-S-H and C-A-H gels, which strengthen internal bonds, reduce porosity, and consolidate the soil matrix.

Mixtures richer in lime (2/8 and 0/10) exhibit lower strength and slower development due to reduced early-age reactivity [18, 19]. Overall, UCS values progressively increase from 7 to 90 days, confirming the continuation of hydration and carbonation processes. These results demonstrate that the 6/4% cement–lime ratio provides an optimal balance between initial strength and long-term durability, making it the most effective formulation for stabilizing sabkha soil.

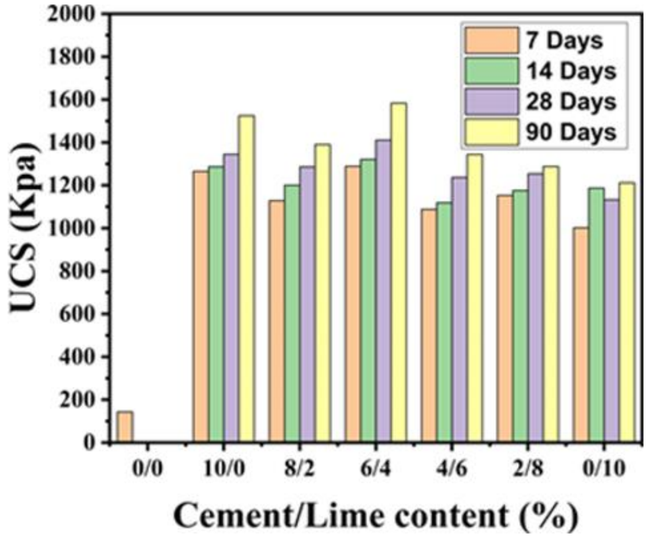

Figure 11. Effect of cement and lime addition on the UCS of sabkha soil

4. MINERALOGICAL EVOLUTION OF SABKHA SOIL BEFORE AND AFTER STABILIZATION AT THE OPTIMAL (6/4%) DOSAGE

Based on the mechanical test results (compressibility, CBR, and UCS), the 6/4% cement–lime mixture was identified as the most effective dosage for stabilizing the sabkha soil. To examine the mineralogical transformations responsible for this improvement, X-ray diffraction (XRD) analysis was performed on both the natural soil and the sample treated with this optimal dosage.

4.1 Mineralogical evolution of sabkha soil before stabilization

The results obtained from the chemical and X-ray diffraction (XRD) analyses of the untreated sabkha soil show a good agreement between the chemical composition and the mineralogical content of the studied material. The XRD quantification (Figure 12) revealed that calcium carbonates (calcite: 25%, magnesium calcite: 15%) correlate well with the chemical data, showing a high concentration of soluble calcium (Ca^{2+} = 391.2 mg/L) and a slightly basic pH (7.49), conditions favorable for the precipitation and stability of carbonate phases in the sabkha environment [42]. The gypsum content detected by XRD (≈ 15%) is consistent with the chemical determination (6.072%), considering that XRD quantifies total crystalline gypsum while chemical analysis may partially dissolve amorphous or poorly crystallized sulfate phases. This mineral, typical of evaporitic environments, forms under high concentrations of sulfates (SO_4^{2-} = 4704 mg/L) and calcium, promoting its crystallization during capillary evaporation [43].

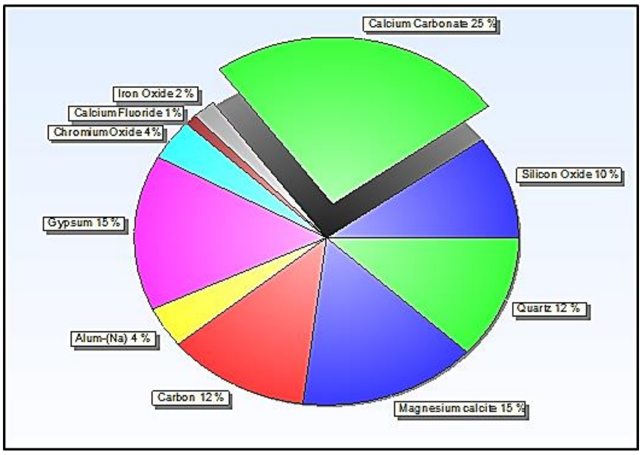

Figure 12. Mineralogical composition of sabkha soil

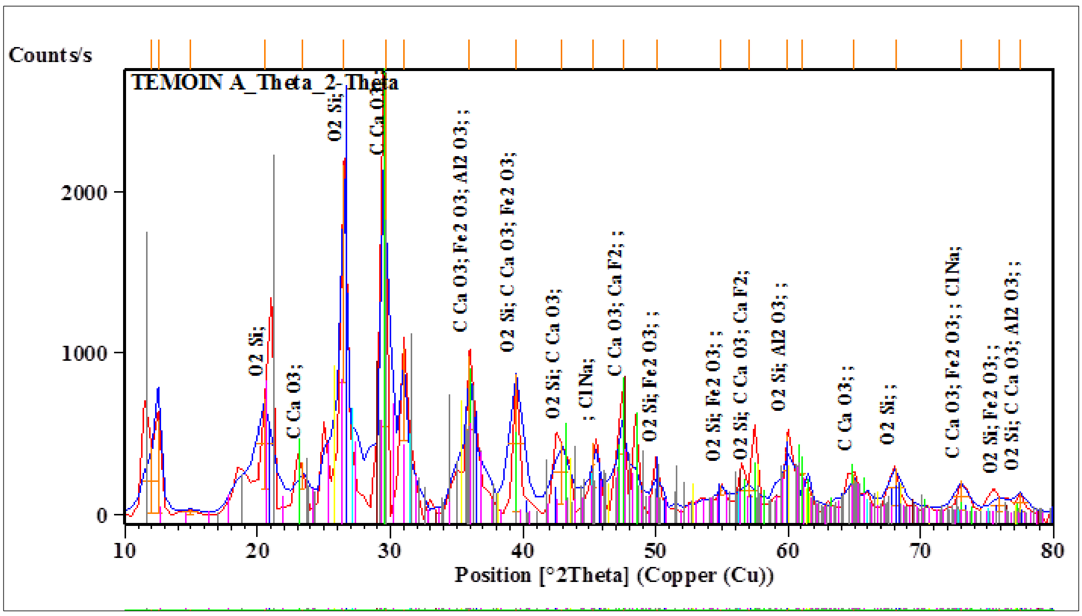

Figure 13. X-ray diffraction diffractogram of sabkha soil

Moreover, traces of halite (NaCl) were identified around 31.7° 2θ (Figure 13), confirming the presence of chlorides (Cl^- = 3585 mg/L) measured chemically. These soluble minerals (gypsum and halite) explain the weak structural stability of the sabkha soil, as their dissolution upon wetting leads to a rapid loss of cohesion and a collapse of the granular framework [43]. Quartz (12%) and amorphous silicates (10%) were also identified, consistent with the sandy-silty texture observed in the geotechnical cores.

Overall, the integration of physicochemical and mineralogical analyses highlights the complexity of the untreated sabkha soil, characterized by unstable saline and evaporitic phases responsible for its low mechanical strength and collapsible behavior. These findings confirm the necessity of prior stabilization treatment before any geotechnical or construction application [32, 33].

4.2 Mineralogical evolution of sabkha soil after stabilization at the optimal (6/4%) dosage

Figure 14 clearly reveals that the sabkha soil treated with a 6/4% cement–lime mixture undergoes a profound mineralogical reorganization, confirming the effectiveness of this formulation for both mineralogical and chemical stabilization of the material. The substantial increase in calcium carbonate content (from 40% in natural soil to 30.7% in treated soil, as main phase) can be directly related to the carbonation reactions promoted by the high pH environment (> 12) created by cement and lime dissolution [36, 44, 45]. The chemical analysis showing elevated calcium concentrations (Ca^{2+} = 391.2 mg/L initially) provides the necessary ions for carbonate precipitation according to the reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

The persistence of gypsum at a relatively high level (28.7%) deserves particular attention. Although the absolute gypsum content measured by XRD remains substantial, the chemical equilibrium analysis reveals important interactions: the sulfate ions (SO_4^{2-} = 4704 mg/L) initially present can react with calcium aluminate phases from cement hydration to form ettringite ($3CaO•Al_2O_3•3CaSO_4•32H_2O$), particularly under wet conditions [7, 46]. While ettringite was not clearly identified in the present XRD analysis, likely due to its poor crystallinity at this curing, its potential formation represents a long-term concern for treated sabkha soils, as it can cause delayed expansive behavior.

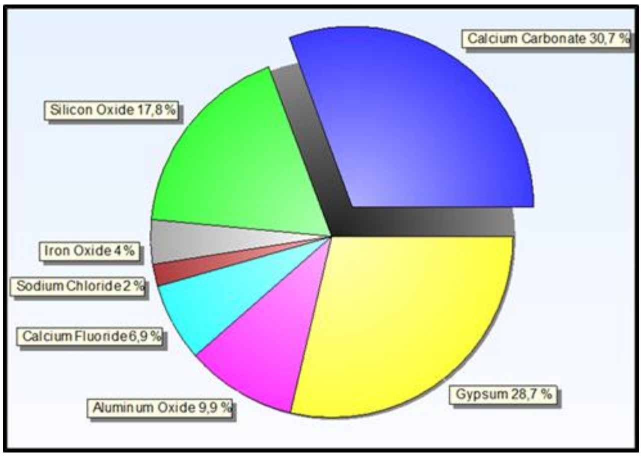

Figure 14. Mineralogical composition of sabkha soil treated with cement/lime (6/4%)

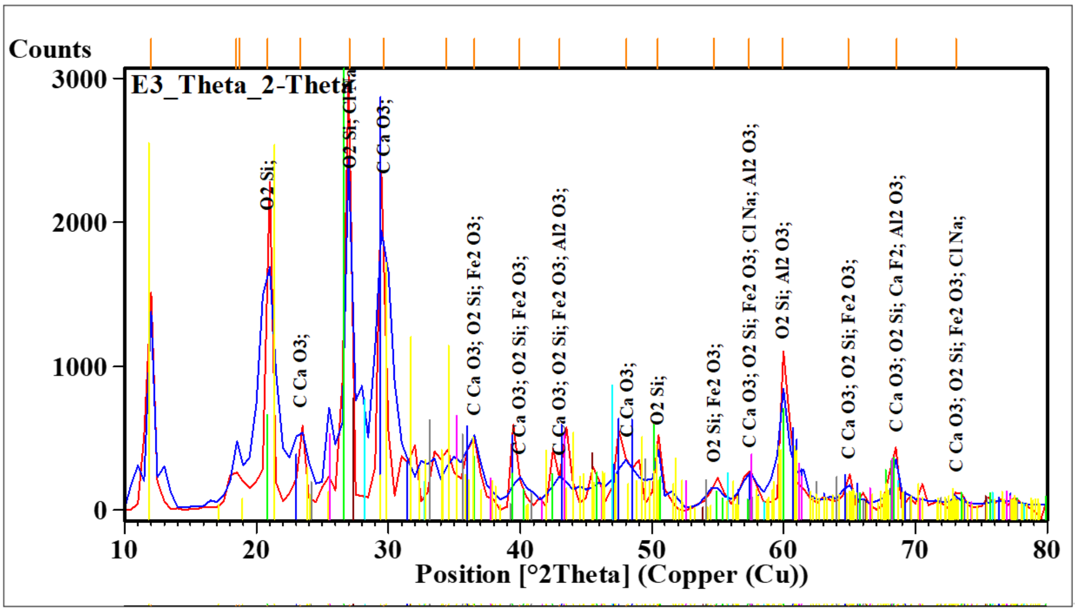

Figure 15. X-ray diffraction diffractogram of sabkha soil treated with cement/lime (6/4%)

In parallel, the significant reduction in halite peaks (from distinct presence to 2% residual content) (Figure 15) confirms the partial dissolution and consumption of chloride salts during the hydration process. This evolution is consistent with the measured decrease in free chloride mobility, as evidenced by the stabilization of electrical conductivity after an initial increase phase

Regarding cementitious products, the marked increase in silica (17.8%) and alumina (9.9%) detected by XRD indicates active pozzolanic reactions between lime-derived $Ca(OH)_2$ and reactive silicates/aluminates present in the soil matrix. These reactions produce calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which act as binding agents between soil particles.

$$Ca(OH)_2 + SiO_2 \left(reactive\right) \rightarrow C - S - H \ (gel) \quad (3)$$

$$Ca(OH)_2 + Al_2O_3 \left(reactive\right) \rightarrow C - A - H \ (gel) \quad (4)$$

Although these hydration products exhibit low crystallinity and broad XRD peaks that make precise quantification difficult [47-50], their presence is indirectly confirmed by:

• The reduction in free lime content,

• The increase in matrix density observed in compressibility tests,

• The substantial strength gains measured in UCS tests (1500-1600 kPa at 90 days) [3].

Both carbonation and pozzolanic reactions consume free lime, reducing long-term risks of lime leaching and contributing to matrix densification.

The synergistic effect between cement hydration (rapid C-S-H formation) and lime pozzolanic reactions (long-term C-S-H and C-A-H development) explains the optimal performance of the 6/4% mixture, combining early strength with sustained durability.

The correlation between XRD findings and chemical measurements thus demonstrates that mineralogical reorganization is driven by coupled processes:

•Carbonation reactions favored by alkaline pH,

•Pozzolanic reactions consuming reactive silica and alumina,

•Partial stabilization of sulfate phases through ettringite formation pathways, albeit with potential long-term implications that warrant monitoring under field conditions [51].

5. CONCLUSION

This study assessed the effectiveness of combined cement–lime stabilization on highly saline sabkha soil from Aïn M'lila (North-Eastern Algeria). The results demonstrated that the 6/4% cement–lime mixture was the optimal formulation, providing the most significant improvements among all tested dosages. Mechanically, the treatment led to a substantial increase in bearing capacity, with the CBR rising by 442.89% (from 15.44% to 83.83%), and a remarkable enhancement in unconfined compressive strength, reaching 1500-1600 kPa after 90 days of curing. In parallel, the collapse potential decreased sharply from 5.6 to 0.9, effectively reclassifying the soil as non-collapsible.

Mineralogically, XRD analyses confirmed the formation of secondary carbonates and cementitious products (C-S-H and C-A-H), which contributed to the densification of the soil matrix and to the observed mechanical improvements. The significant reduction in halite content and the persistence of gypsum highlight the dual effect of stabilization: enhanced structural integrity but also potential risks of delayed ettringite formation under moisture fluctuations. Chemical–mineralogical correlations showed that high alkalinity (pH > 12), increased electrical conductivity and pozzolanic reactions jointly controlled the mineral phase transformations, illustrating the synergistic contribution of cement hydration and lime reactivity.

From an engineering perspective, the cement–lime treatment—particularly at the 6/4% dosage—appears to be a reliable and cost-effective method for improving sabkha soils, especially for road platforms and foundation embankments. However, due to the persistence of sulfate-bearing phases, long-term monitoring under wetting–drying cycles is recommended to ensure the durability of stabilized layers.

REFERENCES

[1] Abbas, H.O. (2012). Improvement of sabkha soil by using geomesh and addition of polycoat. Engineering and Technology Journal, 30(4): 568-576. https://doi.org/10.30684/etj.30.4.4

[2] Akili, W., Torrance, J.K. (1981). The development and geotechnical problems of sabkha, with preliminary experiments on the static penetration resistance of cemented sands. Quarterly Journal of Engineering Geology and Hydrogeology, 14(1): 59-73. https://doi.org/10.1144/GSL.QJEG.1981.014.01.05

[3] Al-Amoudi, O.S.B. (2002). Characterization and chemical stabilization of Al-Qurayyah sabkha soil. Journal of Materials in Civil Engineering, 14(6): 478-484. https://doi.org/10.1061/(ASCE)0899-1561(2002)14:6(478)

[4] Hafhouf, I., Abbeche, K. (2023). Impact of drying-wetting cycles on shear properties, suction, and collapse of Sebkha soils. Heliyon, 9(2): e13594. https://doi.org/10.1016/j.heliyon.2023.e13594

[5] Arifuzzaman, M.D., Habib, M.A., Al-Turki, M.K., Khan, M.I., Ali, M.M. (2016). Improvement and characterization of sabkha soil of Saudi Arabia: A review. Jurnal Teknologi (Sciences & Engineering): 78(6). https://doi.org/10.11113/jt.v78.5352

[6] Al-Amoudi, O.S.B., Abduljauwad, S.N. (1995). Compressibility and collapse characteristics of arid saline sabkha soils. Engineering Geology, 39(3-4): 185-202. https://doi.org/10.1016/0013-7952(95)00016-9

[7] Benrebouh, I., Douadi, A., Hafhouf, I., Merdas, A., Meguellati, A. (2024). Transformative effects of salinity on Sebkha soil properties: Unveiling strength, structure, and stability through advanced remediation strategies. Journal of Architectural and Engineering Research, 7: 60-70. https://doi.org/10.54338/27382656-2024.7-06

[8] Abbas, H.O. (2012). Effect of adding fine gravel and cement on settlement of sabkha soil. Engineering and Technology Journal, 30(1): 87-97. https://mail.uotechnology.edu.iq/tec_magaz/2012/volum302012/No.01.2012/Text%20(8).pdf.

[9] Jennings, J.E.B., Burland, J.B. (1962). Limitations to the use of effective stresses in partly saturated soils. Géotechnique, 12(2): 125-144. https://doi.org/10.1680/geot.1962.12.2.125

[10] Elsawy, M., Lakhouit, A., Alhmari, T.S., Abdelmeguid, H., Shaban, M. (2025). Performance assessment of a foundation resting on reinforced collapsible sabkha soil by deep soil mixing columns using machine learning analyses. Alexandria Engineering Journal, 118: 591-605. https://doi.org/10.1016/j.aej.2025.01.047

[11] Eleslambouly, A., Ali, M.Y., El‐Husseiny, A., Al‐Shuhail, A.A., Bouchalaa, F., Hanafy, S.M., Matsushima, J. (2025). Seismic properties of coastal and inland sabkhas: Implications for static corrections. Earth and Space Science, 12(9): e2024EA003813. https://doi.org/10.1029/2024EA003813

[12] Al-Alawi, H.S., Ganiyu, A.A., Badr, A. (2020). Stabilisation of Sohar's sabkha soil using waste gypsum

plasterboard. IOP Conference Series: Materials Science and Engineering, 849(1): 012028. https://doi.org/10.1088/1757-899X/849/1/012028
[13] Aiban, S., Asi, I., Al-Amoudi, O. (1995). Stabilization of ras al-ghar sabkha soil with lime. In the Fourth Saudi Engineering Conference (Vol. 2).
[14] Asi, I.M. (2001). Stabilization of Sebkha soil using foamed asphalt. Journal of Materials in Civil Engineering, 13(5): 325-331. https://doi.org/10.1061/(ASCE)0899-1561(2001)13:5(325)
[15] Al-Amoudi, O.S.B., Asi, I.M., EI-Naggar, Z.R. (1995). Stabilization of an arid, saline sabkha soil using additives. Quarterly Journal of Engineering Geology and Hydrogeology, 28(4): 369-379. https://doi.org/10.1144/GSL.QJEGH.1995.028.P4.06
[16] Nasr, A.M. (2015). Geotechnical characteristics of stabilized sabkha soils from the Egyptian–Libyan coast. Geotechnical and Geological Engineering, 33(4): 893-911. https://doi.org/10.1007/s10706-015-9872-x
[17] Alshenawy, A.O., Alsanabani, N.M., Alnuaim, A.M. (2022). Cyclic behavior of cement-stabilized sabkha soil. Arabian Journal of Geosciences, 15(8): 700. https://doi.org/10.1007/s12517-022-09968-6
[18] Benrebouh, I., Hafhouf, I., Douadi, A., Merdas, A., Marathe, S. (2025). Effect of sulfate resistance cement treatment on saline soil (Sebkha) subgrades. Indian Geotechnical Journal, pp. 1-19. https://doi.org/10.1007/s40098-024-01156-5
[19] Benrebouh, I., Douadi, A., Hafhouf, I., Merdas, A., Meguellati, A., Del Serrone, G., Moretti, L. (2025). Experimental and statistical analysis of soil stabilization to avoid landfilling. Acta Polytechnica, 65(2): 143-154. https://doi.org/10.14311/AP.2025.65.0143
[20] Al-Rawas, A.A., Hago, A.W., Al-Sarmi, H. (2005). Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Building and Environment, 40(5): 681-687. https://doi.org/10.1016/j.buildenv.2004.08.028
[21] Hamid, W., Alnuaim, A. (2023). Evaluation of the durability and strength of stabilized sabkha soil with geopolymer. Case Studies in Construction Materials, 18: e02051. https://doi.org/10.1016/j.cscm.2023.e02051
[22] Garc, A., Frankenstein, S. (2015). USCS and the USDA soil classification system: Development of a mapping scheme.
[23] NF P94-093. Determination of compaction reference value of soil type-standards proctor test-modified proctor test. https://www.boutique.afnor.org/fr-fr/norme/nf-p94093/sols-reconnaissance-et-essais-determination-des-references-de-compactage-du/fa185491/43924, accessed on Mar. 23, 2024.
[24] Jennings, J.E., Knight, K. (1975). A guide to construction on or with materials exhibiting additional settlement due to collapse of grain structure. 1: 99-105. http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCALGEODEBRGM7720382974.
[25] NF 94-078. Sols-Reconnaissance et essais-Indice CBR apres immersion-Indice CBR immédiat-Indice Portant immédiat-Mesure sur échantillon compacté dans le moule CBR, https://www.boutique.afnor.org/fr-fr/resultats?Keywords=%5B25%5D%09NORME%2C+N.%2C+94-078&StandardStateIds=1.
[26] ASTM, D. (2016). 2166; Standard test method for unconfined compressive strength of cohesive soil. ASTM International: West Conshohocken, PA, USA.
[27] Kafodya, I., Okonta, F. (2018). Density control method for compression test of compacted lime-flyash stabilised fiber-soil mixtures. MethodsX, 5: 848-856. https://doi.org/10.1016/j.mex.2018.04.010
[28] Pansu, M., Gautheyrou, J. (2006). Fractionation of the colloidal systems. In Handbook of Soil Analysis: Mineralogical, Organic and inorganic Methods, pp. 65-82. https://doi.org/10.1007/978-3-540-31211-6_3
[29] Staff, U.S.L. (1954). Diagnosis and improvement of saline and alkali soils. Agriculture Handbook, 60: 83-100. https://books.google.dz/books?hl=fr&lr=&id=KP8_AAAAIAAJ&oi=fnd&pg=PA3&dq=+Diagnosis+and+improvement+of+saline+and+alkali+soils.+Agriculture+Handbook,+60:+83-100&ots=hgAhw56tiF&sig=4g24aqCK9ArmY4LA7opUzUWRnzg&redir_esc=y#v=onepage&q&f=false.
[30] Richards, L.A. (1954). Diagnosis and improvement of saline and alkali soils (No. 60). US Government Printing Office.
[31] Rhoades, J.D., Kandish, A., Mashali, A.M. (1992). The use of saline waters for crop production. FAO Irrigation and Drainage Paper, 48(133): 198.
[32] Bell, F.G. (1996). Lime stabilization of clay minerals and soils. Engineering Geology, 42(4): 223-237. https://doi.org/10.1016/0013-7952(96)00028-2
[33] Sherwood, P. (1993). Soil stabilization with cement and lime.
[34] Bhattacharja, S., Bhatty, J. (2003). Comparative performance of Portland cement and lime stabilization of moderate to high plasticity clay soils. Portland Cement Association, 2066: 60-67. https://www.cement.org/wp-content/uploads/2024/08/rd125.pdf.
[35] Zhang, Y., Daniels, J.L., Cetin, B., Baucom, I.K. (2020). Effect of temperature on pH, conductivity, and strength of lime-stabilized soil. Journal of Materials in Civil Engineering, 32(3): 04019380. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003062
[36] Mathieu, C., Pieltain, F., Jeanroy, E. (2003). Analyse chimique des sols: Méthodes choisies, pp. 408. Tec & doc.
[37] Moretti, L., Natali, S., Tiberi, A., D'Andrea, A. (2020). Proposal for a methodology based on XRD and SEM-EDS to monitor effects of lime-treatment on clayey soils. Applied Sciences, 10(7): 2569. https://doi.org/10.3390/app10072569
[38] Ghobadi, M.H., Abdilor, Y., Babazadeh, R. (2014). Stabilization of clay soils using lime and effect of pH variations on shear strength parameters. Bulletin of Engineering Geology and the Environment, 73(2): 611-619. https://doi.org/10.1007/s10064-013-0563-7
[39] Al-Khafaji, A.W., Andersland, O.B. (1992). Geotechnical engineering and soil testing (pp. xiv+-695). Saunders College Pub. https://www.researchgate.net/profile/Amir-Al-Khafaji/publication/322011747_Solutions_Manual_-_Geotechnical_Engineering_and_Soil_Testing/links/5a6cc716aca2722c947de81e/Solutions-Manual-Geotechnical-Engineering-and-Soil-Testing.pdf.
[40] Mubaraki, M. (2019). Improving road construction on sabkha soil by using lime stabilization and groundwater table monitoring. Journal of Testing and Evaluation,

47(3): 1935-1948. https://doi.org/10.1520/JTE20180273
[41] Fiener, Y. (2023). Stabilization of sabkha soil using cement kiln dust (CKD). Journal of Pure and Applied Sciences, 22(2): 18-21. https://doi.org/10.51984/jopas.v22i2.2509
[42] Lal, R., Shukla, M.K. (2004). Principles of Soil Physics. CRC Press.
[43] Van der Watt, H.V.H., Claassens, A.S. (1990). Effect of surface treatments on soil crusting and infiltration. Soil Technology, 3(3): 241-251. https://doi.org/10.1016/0933-3630(90)90004-M
[44] Al-Amoudi, O.S.B. (1995). Soil stabilization and durability of reinforced concrete in sabkha environments. In Proceedings of 4th Saudi Engineering Conference, 2: 313-338.
[45] Lei, B., Fu, P., Wang, X., Ni, W., et al. (2023). The hydration mechanisms of co-stabilization saline soils by using multiple solid wastes. Processes, 11(9): 2679. https://doi.org/10.3390/pr11092679
[46] Al-Homidy, A.A., Dahim, M.H., Abd El Aal, A.K. (2017). Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust. Journal of Rock Mechanics and Geotechnical Engineering, 9(4): 749-760. https://doi.org/10.1016/j.jrmge.2016.11.012
[47] Wild, S., Tasong, W.A. (1999). Influence of ground granulated blastfurnace slag on the sulphate resistance of lime-stabilized kaolinite. Magazine of Concrete Research, 51(4): 247-254. https://doi.org/10.1680/macr.1999.51.4.247
[48] McCartney, J.S., Zornberg, J.G. (2010). Effects of infiltration and evaporation on geosynthetic capillary barrier performance. Canadian Geotechnical Journal, 47(11): 1201-1213. https://doi.org/10.1139/T10-024
[49] Alshibli, K.A., Abu-Farsakh, M., Seyman, E. (2005). Laboratory evaluation of the geogauge and light falling weight deflectometer as construction control tools. Journal of Materials in Civil Engineering, 17(5): 560-569. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:5(560)
[50] Chindaprasirt, P., Kampala, A., Daprom, P., Jitsangiam, P., Horpibulsuk, S. (2021). Role of fly ash on strength properties of rejuvenated soil cement for pavement materials. Civil and Environmental Engineering, 17(2): 583-596. https://doi.org/10.2478/cee-2021-0059
[51] Boualla, N., Adjdir, M., Benziane, A., Bendraoua, A. (2019). Estimating generalized of global impacts to water quality on soil characteristics in basin of the Great Sebkha of Oran. Applied Water Science, 9: 4. https://doi.org/10.1007/s13201-018-0861-0

OMENCLATURE

PH	Potential hydrogen
EC	Electrical conductivity mS/cm
CP	Collapse potential
CBR	California Bearing Ratio
UCS	Unconfined Compressive Strength
XRD	X-ray diffraction