Heliyon 9 (2023) e13594

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Impact of drying-wetting cycles on shear properties, suction, and collapse of sebkha soils

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ARTICLE INFO

Keywords:
Compacted sebkha soil
Drying-wetting cycles
Salinity
Collapsibility
Suction
Shear strength

ABSTRACT

Sebkha soils are known as saline formations that was rencontred generally in arid and semi-arid regions. With the alternation of drying-wetting cycles (D-W) these soils present variable morphological and geotechnical properties. These cycles D-W have an important effect on the mechanical behavior of sebkha soils which poses enormous problems for the construction of structures in general. In this study, compacted sebkha soil samples from Ain M'Lila, Algeria were subjected to three D-W cycles based on the natural drying process to reach the targeted water contents of 13, 11.4, 7 and 4%, in a laboratory environment. For each of these water contents, laboratory tests were conducted to study the effect of the D-W cycles on the collapse potential Cp, suction, and shear strength of the soil. The results obtained showed that the three components of suction, i.e., total, matric, and osmotic suctions decreased when the number of D-W cycles increased. Moreover, the collapse potential Cp increased with an increase in the number of D-W cycles. Moreover, the results obtained illustrated that the shear strength parameters were affected by the number of D-W cycles a significant decrease in cohesion and an increase in the internal friction angle were observed when the number of D-W cycles was increased. Finally, a correlation was found between the soil salinity and the three factors studied these were affected by the decrease in salinity under the effect of D-W cycles.

1. Introduction

Sebkha soils are generally located in arid and semi-arid regions. These soils are defined as saline soils exhibiting a high salinity. The latter is considered an environmental threat [1,2]. Sebkha soils are not suitable for supporting infrastructure without the risk of high settlement and/or bearing capacity failure [3]. These soils are heterogeneous and variable in their mechanical and geotechnical properties; the latter properties depend on the type and amount of salt present in the soil. According to Ying et al. [4], only dissolved salts affect the thermo-hydro-mechanical behavior of soils, while precipitated salts can be considered as solid materials. These salts are generally calcium carbonate ($CaCO_3$), gypsum ($CaSO_4{\cdot}2H_2O$), and halite (NaCl) [3,5–10]. These salts govern the behavior of the upper layers of sebkha soils knowing that these layers exhibit firm and stiff characteristics in their dry state. When these sebkha soils change to their wet state due to precipitation (rain, snow), the upper layers of sebkha become weak in terms of bearing capacity [9,11,12].

However, most studies on the mechanical behavior of unsaturated saline or unsalted soils have focused on the unconfined compressive strength (UCS), collapse, and suction. The studies of Rao and Revanasiddappa [13] and Rahardjo et al. [14] were devoted to the examination of the collapse of residual soils. These authors showed that the porous structure of the soil was caused by the

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https://doi.org/10.1016/j.heliyon.2023.e13594
Received 21 June 2022; Received in revised form 25 January 2023; Accepted 3 February 2023

leaching of certain types of soil minerals, during which water and air replaced the soluble minerals, resulting in a very high void rate. Ayeldeen et al. [15] defined collapse-prone soils as those with an abrupt volume reduction after flooding. They defined the collapse potential as the percentage of the volume change from the applied vertical stresses before and after saturation. Several studies have been conducted to examine and identify factors affecting soil collapse. Barden et al. [16] considered engineered fills compacted to less than the optimum Proctor moisture content to be susceptible to collapse [17,18]. noted that soil collapse occurs when the dry density and initial moisture content are low. Other factors can influence the collapse of soils, such as mineralogy, applied stress, degree of saturation, and the nature of cementitious agents [19,20]. According to Tang et al. [21] and Ying et al. [4] shallow soils are exposed to D-W drying-wetting cycles, which significantly affect the mechanical behavior of partially saturated soils. In general, saline soils are exposed to D-W cycles. With the alternation of these D-W cycles these soils are considered variable in terms of chemical, physico-chemical and mechanical characteristics. The D-W cycles affected the UCS, shear strength, compressibility, and collapse of these soils. Hafhouf et al. [10]; Hu et al. [22]; Tang et al. [21] and Zhang et al. [23] clearly demonstrated the effect of D-W cycles on the UCS, which decreases with an increasing number of cycles. The studies conducted by Li et al. [24] and Zhang et al. [23] illustrated that the collapse potential increases with an increasing number of W-D cycles. This collapse potential increased in natural soil from 1.75 to 7.35% after two D-W cycles, and the degree of collapse transformed from mild to severe disorders [23]. However, the experimental results obtained by Kholghifard et al. [25] and Rao and Revanasiddappa [13] showed the opposite, that is, the collapse potential decreased when the number of D-W cycles increased. The authors concluded that the maximum stress resulting in a higher collapse potential Cp was 200 kPa. Thus, the effect of D-W cycles on the shear strength differs from one soil to another, with considerable dependence on the soil type. For example, studies by Refs. [24,26,27] on soils containing water-soluble mineral phases showed that the cohesion gradually decreases with an increasing number of D-W cycles, which is because of the loss of bonds between soil grains provided by cementing these mineral phases. This was confirmed by Hafhouf et al. [10]. These results how that D-W cycles result in a significant reduction in soil salinity owing to the presence of saline mineral phases such as gypsum and halite. In addition, studies have shown that the effect of D-W cycles on shear strength differs for soils that do not contain water-soluble mineral phases in their structures. According to Liu et al. [28], increasing the number of D-W cycles from 0 to 4 induces a 109% increase in the cohesion value, which is justified by the increase in contact forces between fine soil particles as the number of D-W cycles increases. In addition, the role of suction in soil shear strength has been addressed in recent investigations. Tang et al. [21] found that for each drying cycle, suction increased with decreasing water content, causing an increase in soil strength. However, the effect of D-W cycles on the suction remains insignificant, because for a given water content, the suction remains constant regardless of the number of cycles. The total suction in unsaturated soils is the sum of the matric and osmotic suctions, indicating that the latter is due to the presence of soluble salts in the pore water of soils. According to Zielinski et al. [29] in non-saline soils, the osmotic suction is always negligible before matric suction. However, according to Ying et al. [30], the salinity of the soil pore water controls osmotic suction. Therefore, the latter is considered to be one of the main factors affecting the hydromechanical behavior of soil with salinity. Consequently, studies [30–33], have considered that osmotic suction plays an important role in soils with high plasticity and is plausible for soils with low plasticity. Therefore, determination of osmotic suction is essential to better understand the hydromechanical behavior of saline soils.

However, the construction of buildings, road infrastructure, roads, and networks in sebkha soils is a significant problem considering the damage they cause. These soils have only been studied recently because they are located in virgin areas and are often less favorable than the soils in areas that are already urbanized. Following the technological and demographic evolution of humans and their vital need for these areas, they have invaded these areas to better exploit them (industrial, urban, and road traffic needs). Thus, and after having studied in a first step the effect of D-W on UCS and the salinity of sebkha soils and clarified that salinity significantly affects UCS [10]. In the second step, to complement information for a better understanding of the mechanical behavior of the sebkha soil of Ain M'Lila, it was deemed useful to study the effect of D-W cycles and salinity on the collapse, suction, and shear strength properties. Although research has been conducted to study this type of soil, studies related to these three factors (collapsibility, suction, and shear

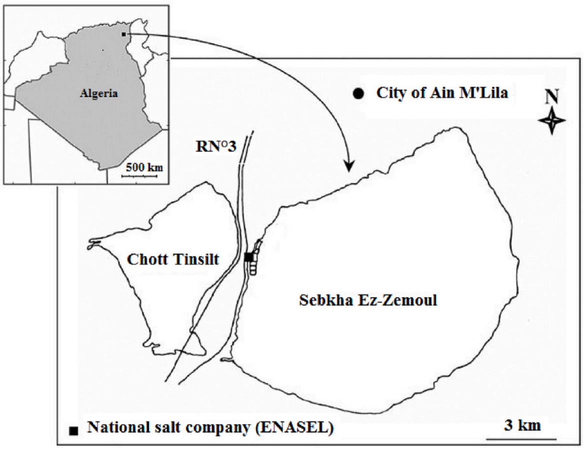

Fig. 1. Location of the study area.

strength) of sebkha soils under the effect of D-W cycles as well as salinity are rare. However, the primary goal of this research is to study the mechanical behavior of sebkha soils of Ain M'Lila basing on the effects of D-W cycles and salinity. To this end, a series of collapse, suction, and shear tests on compacted sebkha soil samples using open-air drying to achieve the targeted water content values (4, 7, 11.4, and 13%) were conducted in the laboratory. The study was subject to geotechnical, chemical, mineralogical, and thermal characterization.

2. Materials and tests

2.1. Materials

The collection of soils in the present study was carried out in the sebkha of Ain M'Lila in northeast Algeria (Fig. 1). It is well understood that seasonal climatic changes have an effect on the variation of soil salinity in this sebkha. However, with the important evaporation in summer, the concentration of salts increases and accumulates on the surface in the form of a white saline crust (Fig. 2 (a)), the latter dissolves with the repetitive precipitations in winter (Fig. 2(b)) leading to a decrease in soil salinity. Moreover, the surveys carried out showed that the sebkha soil of Ain M'Lila is heterogeneous containing numerous bands and nests of salts. The presence of centimetric pieces of gypsum crystals and halite was also noticed. In any case, the morphology and geology of the soils of the sebkha of Ain M'Lila were given by Hafhouf et al. [10].

However, the identification of the above mentioned crystals was achieved by mineralogical analysis performed by X-ray diffraction (XRD) tests (Fig. 3). It should also be noted that, the thermal analysis of thermogravimetry (TGA) and differential thermal analysis (DTA) (Fig. 4 (a and b)) confirmed what was found by the X-ray diffraction tests. For example for the gypsum crystal Fig. 4(a) shows a significant endothermic peak at 156.72 °C corresponding to the dehydration of gypsum ($CaSO4\cdot 2H2O$) accompanied by a mass loss of 16.5% [34]. For the halite crystal as well, Fig. 4(b) shows a large endothermic peak at 800 °C corresponding to the melting of halite (NaCl) [35]. In addition another small endothermic peak at 150 °C was found corresponding to the dehydration of uncrystallized gypsum probably present in the halite pieces in small amounts as an impurity as shown by the small mass loss which is 0.3%.

The results of the study conducted by Hafhouf et al. [10] on the same soil subject of this study show that this soil has an electrical conductivity of 16.3 $dS\cdot m^{-1}$ (Table 1). According to US Salinity Laboratory Staff [36] this soil is classified as a highly saline soil. The results also show that the main ionic types, which contains the saturated soil paste extract are Cl^- (3585 $mg\cdot l^{-1}$) and SO_4^{-2} (4704 $mg\cdot l^{-1}$). The physical and geotechnical properties of this soil are listed in Table 2. The soil has a liquid limit WL = 34%, a plastic limit WP = 16.70% and a plasticity index IP = 17.30%. The soil is classified as lean sandy clay (CL) according to the soil classification (USCS). It is noted that, the mineralogical composition obtained by reconciling the results of X-ray diffraction (XRD) and X-ray fluorescence spectrometry (XRF) tests showed that the studied soil is composed mainly of quartz, calcite, gypsum, halite and traces of kaolinite. These results are in good agreement with the results obtained by Thermogravimetric Thermal Analysis (TGA) and Differential Thermal Analysis (DTA) (Fig. 5). For example, for temperatures ranging from 0 to 200 °C, two endothermic peaks were observed at 90 and 145 °C corresponding to water evaporation and gypsum dehydration, respectively, accompanied by a 3.2% loss in mass [34]. Similarly, the endothermic peak at 800 °C corresponds to the fusion of halite already confirmed on the halite crystal.

2.2. The tests

2.2.1. Preparation of samples

As previously mentioned that the soils of the sebkha of Ain M'Lila are heterogeneous. So before proceeding to the preparation of soil samples for the various tests. It is necessary to homogenize the collected natural soil based on the steps described by Aiban et al. [37] and Hafhouf et al. [10]. However, the collected soil was dried, then crushed and sieved with a 5 mm sieve. Then, this homogenized soil was moistened with distilled water to obtain a water content close to saturation w = 14% corresponding to a saturation

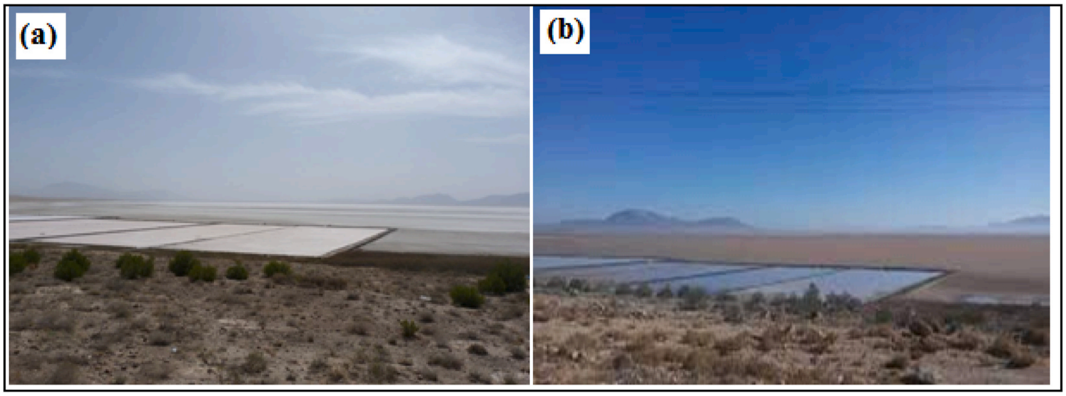

Fig. 2. Condition of the sebkha surface of Ain M'Lila: (a) in summer; (b) in winter.

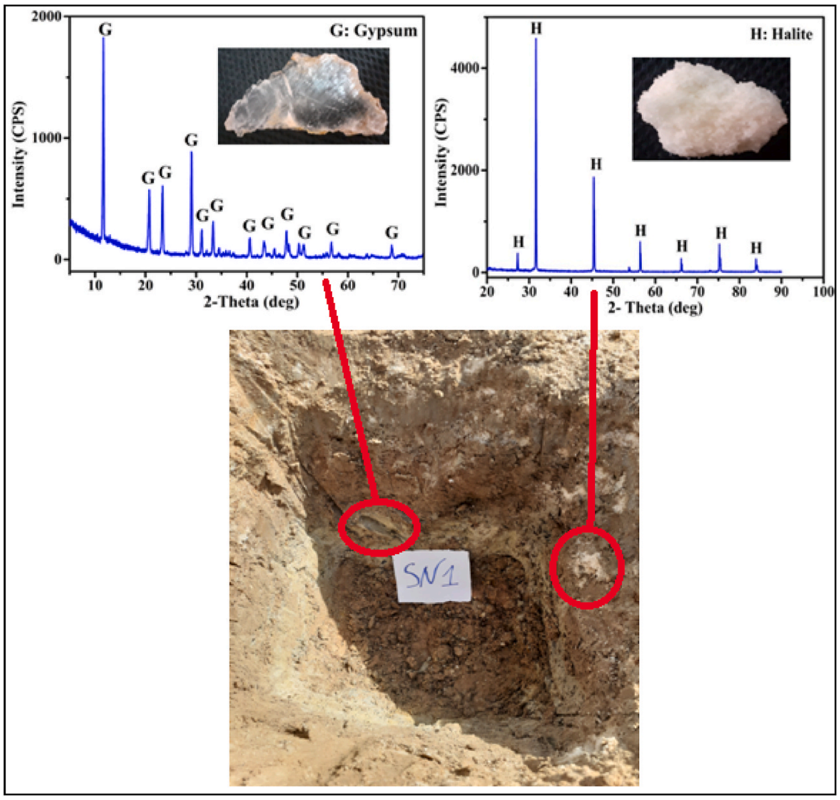

Fig. .3. Mineralogical nature of the crystals found in the soil.

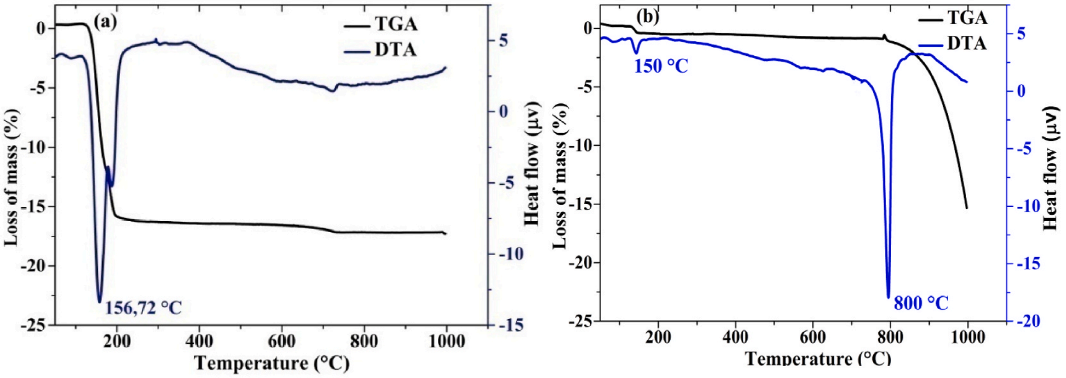

Fig. 4. Thermal description (TGA and TDA) of crystals: (a) gypsum crystal; (b) halite crystal.

Table 1
Results of chemical analyses obtained on the saturated soil paste extract.

ECe ($dS{\cdot}m^{-1}$)	Salinity ($g{\cdot}l^{-1}$)	pH	Soluble salt content in soil extract ($mg{\cdot}l^{-1}$)						
16.3	**10.45**	**6.53**	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}
			2323	50	391.2	156.5	10	3585	4704

degree Sr = 93%. To standardize the water content of the soil the soil and water mixture was sealed in a plastic bag for 2 h. For the preparation of soil samples for shear, collapse and suction tests, the preparation method described in Soltani et al. [38] was used. For this purpose, the soil so prepared was placed in a mold of 60 mm inner diameter and 20 mm height is compacted in three layers of equal height with static compaction at a speed of 1.27 mm/min using the CBR press. The target dry density is 1.815 g/cm^3, which is 95% of

Table 2
Physical and mechanical properties of soil.

Soil properties	Values
Specific gravity	2.70
Consistency limits	
Liquid limit (LL)	34.00%
Plastic limit (PL)	16.70%
Plastic index (PI)	17.30%
USCS classification	CL
Compaction study	
Optimum water content	11.4%
Maximum dry density	1.911 g/cm^3
Grain size analysis	
Gravel	4%
Sand	36%
Silt	57%
Clay	3%

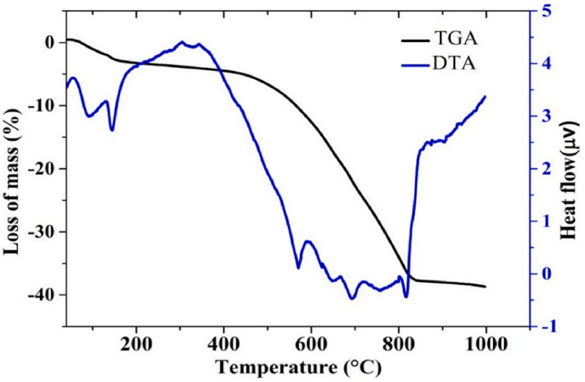

Fig. 5. Thermal analysis TGA and DTA on the sebkha soil of Ain M'Lila.

the normal Proctor optimum γd_{opn}.

2.2.2. *Drying-wetting cycles*

In this study three D-W cycles were applied to the compacted soil samples from the Ain M'Lila sebkha. For the drying cycles, the open air drying procedure was adopted, as it reflects the significant drying time that occurs in the field [10,21]. For this purpose and during the first drying cycle, the prepared samples were placed on trays which were placed on shelves in a laboratory environment at a temperature of 20 ± 2 °C. A series of water contents of $w = 13\%$, $w = 11.4\%$, $w = 7\%$ and $w = 4\%$ were set to control the drying process. These water contents were determined gravitationally basing on masse differences. In this first drying step and when target contents were reached, parallel samples were collected and stored in plastic bags for one week to allow the water to distribute evenly throughout the soil sample. These samples will be used for collapse, shear and suction tests. It is noted that the samples with water contents $w = 13\%$, $w = 11.4\%$ and $w = 7\%$ were intended for the shear and suction tests. On the other hand, the samples with water contents of $w = 11.4\%$ and $w = 4\%$ were intended for the collapse tests. For the shear and suction tests, we note that the choice of these values of water content is justified by the analysis of the hydrous state of the soil, i.e. the dry slope corresponding to $w = 7\%$ compared to the Proctor optimum; $w = 11.4\%$ (Proctor optimum) and the wet slope corresponding to $w = 13\%$. In addition, for the collapse tests, the water contents of $w = 11.4\%$ and $w = 4\%$ located in the dry slope were justified by the requirements of the test itself. The remaining

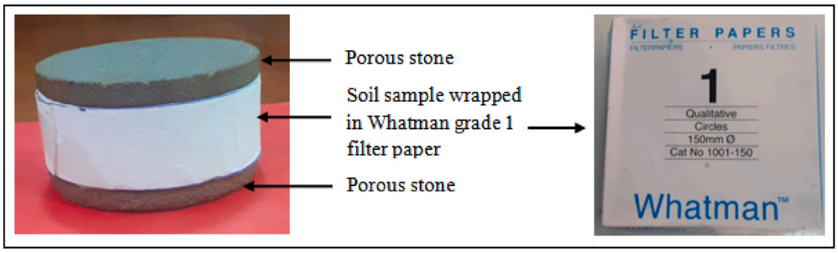

Fig. 6. Soil sample wrapped in Whatman grade 1 filter paper with two porous stones.

samples were then dried to a residual water content of 3 ± 1% where the mass change is less than 0.1 g for 48 h. To begin the next saturation step, the dried soil sample was wrapped in Whatman grade 1 filter paper, reference 1001–150 (Fig. 5). This paper is characterized by medium filtration that allows water and soluble salts to easily penetrate while preventing filtration of soil particles. Two porous stones were placed on the bottom and top surfaces of the sample (Fig. 6), and then the assembly was placed in a modified oedometer cell described in detail in Al- Amoudi and Abduljauwad [6], and then soaked with distilled water under low pressure (1 kPa) for 24 h, until saturation. The main reason for choosing this method is due to the unreliability of other saturation methods. The oedometer cell method allows water to easily percolate into the soil, making the soil saturated. In addition, this method is similar to the percolation of rainwater under the influence of a storm through the upper layers of the sebkha [6]. After saturation, the samples were collected with a measured water content of 22 ± 1%. To repeat the second drying step, the same procedure as above was used. By repeating the above procedures, a total of three drying-humidification cycles, were applied to the samples.

2.2.3. *Oedometer tests*

Samples were made in a mold of 60 and 20 mm internal diameter and height, respectively. For each drying cycle, these samples underwent a slight shrinkage. In order to have zero transverse deformation during the oedometer test, as stipulated in the test standard XP P94 090–1 [39], the soil sample dried to the target water content was cored with an oedometer ring of 50 and 19 mm diameter and height, respectively. Coring was performed by a lateral cut with a wedge, and the ring was driven using a special device, as shown in Fig. 7. To study the collapse of unsaturated soils, two methods can be considered: the single and double oedometer tests [40]. According to Medero et al. [41], for a stress of 200 kPa, the two methods give almost identical results. In this study, the double-oedometer test method was adopted to determine the collapse potential (Cp). This method involves placing two dried soil samples at the target water content in two oedometers; the first one was flooded with water under vertical stresses until the deformation stabilized [42], whereas the second one was dry-loaded at the target water content until the end of the unloading–loading process. Moreover, during the test, the upper part of the odometer cell where the sample was located was covered by petroleum jelly to avoid excessive evaporation, which might result in a decrease in the water content, leading to erroneous results. The collapse potential (Cp) was calculated using the formula described by El-Howayek et al. [43]:

$$Cp = \frac{(e_{dry} - e_{sat})}{1 + e_0} = \frac{\Delta e}{1 + e_0} \tag{1}$$

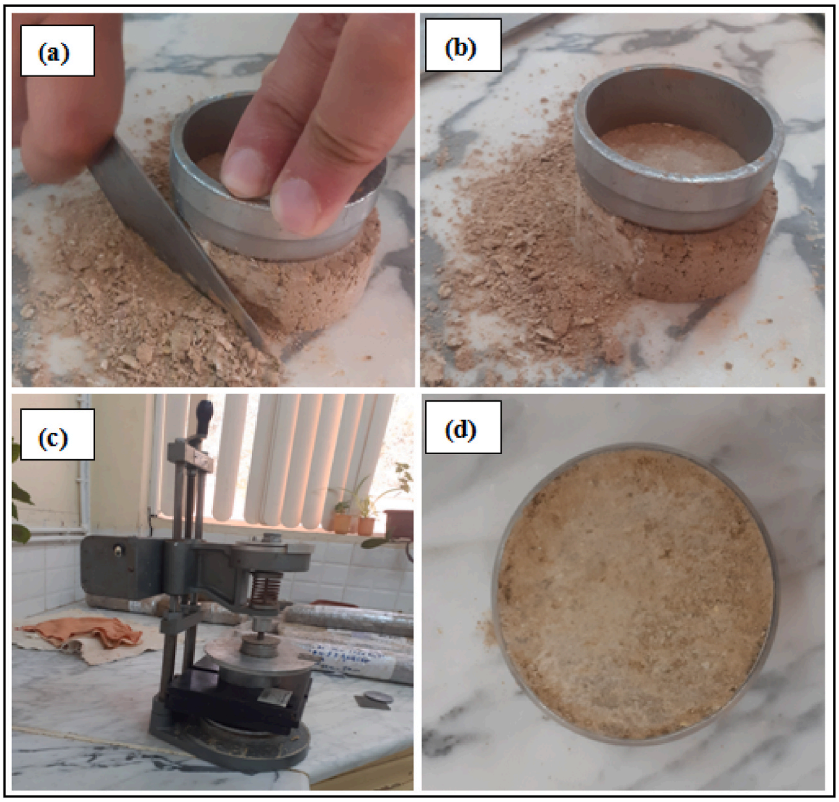

Fig. 7. Steps in the coring of a specimen for the oedometer test: (a) and (b) cutting of the specimen; (c) special device used to push in ring; (d) finished specimen.

$$\Delta e = e_{dry} - e_{sat} \tag{2}$$

Where, e_0 = Initial void ratio; e_{sat} = Saturation void ratio; e_{dry} = Dry void ratio

2.2.4. Direct shear tests

To determine the parameters of the soil shear strength under the effect of D-W cycles, direct shear tests were performed according to the standard ASTM D3080-98 [44] on soil samples made in a mold of 60 and 20 mm diameter and height, respectively. Since the studied soil is partially saturated, the type of direct shear test performed is the unconsolidated undrained one. Therefore, for each drying cycle and for each target water content, the actual surface area of the sample that had undergone slight shrinkage was determined by measuring the diameter of the sample with a caliper, and subsequently, it was placed in the direct shear apparatus with displacement and load sensors. The sensors were installed and connected to a data logger. Then, normal stress was applied to the specimen, the fixed bolt was removed, and the direct shear test was started instantly. The normal stresses applied for each test were 100, 200, and 300 kPa.

2.2.5. Suction test

In this study, Whatman No. 42 filter paper was used to measure the matric and total suction according to ASTM D5298-10 [45]. Osmotic suction is determined by the difference between the total and matric suctions [30]. Filter paper is a simple and economical laboratory technique [46] that can measure a wide range of suctions up to 100 MPa [29]. For the measurement of matric suction, the method involves placing three filter papers between the two soil samples after drying these three filter papers in an oven for 24 h. The central filter paper used for the matric suction measurement is usually slightly smaller in diameter than the other two papers to avoid direct contact with the two soil samples. All samples and filter papers were placed in a glass jar. For the measurement of total suction, two filter papers were placed on the two soil samples using a support (Fig. 8). The glass jar was tightly closed, wrapped in plastic film, and stored in a humid chamber with a relative humidity of 100% and a temperature of 20 °C for 15 days to achieve a water balance between the soil and filter paper. According to ASTM D5298-10 [45], the following equations of the Whatman No. 42 filter paper calibration curves were used to transform the water content of the filter paper into matric and total soil suction.

$$log_{10}\ \psi = 5.327 - 0.0779 w_f \left(w_f \le 45.3\%\right) \tag{3}$$

$$log_{10}\ \psi = 2.412 - 0.0135 w_f \quad \left(w_f > 45.3\%\right) \tag{4}$$

Where ψ is the matric or total suction of the soil sample (kPa); w_f is the water content of the filter paper (%).

2.2.6. Measurement of soil salinity

In order to measure the salinity of the soil there are several methods including those used in the laboratory. They are based on the measurement of the electrical conductivity of saturated paste extract or diluted soil extract (e.g. 1/5). In the present study, the saturated paste extract method was used. This method was described in detail by Hafhouf et al. [10] with reference to the method recommended by US Salinity Laboratory Staff [36]. Although this method presents some difficulties related to its implementation procedure. It is cumbersome to implement because of the difficulty of making the paste and extracting the solution but it remains an

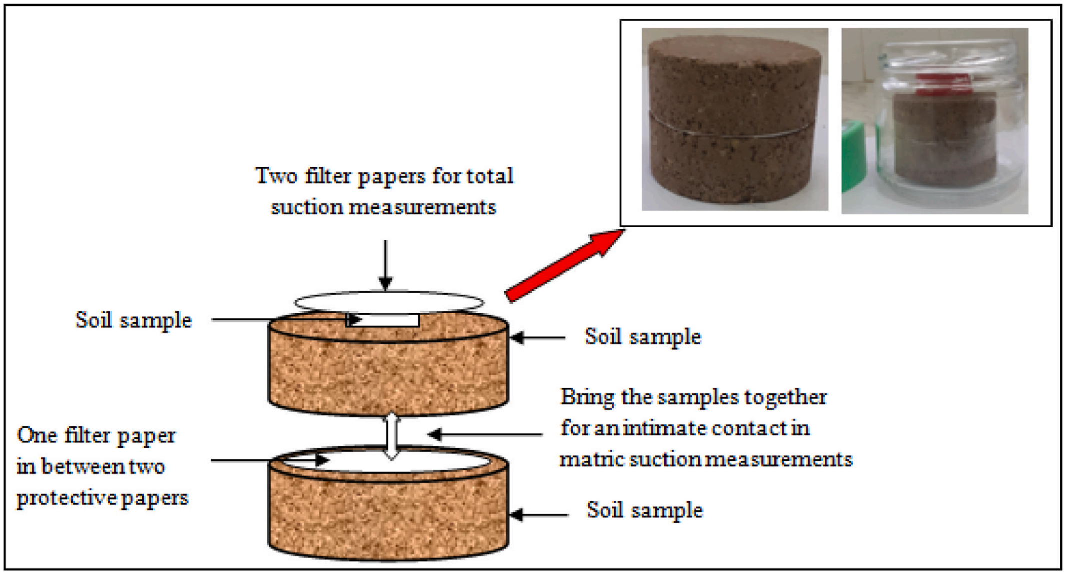

Fig. 8. Principle of measuring total and matric suction by the filter paper method.

international reference method for measuring soil salinity.

3. Results and discussion

3.1. Effect of D-W cycles on soil salinity

The variation of the salinity reported in terms of electrical conductivity measured on the saturated paste fragment (ECe) versus of the number of D-W cycles is presented in Fig. 9. From the latter, we see that the salinity is inversely proportional to the number of cycles. However, decreases of the salinity of 82.8 and 65.7% were recorded between the first and third and first and second cycles, respectively. Based on these results and according to the classification of US Salinity Laboratory Staff [36], the sebkha soil of Ain M'Lila changed from highly saline to low saline after three D-W cycles, which was confirmed by Hafhouf et al. [10] considering the same soil object used in this study. Nevertheless, a difference in values was noted between the two studies, which was because of the geometric shape of the samples and the saturation method used. This decrease in salinity is owing to the leaching of certain salts present in the soil under the effect of saturation. Chemical analyses performed by Hafhouf et al. [10] on soil samples subjected to four D-W cycles showed a decrease in three chemical elements: chloride (Cl), sodium oxide (Na_2O), and sulfur trioxide ($S0_3$). These results correlated with the results of X-ray diffraction (XRD) tests, which showed the disappearance of the halite (NaCl) salt mineral phase and a decrease in gypsum ($CaSO_4 \cdot 2H_2O$). In case of the latter (Fig. 10(a) and (b)), the results of the thermogravimetric analysis (TGA) obtained for each drying cycle confirmed their decrease with the increase in the number of D-W cycles. For example, for the first drying cycle, a mass loss of 3.2% (Fig. 10(b)) was determined, and part of this loss was because of the dehydration of the gypsum. Following three D-W cycles, a decrease of 0.68% in mass loss was observed, explaining the decrease in gypsum content after these three D-W cycles. Moreover, the decrease in ECe was more significant between the first and second cycles (Fig. 9). After comparing this result with that of TGA, an accounting between the two results was clearly observed because, according to Fig. 10 (a and b), the difference in the decrease in mass loss between the first and second cycles is greater than that between the second and third cycles.

3.2. Effect of D-W cycles on suction

For each drying cycle, the filter paper method was used to measure the variation in total and matric suction in the saline sebkha soil of Ain M'Lila. The variations in these two suctions as a function of the water content are shown in Fig. 11(a). The results showed the influence of drying on the two suctions (total and matric). Both suctions increased with decreasing water content; however, the influence of drying was more marked on the matric suction than on the total. For example, for the first drying cycle and for a water content of w = 13%, the total suction was much higher than the matric suction, as with continuous drying translated by the decrease in the water content, the matric suction curve converged towards the total suction curve. However, in this study, measurements of total and matric suction for water contents below 7% were not performed because of the limitation of the maximum value measured by the filter paper method, which is on the order of 100 MPa [29]. It is well understood that osmotic suction is equal to the difference between total and matric suction. Fig. 11(b) shows the variation in osmotic suction with water content and the effect of drying on this suction. The behavior of the latter is similar to that of the total and matric suctions, that is, for the three drying cycles, the osmotic suction increased with a decrease in the water content, except for the first drying cycle, where a decrease in this suction was observed at the level of w = 7% and probably this is due to the crystallization of salts on the surface of the soil samples, causing the creation of a saline crust, which seals the outer surface and prevents the correct balance between the suction of the filter paper and that of the soil. Knowing that the measurement of suction by the filter paper method is performed by the direct transfer of water between the soil and the filter paper (matric suction) and by the intermediary of relative humidity (total suction), that is to say that the exchanges between

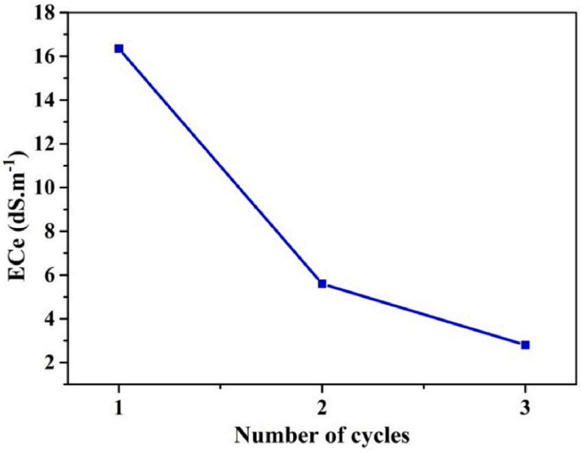

Fig. 9. Electrical conductivity as a function of the number of cycles.

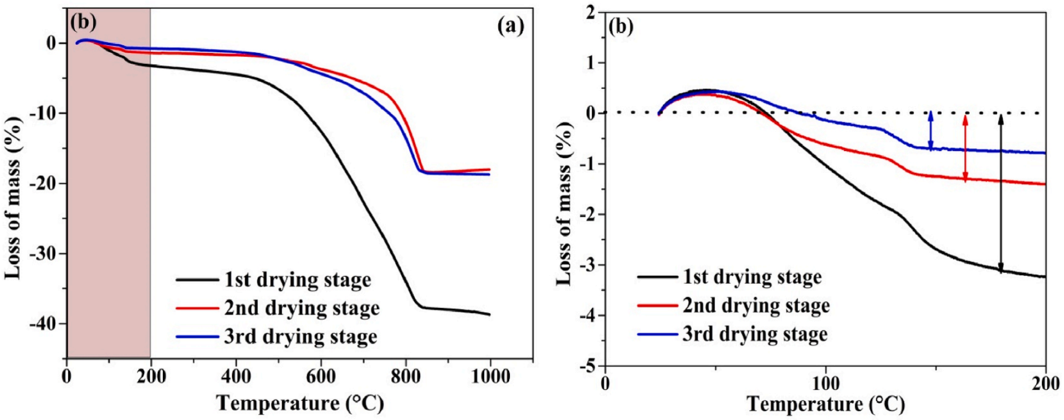

Fig. 10. TGA analyses for each drying cycle: (a) from 0 to 1000 °C; (b) from 0 to 200 °C.

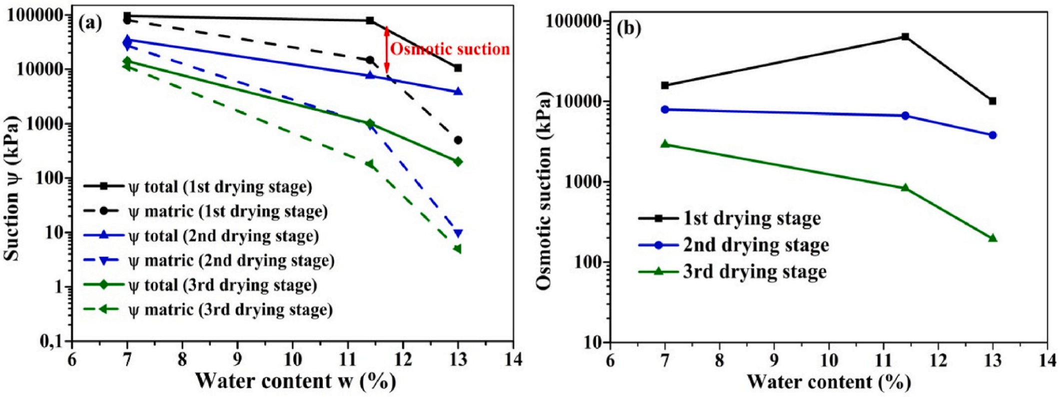

Fig. 11. Variation of suction with water content for each drying cycle: (a) total and matric suction; (b) osmotic suction.

the paper and the soil are carried out either by adsorption from the soil or by exchange without contact by vapor phase [47]. This behavior is consistent with that reported by Ying et al. [30], who indicated that for saline soils the salinity of the pore water in the soil was increased with the decrease in water content. Moreover, as the osmotic suction is related to the salinity of the pore water in the soil it can be distinguished that the increase in osmotic suction with the decrease in water content is because of the increase in salinity of the pore water in the soil. In addition, the study conducted by Hafhouf et al. [10] on the same soil object as this study showed that drying causes a slight decrease in the volume of the soil, and the saline solution in the soil recrystallizes increasingly with the drying process. Consequently, densification of the soil after compaction occurs, leading to an increase in the matric suction. This densification occurred in the absence of shrinkage cracks for each drying cycle because of the low clay fraction that contained this soil object in this study. Thus, the effect of the cracks on the three suctions was not considered.

Fig. 11(a) and (b) also show the effect of D-W cycles on the total, matric, and osmotic suctions. It is evident that regardless of the water content, all three suctions decrease when the number of D-W cycles increases. For example, for the first drying cycle and for a low water content of $w = 7\%$, the values of the total, matric, and osmotic suctions were 95800, 80000, and 15800 kPa, respectively. In contrast, for the latter and after three drying cycles, the values were 14125, 11220, and 2905 kPa, corresponding to decrease rates of 85, 86, and 82%, respectively. These results differ significantly from those obtained by Tang et al. [21], who studied the effects of three D-W cycles on non-saline clay soil, and the authors concluded that for this clay soil, the effect of the D-W cycles was insignificant. They stated that for the same water content, the suction was constant regardless of the number of D-W cycles. Therefore, based on the results of Tang et al. [21], for this clayey soil, the total suction is equal to the matric suction because the osmotic suction is null, which explains the insignificant effect of D-W cycles on this type of soil. In the present study, an increasing number of D-W cycles caused a significant decrease in soil salinity, as expressed by the ECe (Fig. 9). Fig. 12(a, b, and c) show the effect of salinity on the three suction. It is evident that they decrease with decreasing salinity, regardless of the water content. It is also noted that the variation of the three suction as a function of salinity expressed by the electrical conductivity and whatever the water content, is a linear variation represented by lines whose correlation coefficients close to 1. Regarding matric suction, these results are not in agreement with those obtained in several studies, namely, those conducted by Sreedeep and Singh [32] and Ying et al. [30]. The latter showed that the effect of salinity on the matric suction is negligible. According to Ying et al. [30], samples were prepared at the same density but with different salinity levels.

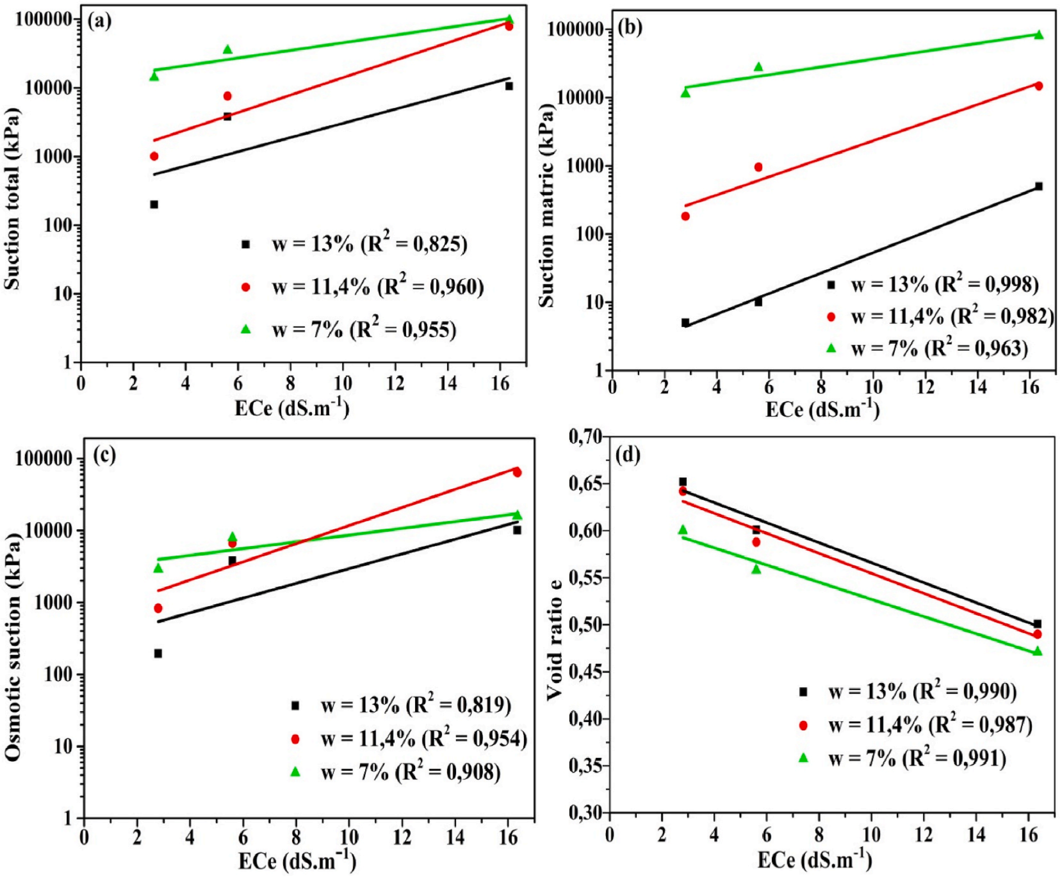

Fig. 12. The effect of salinity on suction and void ratio: (a) on total suction; (b) on matric suction; (c) on osmotic suction; (d) on void ratio.

They concluded that the void index remains constant regardless of the salinity value. However, the technique used by Ying et al. [30] to vary salinity was found to be inconsistent with the actual situation occurring in nature; that is, this technique did not consider the effects of D-W cycles on salinity. However, from a practical perspective, shallow soils are exposed to D-W cycles, which significantly affect salinity [10]. Moreover, according to Fig. 12(d), the decrease in salinity under the effect of D-W cycles results in an increase in the void index in the soil. This increase in (e) was owing to the leaching of certain salts, such as halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$) [10]. This behavior is in good agreement with that found by Tang et al. [21]. These authors found that the void index increases with the increase of soluble mineral phases, as the disappearance of the latter causes the increase of local porosity leading to a honeycomb fabric in the soil samples. According to Estabragh et al. [48], an increase in the void index leads to a decrease in matric suction. Therefore, in the present work, the decrease in matric suction is generated by the decrease in salinity because the latter triggers an increase in the void index. However, the behavior of osmotic suction under the effect of salinity is consistent with the studies cited above, because this suction component is governed by soil salinity; therefore, the decrease in salinity under the effect of D-W cycles causes a decrease in osmotic suction.

Finally, through the results obtained in this study, it was concluded that the decrease in the three components of suction (total, matric, and osmotic) was because of the decrease in salinity in the soil under the effect of the D-W cycles and precisely because of the leaching of part of the salts such as halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$). This indicates that the three suction of the sebkha soil of Ain M'Lila are always controlled by salinity and D-W cycles.

3.3. Effect of D-W cycles on collapse

To illustrate the effect of D-W cycles on the collapse potential (Cp) of Ain M'Lila sebkha soils, the initial water content was set as w = 11.4% (normal Proctor water content) and w = 4%, considering that, according to the literature and when soils have undergone compaction at water contents less than or equal to the optimal water content of Proctor, they become susceptible to collapse [16]. Cui et al. [17] and Loiseau et al. [18] showed that soil collapse occurs when the initial water content is low.

Fig. 13(a) and (b) show the variation of Cp as a function of applied stresses for different D-W cycles (double oedometer test). The results show that the collapse potential Cp increases with increasing applied stress up to 800 kPa. For example, for the first drying cycle and for the two water contents of w = 11.4 and 4%, the two Cp values obtained were 3.2 and 5.1%, respectively, at a stress of 800 kPa.

This behavior of increasing Cp with increasing applied stress has been observed by several researchers and for different types of soils, particularly soils that contain saline and water-soluble mineral phases [6,24,49]. The latter explained this behavior by the dissolution of these mineral phases in water, which causes the rearrangement of soil grains, leading to a significant reduction in volume. In the present study, it is recalled that the soil of Ain M'Lila contains mineral phases soluble in water, such as halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$), which explains the accounting of this behavior to that obtained by the studies cited above. Moreover, according to ASTM D5333-92 [50], the stress level used to obtain a representative Cp is 200 kPa; thus, this value of stress was considered useful as a basis for interpreting and discussing the results obtained. According to Fig. 13(a and b) and 14(a), at a stress of 200 kPa, it is evident that the Cp increases with the increase in the number of D-W cycles. For example, for the first and third drying cycles, the Cp potentials varied from 1.4 to 5% for an initial water content of w = 11.4% and from 1,7 to 7% for a water content of w = 4%. These results correspond to headings ranging from mild to moderate risk according to ASTM D5333-92 [50]. Further, Cp is inversely proportional to the water content, that is, each time the water content is increased, Cp decreases regardless of the number of D-W cycles. However, for the first and third drying cycles and for an initial water content of w = 4%, increases in the collapse potentials Cp of 21.4 and 40% were recorded, respectively, compared with the Cp obtained at a water content of w = 11.4%. This result of the increase in Cp with decreasing water content is clarified based on the suction, that is, when the water content is decreased, the suction increases, leading to an increase in the capillary pressure, which increases the resistance of the soil. In fact, when the water content increases, the suction decreases, resulting in low capillary pressures and significant drops in resistance, causing an important Cp. Further, the increase in Cp with increasing number of D-W cycles is consistent with that reported by Ref. [24]. The latter study investigated the effect of D-W cycles on the loess Cp and it was shown that this result is because of the loss of mineral-containing phases in this loess when the number of cycles increased, leading to a high void index. It is known that Cp varies proportionally with the void index of the soil. However, for the sebkha soil of Ain M'Lila, which contains saline mineral phases (halite and gypsum), these mineral phases are influenced by D-W cycles. Fig. 14(b) shows the linear variation of Cp as a function of ECe. In addition, when ECe decreases, Cp increases, considering that the decrease in ECe caused by the dissipation of saline phases during the D-W cycles leads to an increase in the void index of the sebkha soil, which generates an increase in Cp. Thus, it can be concluded that the Cp is directly related to the salinity of the soil. Moreover, by increasing the number of cycles D-W, a significant increase between the first and second drying cycles was observed compared with the increase obtained between the second and third drying cycles (Fig. 13(a and b)). By analogy and according to Fig. 9, a more marked decrease in salinity is observed between the first and second cycles compared to that obtained between the second and third drying cycles, which explains the significant loss of cementitious bonds in the Ain M'Lila soil between the first and second cycles following the evacuation of the saline phases. Thus, this explains the increase in Cp observed between the first and second drying cycles.

3.4. Effect of D-W cycles on shear strength

The results of the direct shear tests obtained on samples of sebkha soil of Ain M'Lila as a function of D-W cycles are shown in Fig. 15 (a) and (b). For each cycle of drying, when the water content decreased, there was an increase in the cohesion and angle of internal friction of the sebkha soil of Ain M'Lila. For example, for the first drying cycle and for a water content w = 13%, the cohesion and friction angle were 77 kPa and 26°, respectively. There was a significant increase for a low water content of w = 7% and yielding 150 kPa and 34°, respectively. According to Hafhouf et al. [10], the mechanical behavior of saline soils is controlled by water-soluble salts, particularly when these soils are in a dry state or with low water content. However, during the drying process, the soluble salts in the soil pore water move to the soil surface, and with the migration of moisture, these salts crystallize and accumulate, leading to the formation of a saline crust on the soil surface (Fig. 17). This saline crust caused an increase in the lateral confining stress of the soil. In addition, the saline solution in the soil recrystallizes increasingly with the drying process, causing the cementing of the grains because the crystallization of the saline solution in the pores of the soil leads to the transfer of this solution from the liquid phase to the solid phase knowing that the volume of the voids in the soil is obtained by the sum of the volume of the gas phase as well as that of the liquid

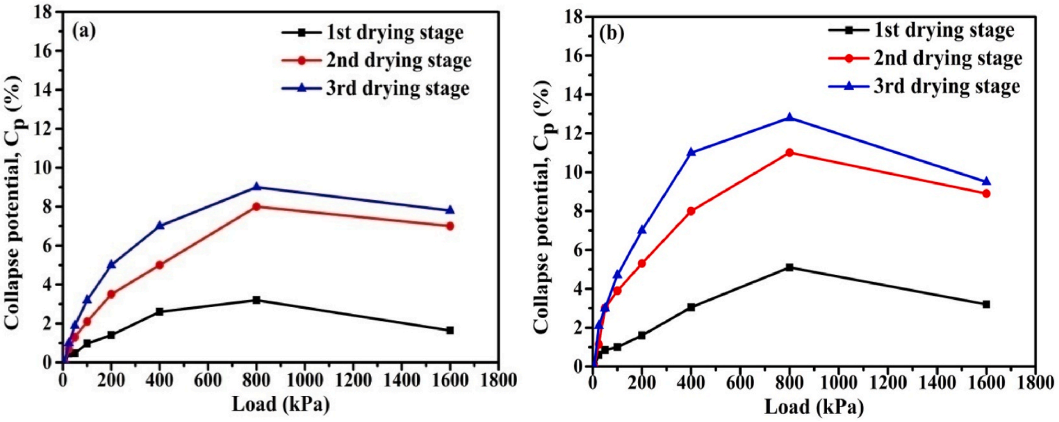

Fig. 13. Variation of Cp as a function of applied stress for different D-W cycles: (a) for w = 11.4%; (b) for w = 4%.

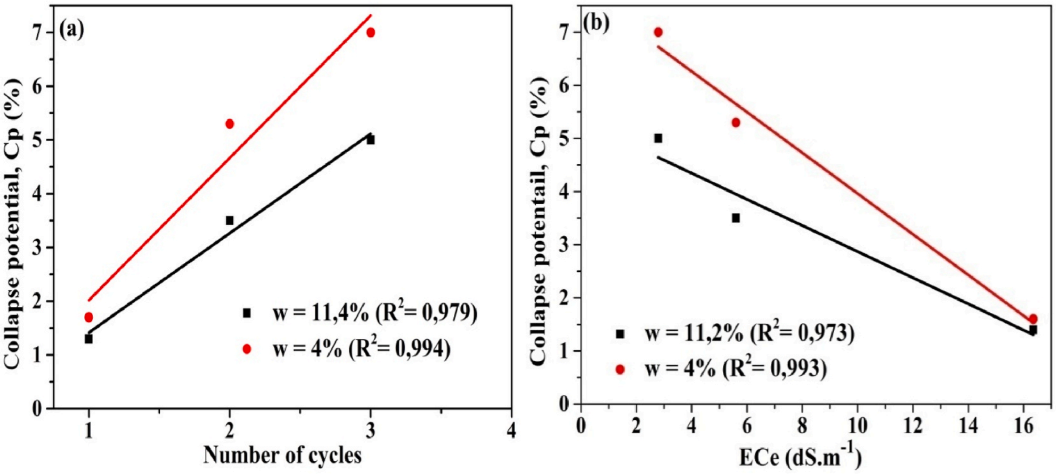

Fig. 14. Variation of Cp as a function of cycle number and ECe for a stress of 200 kPa: (a) as a function of cycle number; (b) as a function of ECe.

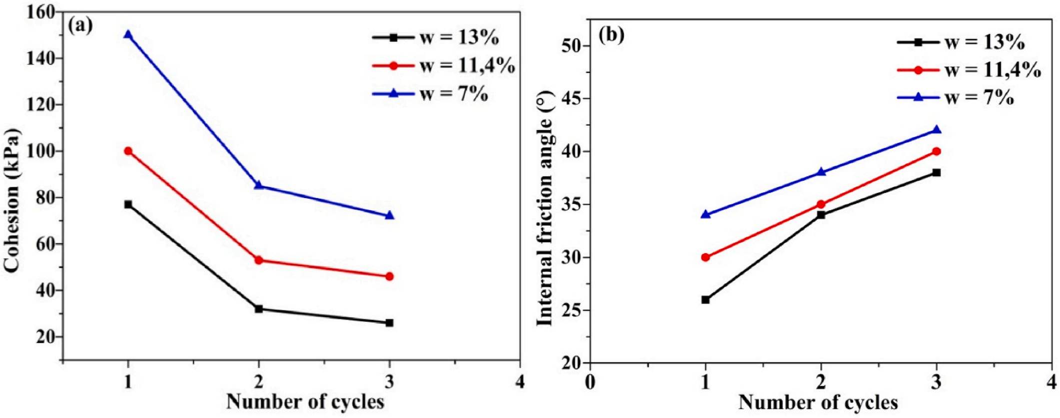

Fig. 15. Variation of the cohesion and the internal friction angle as a function of the number of cycles: (a) for the cohesion; (a) for the internal friction angle.

phase. So the transfer of this last one in solid phase causes the decrease of the index of the voids which increases the bonds between the grains, thereby leading to an increase in cohesion. It is also worth noting the role of suction in increasing the cohesion. Several researchers have studied the effect of varying water content on the shear strength of unsaturated soils. Among these researchers are Goh et al. [51] who showed that the soil has a higher shear strength when the water content is low. They considered this result to be because of the increase in suction, which plays an important role in improving the bonds between the soil particles, leading to an increase in soil cohesion. It should be noted in the present work that the cohesion and angle of internal friction were influenced by the number of D-W cycles. For the same value of w and when the number of cycles D-W increased, the cohesion decreased and the angle of internal friction increased. For example, for the first drying cycle and a water content of $w = 11.4\%$, the cohesion and internal friction angle of the soil were 100 kPa and 30°, respectively. After three drying cycles, these values were 50 kPa and 37°, respectively. Thus, a 50% decrease in cohesion and 23% increase in the friction angle were recorded. These results differed from those reported by Liu et al. [28] who studied the effect of D-W cycles on the mechanical behavior of non-saline laboratory-reconstituted granitic-residual soils. They found a 109% increase in cohesion after increasing the number of D-W cycles from 0 to 4 and explained this result considering the increase in contact bonds between soil grains when the number of D-W cycles. The same authors noted that the increase in D-W cycles results in the rearrangement of soil particles, leading to the densification of the latter, which increases the cohesion. However, the study conducted by Wang et al. [52] on an expansive clay soil illustrates the complexity of the shear behavior. According to the results obtained by these authors. These denote a sharp decrease in cohesion during the first D-W cycle, then a gradual increase and finally stabilize when the number of D-W cycle is increased. However, crack development; increased chemical bonding and cementation of the soil grains and reduction in void ratio are the main factors by which D-W cycles affect the shear strength [52]. Also the soil studied by Chen et al. [53] containing a significant clay fraction (30%) leading to significant volume variations. According to these authors a decrease in void index was found when the number of D-W cycles is increased knowing that this decrease becomes very significant during the first two D-W cycles causing soil densification inducing a slight increase in soil shear strength. For saline soils case of the present study. After proving previously that with an increasing number of D-W cycles, an important decrease in the salinity of the soil, expressed by the electrical conductivity ECe, was observed (Fig. 9). It should be noted that the salts accumulated on the surface are in direct contact with water during saturation events, which causes the leaching of these salts, generating a loss of the confining constraint as well as a decrease in the bonds between the grains provided by these salts in the soil. It should be noted that decreasing salinity causes the void index in the soil to increase (Fig. 12(d)) and makes the soil less dense. It is evident that the variation in the cohesion and internal friction angle of the soil is linear, as shown in Fig. 16. For each water content, a decrease in cohesion with a decrease in salinity, expressed by the ECe, was observed. However, a linear increase in the internal friction angle with a decrease in salinity was observed. Moreover, the decrease in cohesion observed between the first and second drying cycles was greater than that between the second and third drying cycles. This behavior follows the pattern of decrease in salinity as a function of the number of D-W cycles. Furthermore, it is known that suction is an important property in the evolution of the shear strength of unsaturated soils, and as mentioned before, suction decreases with an increasing number of D-W cycles and also causes a decrease in cohesion. Thus, it was deduced that with an increasing number of D-W cycles, the decrease in cohesion was because of the decrease in the salinity and suction of the saline soil.

4. Conclusion

Suction, oedometer, and direct shear tests on samples of compacted sebkha soils of Ain M'Lila subjected to drying-wetting cycles were conducted to illustrate the effect of these D-W cycles on the mechanical behavior of these soils, with emphasis on suction, collapse potential, and shear strength. The following conclusions were drawn from the results.

- For each drying cycle, the three suction components, namely total suction, matricsuction and osmotic suction, increase with decreasing water content. The crystallization of salts in the soil causes a decrease in the void index which results in an increase in matric suction with decreasing water content. In addition, with the decrease of the water content in the soil for each drying cycle, the concentration of salts in the pore water increases, which causes the increase of the osmotic suction. The increase of these two suction components also causes the increase of the total suction.
- Suction is affected by D-W cycles. The three components of suction: total, matric, and osmotic suction, decreased when the salinity decreased under the effect of cycles. The decrease in osmotic suction was related to the decrease in the concentration of salts in the soil pore water as the number of cycles increased. The decrease in matric suction with decreasing salinity was because the dissipation of salts under the effect of D-W cycles, leading to an increase in the void index of sebkha soils.
- The effect of D-W cycles is significant on the collapse potential Cp of saline soils. The Cp increases with the increase in the number of D-Ws, because the D-Ws cause an increase in the void index due to the decrease in soil salinity. It is well understood that the increase in Cp is also related to the decrease in initial water content, because when the latter is low, leads to a significant suction. However, flooding leads to a significant reduction in these suctions, causing an increase in Cp.
- The shear strength properties of sebkha soils were affected by the D-W cycles, as well as by salinity. However, during each drying cycle within the soil structure, an increase in inter-granular bonds was obtained owing to the crystallization of salts and the increase in suction, which creates a saline crust, resulting in an increase in the confinement constraint. These two results result in an increase in shear strength during drying. However, when the number of cycles D-W increased, the cohesion of the soil sebkha decreased, and the angle of internal friction increased due to the decrease in suction as well as the softening of the bonds between the grains provided by the salts.

Author contribution statement

Ilyas hafhouf; ABBECHE KHELIFA: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

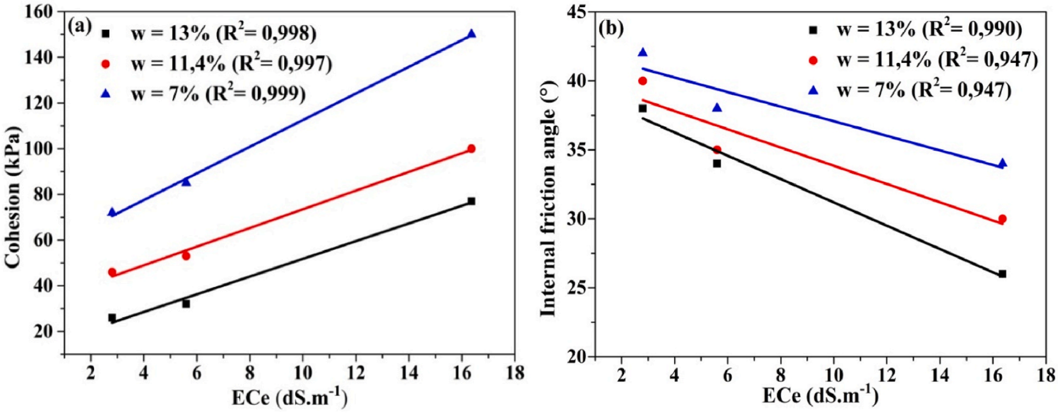

Fig. 16. Variation of cohesion and internal friction angle with salinity: (a) for cohesion; (b) for friction angle.

Fig. 17. Surface condition of a soil sample after drying.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Acknowledgments

The authors would like to thank the LTP Est SETIF laboratory for allowing access to the authors for the realization of a part of the experimental program. The authors also present their thanks to the anonymous reviewers for their useful suggestions which allowed to improve this article.

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