International Journal of GEOMATE, May, 2022, Vol.22, Issue 93, pp.98-105
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.93.3270
Geotechnique, Construction Materials and Environment

INFLUENCE OF SALT DISSOLUTION RATE ON THE HYDRAULIC CONDUCTIVITY OF SABKHA AND DUNE SAND ARID SOIL DEPOSIT SAMPLES FROM KUWAIT

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*Corresponding Author, Received: 12 Aug. 2021, Revised: 21 Feb. 2022, Accepted: 27 March 2022

ABSTRACT: The geotechnical characteristics of salt-cemented arid soils may be affected by flooding. Due to the loss in cementing salt bonds caused by a continuous water flow, the salts and fines may be washed out, and the geotechnical properties may deteriorate. Therefore, investigating the relationship between hydraulic conductivity and salt dissolution is of primary importance. In this study, the variation in hydraulic conductivity with salt dissolution was investigated. The samples of two primary soil surface deposits in Kuwait—sabkha and dune sand soil samples—were permeated with distilled water in a leaching cell under 3-psi pressure for more than 50 pore volumes. The hydraulic conductivity and total dissolved solids were measured at intervals of 5 pore volumes. The test results showed a 250% increase in the hydraulic conductivity of the sabkha soil compared with its initial value due to salt dissolution. An increase of 110% was observed in the hydraulic conductivity of the dune sand. Increasing the hydraulic conductivity values correlates well with the soil samples' salt dissolution rates (TDS), which were higher for the sabkha soil in the first pore volumes. A deep understanding of the salt dissolution behavior of sabkha soils will help select their suitable stabilization mechanism.

Keywords: Dissolution, Dune, Hydraulic conductivity, Sabkha, TDS.

1. INTRODUCTION

Kuwait is located in the northwestern corner of the Arabian Gulf. The landscape of Kuwait is characterized by flat, gentle, and low relief desert surfaces. Kuwait experiences very high temperatures during the summer months, particularly in July and August, and relatively low temperatures in winters [1]. Rainfall occurs during winter and spring between November and April, with an average of 115 mm and extreme minimum and maximum rainfall of 28 and 260 mm, respectively [2].

As shown in Fig.1, the Kuwaiti desert sediments comprise aeolian, residual, playa, desert plain, slope, and coastal deposits. Aeolian sand deposits are the most common and cover more than 50% of the land surface [3,4]. In addition, parts of northeast Kuwait are covered with uniform, sensitive saturation, and high permeable windblown dune sand [5-8].

Conversely, large parts of the deposits on the north and the south coasts of Kuwait comprise salt-encrusted flats known as sabkha. Clays, silts, sands, and salty mixtures are predominant on the north and south coasts [9]. High moisture content and groundwater table are generally found in sabkha deposits [10-13].

Sabkha soil development results from low-wave energy, enabling fine soil particles to settle and be weakly cemented by saturated brines [14].

Fig.1 Kuwait location map and sampling locations

Generally, the unstable and collapsible conditions found in arid soils are due to the high content of salts, which can be leached [15,16]. Leaching can adversely affect the geotechnical characteristics of these soils [11,12], resulting in excessive soil settlement and bearing capacity failure. In Kuwait, stabilizing marginal abundant soils, such as dune sands and sabkha soils, has become a significant issue concerning the protection of limited natural soil resources. If this issue remains unaddressed, these resources may be depleted because of extensive use for construction purposes. Several studies by Al-Otaibi [15,16] and Al-Otaibi and Aldaihani [8,17] report the behavior of arid soils under the leaching effect.

2. RESEARCH SIGNIFICANCE

Arid soils are considered problematic owing to their high sensitivity upon inundation. The wide variation in the chemical properties of these soils warrants continued research regarding the adoption of an effective stabilization technique. This study contributes toward a deep understanding of the salt dissolution rate's effect on the hydraulic conductivity of dune sand and sabkha soil deposits, the main surface arid deposits in Kuwait. Therefore, this and other studies in this field may help develop a geochemical model for arid soils that will allow simulating the rate of salt dissolution, which will aid in predicting arid soils' long-term geotechnical behavior and the efficiency of the stabilizing technique.

3. MATERIALS AND METHODS

3.1 Soil Sampling Location

The two sites for soil sampling in the current study were chosen based on previous soil surveys conducted by researchers in south Kuwait to represent the two tested soil surface deposits sabkha and dune sands [15,16,18,19]. These sites represent two main types of surface deposits in Kuwait and are located 70–80-km south of Kuwait City. The first sampling location is Al-Khiran, which is representative of southern sabkha, and the second location represents dune sand accumulations in the Al-Wafra area. These two selected sites are located 20-km apart, as shown in Fig.1.

3.2 Soil Sampling

Based on a field reconnaissance survey performed at the two selected locations, four soil samples were collected from virgin soil at each site. Since these soils deposits will be discarded as soil waste, this study did not concentrate on the in-situ field conditions. These soils will be investigated for possible future usages after suitable treatment.

In the case of sabkha soil, the surface layer was removed up to a depth of 5 cm, and the representative layers of the profiles were sampled. Subsequently, 20 kg of disturbed sabkha soil samples were excavated and collected from a 5–50 cm depth from each sampling pit, as shown in Fig.2. In addition, dune sand samples were taken from the dune sands accumulated in the Al-Wafra area south Kuwait.

Fig.2 Sabkha soil excavation pit showing salts concentrations.

Each collected soil sample was thoroughly mixed in containers to create a single, highly consistent composite in the laboratory. The required quantity was oven-dried for 3 days up to 60°C to reduce considerable changes in the sabkha soil characteristics [20]. The soils were gently separated with a rubber hammer, sifted using a 4.7-mm (4-mesh) stainless steel sieve, and stored in plastic bags for subsequent sample preparation and analysis.

3.3 Index Properties

To assess their physical properties, different soil samples were tested for their particle size distributions, consistency limits, specific gravities, and compaction. As the tested soil samples contained considerable fines, mechanical sieving and hydrometer analyses were performed. These tests were performed according to ASTM D422 [21]. The particle size distribution parameters of the soil sample (D_{10}, D_{30}, and D_{60}), coefficient of uniformity (Cu), and coefficient of curvature (C_c) were determined from the grain-size distribution curve. Natural sabkha soil consistency tests, liquid limit (LL), and plastic limit (PL) were conducted according to ASTM D4318 [22]. The tested soils were classified according to the unified soil classification. Soil-specific gravity (Gs) was determined according to ASTM D854 [23]. The respective maximum dry density (MDD) and optimum moisture content (OMC) values were obtained from the compaction test, which was conducted using the modified Proctor method according to ASTM D1557 [24]. The minerals in the sabkha soil and dune sand were distinguished via X-ray diffraction (XRD) analysis.

3.4 Leaching Process and Chemical Analysis

The primary goal of this study is to investigate the variation in the hydraulic conductivity of the soil samples with varying total dissolved solids (TDS) amounts. TDS is one of the measures used to determine the salinity of leachate. It represents the weight of the dissolved materials obtained by evaporating a known volume of leachate to dryness.

The leaching process was performed as per the leaching tests using a leaching cell (Fig.3) and as described by Al-Otaibi [18] and Al-Otaibi et al. [19]. Each soil sample was compacted in the leaching cell across five layers according to their compaction parameters obtained from the modified compaction test. The following assumption was made to determine the pore volume of the tested soil samples in the leaching cell: the pore volume was equal to the amount of water required to fill the soil pores. This amount is equal to the product of the bulk volume and total porosity. Distilled water was used in the leaching process because it has a negligible concentration of ions and hence a minimal effect on the chemical analysis. Initially, the distilled water percolated into the leaching cell from the bottom of the cell at low pressure (1 psi) to ensure sample saturation. The following day, the sample was leached from top to bottom under 3-psi pressure. The applied pressure represents a 2.1-m head, which was selected after several trials and based on the author's experience working with these soils. A higher pressure (7 psi) was used in previous studies by Al-Otaibi **[15,16]** on sabkha soils to increase the leached pore volumes within a reasonable time. However, such high pressure is unsuitable for the dune sand soil sample examined in the current study.

Experiments were conducted at a controlled room temperature (25°C) with variability of ±0.5°C. Leachate was collected in a glass bottle for each pore volume and refrigerated until further TDS analysis had to be performed.

4. RESULTS AND DISCUSSION

4.1 Soil Characterization

4.1.1 Soil mineralogy

Mineralogical composition results for tested soil obtained using XRD analysis are shown in Fig.4. The predominant component of the sabkha soil was silicon dioxide (SiO_2), followed by calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$); the minor minerals were aragonite ($CaCO_3$) and halite (NaCl). The mineralogical analysis for the dune sand revealed that it mainly comprised quartz, with lesser quantities of calcite and feldspar, and clay minerals were rarely present. These results agree well with other reports on the surface deposits in Kuwait [6-8,15-18,20].

Fig.3 Experimental setup for the leaching test

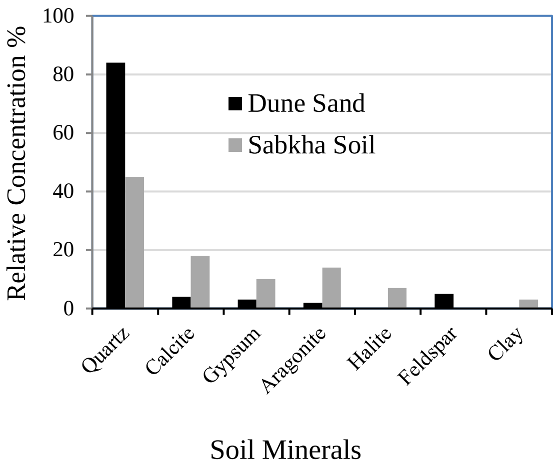

Fig.4 Mineralogical analysis of tested soils

4.1.2 Physical soil properties

The grain-size distribution curves obtained from the sieve and hydrometer test results for the sabkha, and dune sand soil samples are shown in Fig.5 and Fig.6, respectively.

Figure 5 shows that the collected sabkha samples comprise sand without any gravel with 10%–18% of fines passed through a 63-μm sieve. By contrast, the dune sand samples are uniform medium-to-fine sands with <3% fines, as shown in Fig.6. The soil grain size analysis results for the tested sabkha and dune sand soil samples from the tested locations are summarized in Tables 1 and 2, respectively.

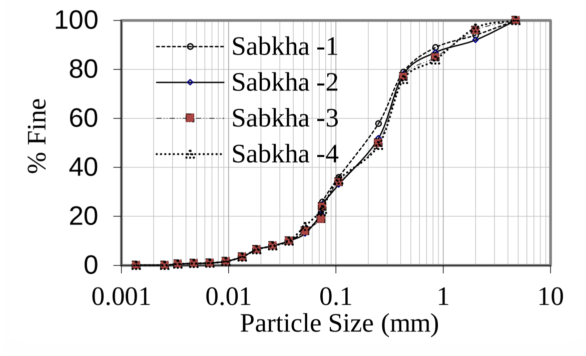

Fig.5 Gradation curves for sabkha soil samples

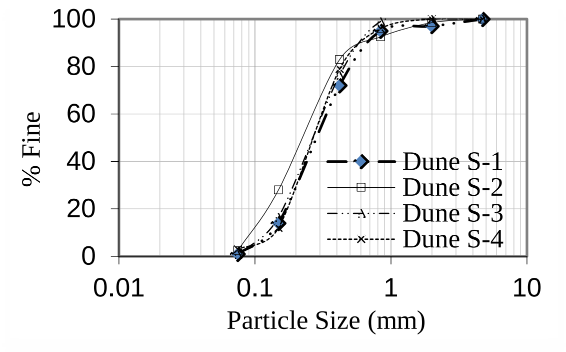

Fig.6 Gradation curves for dune sand samples

Similar results for soil gradation have been observed in various studies regarding the investigations on sabkha soils in southern Kuwait [15,16,18,25] and dune sands [6-8,26].

Grain-size distribution curves shown in Fig.5 and Fig.6 indicate that the collected soil samples have similar gradation curves. Figure 7 shows the grain-size distribution curves of soils used in the leaching tests.

Table 1 Physical characteristics of the tested sabkha soil samples

	Sabkha-1	Sabkha-2	Sabkha-3	Sabkha-4
D_{10}	0.08	0.02	0.017	0.05
D_{30}	0.14	0.12	0.13	0.15
D_{60}	0.2	0.27	0.25	0.28
Cu	2.5	13.5	14.7	5.6
C_c	1.2	2.7	4	1.6
FINE%	11	20	18	12
PL%	17	15	17.5	16.5
LL%	19.5	18	19.5	18
PI%	2.5	3	2	1.5
USC	SP-SM	SP-SM	SP-SM	SP-SM
GS	2.68	2.65	2.7	2.65
OMC%	11.8	10.75	13	9.78
MDD g/cm^3	1912	1945	1918	1936

Table 2 Physical characteristics of the tested dune sand samples

	Dune S-1	Dune S-2	Dune S-3	Dune S-4
D_{10}	0.14	0.095	0.13	0.15
D_{30}	0.21	0.17	0.18	0.2
D_{60}	0.35	0.275	0.31	0.32
Cu	2.5	2.9	2.4	2.1
C_c	0.9	1.1	0.8	0.8
FINE%	1	2.5	0.8	3
PL%	-	-	-	-
LL%	-	-	-	-
PI%	NP	NP	NP	NP
USC	SP	SP	SP	SP
GS	2.75	2.8	2.8	2.78
OMC%	12.25	8.75	10.5	11.5
MDD g/cm^3	1710	1685	1710	1680

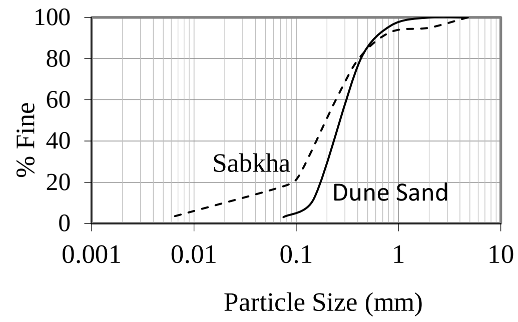

Fig.7 Gradation curves for sabkha and dune sand samples used in the leaching tests

4.1.3 Consistency limits

The plastic properties of the sabkha and dune sand soil samples are summarized in Tables 1 and 2, respectively (Section 3.1.2.). Almost all sabkha soil samples had low plasticity, while the dune sand samples were nonplastic. The low plasticity value for the sabkha soil sample is expected to be due to the low content of clay and fine contents [27]. Furthermore, the consistency limits of the soil may differ because of the high concentration of soluble salts [28]. Similar observations were reported by Al-Otaibi [18] and Al-Otaibi et al. [19] on soil properties in southern Kuwait.

4.1.4 Soil classification

The sabkha soil samples were classified as poorly-graded sand with silt (SP-SM), while the dune sand samples were poorly-graded sand (SP). Similar soil classification results were reported for southern sabkha soils in the literature [6-8, 15,16,18].

4.1.5 Specific gravity

The specific gravity values of the sabkha and dune sand soil samples were 2.65 and 2.8, respectively (Tables 1 and 2; Section 3.1.2). The specific gravity values of sabkha soil samples are lower than those of typical or silty sands, similar to the values reported by Al-Amoudi et al. [11]. The lower values of specific gravity for sabkha soils are due to the low oven temperature (60°C) at which the specific gravity was determined [20] and the high salt content of sabkha soils. The specific gravity value obtained in the current work is within the range of those reported for southern sabkha soils in Kuwait [15-17,29,30].

4.1.6 Compaction characteristics

Figures 8 and 9 represent the results of the modified Proctor compaction tests for the sabkha and dune sand soil samples, respectively. The compaction curves of the sabkha soil samples shown in Fig.8 have clearly defined peaks, whereas the compaction curves of the dune sand soil samples presented in Fig.9 are flatter with double peaks. The MDD and OMC values for the collected soil samples, calculated using the compaction curves, are listed in Tables 1 and 2 (Section 3.1.2).

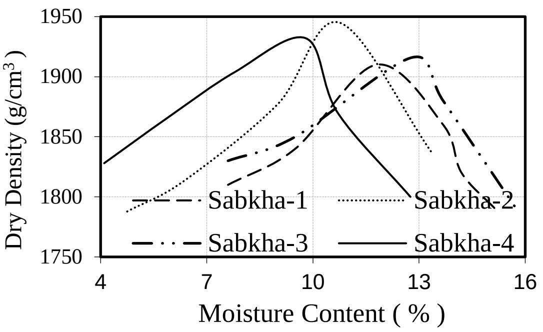

Fig.8 Sabkha soil samples' compaction curves

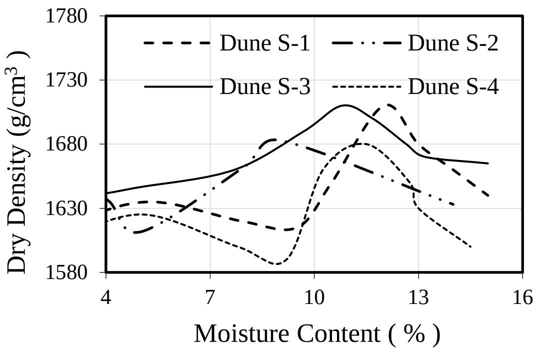

Fig.9 Dune sand samples' compaction curves

The low acceptable content of dune sand soil creates voids in the compacted soil, resulting in low dry density values. In addition, the degree of cementation between the soil particles may affect the soil mass because the percentage of the fines in the soil is proportional to the degree of cementation [30]. Furthermore, the low specific gravity of the dune soil samples reduces its dry density because the specific gravity values affect the dry density of the compacted soil [31]. The MDD and OMC values found in this study agree with the results reported in other studies on sabkha soils in Kuwait and the Gulf region [14,16,18,30].

The compaction curves of the sabkha and dune sand soil samples shown in Fig.8 and Fig.9 indicate that the tested samples in each location have similar characteristics. The compaction curves of the sabkha and dune soil samples subjected to the leaching tests are shown in Fig.10.

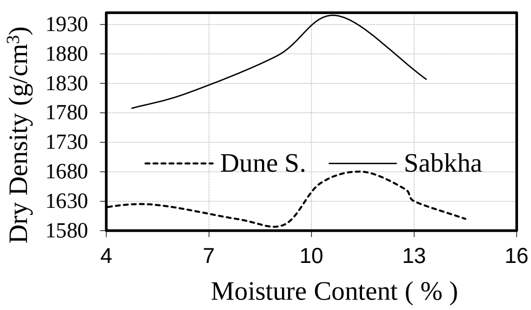

Fig.10 Compaction curves for sabkha and dune sand samples used in the leaching tests

4.2 Leaching Analysis Results

The sabkha and dune sand soil samples' hydraulic conductivity and salt dissolution rate were measured at different pore volumes. The leaching tests results for the sabkha and dune sand soil samples are shown in Fig.11 and Fig.12, respectively. These two figures depict the hydraulic conductivity coefficient (k) as a function of percolated pore volumes.

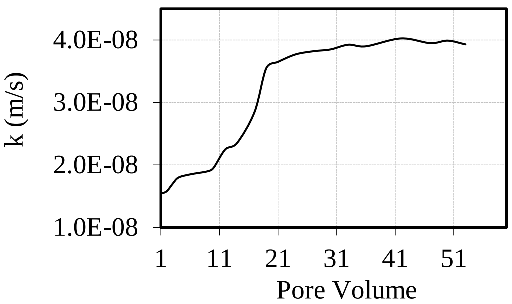

Fig.11 Relationship between hydraulic conductivity and pore volume

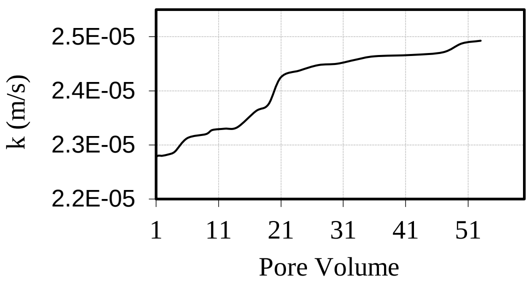

Fig.12 Relationship between hydraulic conductivity and pore volume for the tested dune sand samples

The initial hydraulic conductivity coefficients for the sabkha and dune sand samples were 1.155E−08 and 2.248E−05 m/s, respectively. Notably, the initial hydraulic conductivity coefficients were measured after the first pore volume for each soil sample. Figures 11 and 12 show that the soil hydraulic conductivity coefficient values (k) for both types of tested soil samples increase at different rates with increasing pore-volume percolation. The k values of the sabkha soil sample increased sharply to 20 pore volumes, with a k value of 3.55E−08 m/s at this pore volume. After 20 pore volumes, the k value increased slower until 53 pore volumes. The variations in the hydraulic conductivity values for the dune samples were lower than those in the sabkha soil sample.

To demonstrate the change in the hydraulic conductivity values for the tested soil samples, the percentage variations of the hydraulic conductivity values, which represent the percentage variation between the hydraulic conductivity values of the soil sample (k_i) at any pore volume concerning the initial hydraulic conductivity value (k_0), were calculated as $(k_i/k_0) \times 100$. Figure 13 shows the percentage variations in hydraulic conductivity values plotted as a function of percolated pore volumes.

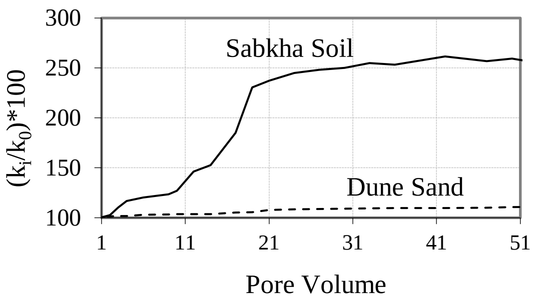

Fig. 13 K_i/K_0 versus pore volume for the tested soil samples

The hydraulic conductivity coefficients of the tested soil samples increased at different rates with continuous pore-volume percolation. In the case of the sabkha soil sample, the hydraulic conductivity variation was 230% and 259% at 20 and 50 pore volumes, respectively, compared with the initial values. For the dune sand sample, the variation percentage of hydraulic conductivity values was 110% at the end of testing, much smaller than the variation in the sabkha soil sample. Figure 14 depicts the relationship between the TDS concentrations with the leached effluent (pore volumes) for the tested soil samples.

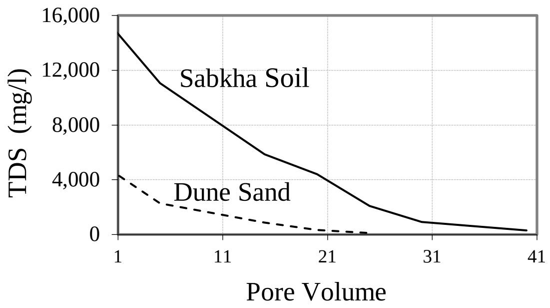

Fig. 14 Relationship between TDS and pore volume for the tested soil samples.

Figure 13 shows a clear trend of decreasing TDS concentration against increasing pore volume for the tested soil samples. The TDS concentration was 11000 and 2275 mg/l at the first five pore volumes for the sabkha and dune sand soil samples, respectively. The TDS concentration is a measure of the solubility of different types of salts, such as sulfate (SO42−), chloride (Cl−), and calcium (Ca2+) ions [15-17,25]. The higher TDS concentration of the sabkha soil sample is attributed to its high salt contents, which agrees with the findings of the previous mineralogical analysis (Section 3.1.1) and appears in the testing pit shown in Fig.2. The results indicate a more significant reduction in the TDS concentration values for the sabkha soil sample compared with the dune sand soil sample. Figure 15 shows an increase in the accumulated TDSs during leaching, which indicates the amount of salt erosion and extent of voids created and channels opened in the tested sabkha soil sample.

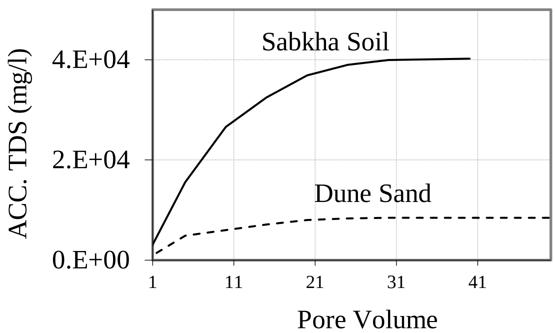

Fig. 15 Accumulated TDSs with pore volumes

The sabkha soil sample had a higher concentration of accumulated TDSs than the dune sand sample. The increase in the concentration sharply rises to the 20-pore-volume stage. The higher variation in the infiltration rate of the sabkha soil sample compared with that of the dune sand sample (Fig.13) may be attributed to the broader opened channels between soil particles due to salt dissolution. The dramatic increase in the hydraulic conductivity values between 14 and 19 pore volumes may be attributed to higher salt dissolution in this stage, as explained previously. Al-Otaibi **[**15,16] and Al-Otaibi et al. [19] reported similar results in their studies on sabkha soils in southern Kuwait. They attributed their findings to the calcareous nature of the leached soil samples. An increase in hydraulic conductivity with continuous leaching was also observed by Al-Otaibi and Wegian [19] and Al-Otaibi [15,16], who concluded that the primary dissolved ions in sabkha soils are Cl^{-}, SO_4^{2-}, and Ca^{2+} ions. The drainage flow rate generally increases in long folding due to fine particles erosion [32].

5. CONCLUSIONS

This study investigates the hydraulic conductivity variation in two main types of natural soil deposits in Kuwait (sabkha soils and windblown surface dune sands), with changes in the salt dissolution rate. Soil characterization revealed a higher concentration of salts in the sabkha soil sample than in the dune sand sample. The tested soil samples' hydraulic conductivity and TDS measurements were performed at 5 pore-volume intervals with continuously distilled water percolation. The key findings of this study are as follows.

1. The variation percentages in hydraulic conductivity were 250% and 110% for the sabkha and dune sand samples, respectively.
2. The TDSs of the sabkha soil sample were five times the dissolution of the salt value in the dune sand sample.
3. The tested soil samples' hydraulic conductivity variation was strongly correlated with the TDS concentration.
4. When selecting **a** stabilization mechanism for sabkha soil, the primary consideration should be to reduce salt dissolution.

6. ACKNOWLEDGMENTS

Part of this study was conducted during the Covid-19 pandemic, and the author wishes to thank all the technicians and workers who kept the work running as planned in these difficult conditions. The author would also like to acknowledge the Public Authority for Roads and Transportation for providing help during the sampling process of this study and the Kuwait Institute for providing access to the Scientific Research laboratory (KISR). The author would like to express his thanks to Engineer Dhai Fahad Al-Otaibi for providing technical support.

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