DISSOLUTION BEHAVIOR OF CORROSIVE ANIONS FROM SABKHA SOIL SOUTHERN KUWAIT UNDER LONG TERM LEACHING

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ABSTRACT: Corrosive anions leaching from sabkha soil due to continuous surface or subsurface flow, to ground water can create a corrosive environment for underground structures. This study aimed to investigate the amount of leached chloride (Cl⁻) and sulfates (SO₄²⁻) corrosive anions in terms of quantity and rate as a ratio of Total Dissolved Solids (TDS). In this study representative Sabkha soil sample from southern Kuwait was leached for 40 pore volumes with distilled water. It was determined that corrosive anions, chloride and sulfate, contributed to the high effluent TDS levels in the leachate. For TDS, the corrosive anions dissolution was over 50% in first leached pore volume, increasing to over 75% in the final stages of leaching. Results also showed a distinct tendency of reduction with pore volume in the concentration of SO₄⁻² and Cl⁻ anions. These findings will help allow the prevention of underground structure corrosion by evaluating the numerical criteria for particular anions such as chloride and sulfate. In establishing appropriate stabilization techniques, it is necessary to consider anion dissolution as one of the prime criteria.

Keywords: Sabkha, Corrosive, Dissolution, Sulfate, TDS, Chloride, Leaching.

1. INTRODUCTION

The surface soil layer, sabkha, showed a high salt concentration formed because of low precipitation and high evaporation rates in the arid environment. Differences in the type and concentration of precipitated salts lead to variances in the geotechnical properties of sabkha flats. Unfavourable geotechnical qualities in the flats, according to [1] are caused by the existence of chloride, carbonates, and sulfates that can be leached. [2] report that the quartz particles are left covered in a thin loose mat of illitic clay, with large voids, after the dissolution and leaching of halite, calcarenite and gypsiferous cements. Inundation of sabkha flats and water leading to the dissolution of these materials can cause major problems for buildings erected on them [1]. The natural cementation is destroyed by the percolation of distilled water through the sabkha. The results are an increase in permeability, the reduction in strength, increased settlement and possible collapse [3]. Buildings on these flats are subject to different levels of structural damage ranging from cracks to tilting to collapse. Chemical and physical weathering on buildings in Kuwait built on sabkha soils are very evident [4]. The salinity of sabkha soil and groundwater, according to [5] lead to major problems with corrosive action. [6,7] observe that sulfate and chlorides, corrosive anions, make sabkha flats hazardous for concrete and steel structures built on them, causing, eventually,

physical and chemical corrosion failure. The Environmental Protection Agency (EPA), USA, has designated chloride and sulfate anions as secondary contaminants. Therefore, they have been given a Second Maximum Contaminant Level (SMLC) classification. The SMCL for chloride and sulfate is set at 250 mg/L by the EPA, [8,9]; and [10] observe that sabkha sediment has a high concentration of chloride and sulfate salts, corroding steel reinforcements and decaying the concrete itself.

Expansion failures of mortar, clay bricks and concrete are observed due to salt crystallization [11]. The high gypsum content in the soil leads to a sulfate attack on the cement stabilizer [12] where ongoing chemical expansion and corrosion leading to major structural damage in cement-based construction. [7] state that the heat and high humidity of Kuwait stimulate deterioration and corrosion in reinforced concrete foundations on sabkha soil. Extreme hazards for the foundations of subsurface utilities and structures built on the sabkha [5] are exacerbated by the high chloride and sulfate contents of the soil and the groundwater. In contrast to the findings of many research projects, [13] maintains that soil permeability is unaffected by the leaching process, whereas leaching produces a definite collapse by softening and the dissolution and effusion of salts from the soil skeleton [2]. The concentration of sodium and chloride ions correlated with the volume of flow, and, therefore, the permeability of sabkha, reducing to very small amounts after two days as the ions reduced, [3] and the flow reduction was also reduced. The number of soluble salts removed by leaching significantly influence leaching and is found to be directly proportional. When investigating the stabilising of sabkha soil, [14-17] found an increase in soil permeability with continuous salt dissolution.

There is a lack of studies of sabkha soil corrosive anions dissolution rates in Kuwait. Experimental findings on the corrosive anions dissolution behavior would be extremely useful, particularly in relation to the type, rate and quantity, to benefit safe construction in Kuwait. It showed the effect of soil composition on corrosive anions dissolution should be included in mathematical models describing the simultaneous transport of these salts in soils. This research is aimed to increase understanding the rate of corrosive anions dissolution from sabkha soil under long-term distilled water leaching.

2. MATERIAL AND EXPERIMENTAL PROGRAMME

2.1 Soil Sampling

The sampling area is 75 km south of Kuwait City, a part of the sabkha flats along the southern coastal area (Fig.1). The site was chosen to take into account the open level ground, which is liable to flooding and therefore receives direct runoff waters.



Fig.1 Sampling location map [18].

Samples were taken at the end of the summer, in October 2018, with the highest salt concentrations following the high evaporation of summer and the dry state making the ground stable for sampling purposes, with the cementation effect of different salt levels and crystals in dry conditions.

Soil samples were extracted after determining the level of high salt concentration level from a borehole. Using the borehole log, four samples were taken from a depth of 50 cm at random points in the area. To ensure the samples equated to the representation of the original sample, a standard soil splitting procedure was used to split the collected 10 kg samples.



Fig.2 Sampling location during rainfall and dry seasons.

2.2 Laboratory Preparation

A mix of all samples ensured the creation of one consistent composite. The sample was air dried before each test and the selected amount was oven-dried to approximately 60°C to inhibit the transformation of gypsum-anhydrite phases, as recommended by [19]. Separation with the careful use of a rubber hammer was followed by sieving through a 4.75 mm (4-mesh) sieve. The materials were then mixed again, homogenised and stored in a container.

2.3 Index Properties

The physical properties of the different soil samples were measured for consistency limits, particle size distribution, specific gravity and compaction tests to assess their physical properties. As the samples contained a high volume of fines, mechanical sieve and hydrometer analyses were conducted, in accordance with the American Society for Testing and Materials (ASTM D422) standard [20]. Particle size distribution D10, D30, D60, the uniformity coefficient (Cu), and the coefficient of curvature (Cc) were determined. Adopting the modified Proctor method according to [21], the compaction test was conducted to record their respective Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). In accordance with [22], plasticity characteristics were conducted on the natural sabkha soil sample. The Plasticity Index (PI) was calculated from the two values. To establish main soil constituents and bulk mineralogical composition, a sample was prepared for X-ray Diffraction analysis (XRD). According to [23], the specific gravity (Gs), or particle density of different soil samples, was determined.

2.4 Leaching Test

Leaching is the process where soluble materials are removed from a section of the soil profile, [24]. Leaching for the current research was conducted using leaching tests as described by [14-16] (Fig.3), Identified by their compaction parameters from the modified compaction test, the sabkha samples were compacted on five layers in the leaching cell.



Fig.3 leaching cell apparatus [14].

2.5 Chemical Analysis

As stated initially, the prime aim of this study is to research the amount of leached corrosive chloride (Cl⁻) and sulfates (SO₄²⁻) anions as a ratio of the total ionic concentration of dissolved minerals in water in terms of TDS.

In order to identify the dissolution characteristics of the sabkha soil samples, chemical analysis was conducted. The collected pore volumes were analysed for the Cl⁻, SO_4^{2-} anions and TDS using ion chromatography technique (IC) [25].

2.6 Type of Leachate

Following previous studies by [2,14,15], distilled water was used in the leaching process. The water has a higher teaching capacity than brackish water and there are negligible volumes of ions to affect the chemical analysis [12].

2.7 Pore Volume

On the assumption that the volume of tested soil in the leaching cell would be equal to the volume of water needed to fill the soil pores, the volume was the same as the product of the bulk volume together with the total porosity.

2.8 Leaching Process

At first, the distilled water percolated from the bottom at a lower pressure (1 psi) to give sample saturation. The sample was percolated from the top to the bottom on the following day under a pressure of 5 psi. The pressure equated to 3.5 m water head. This figure was decided by the author and was based on his experience with sabkha soil and this pressure will increase the leached pore volumes in a reasonable time [15, 16]. Typical pressure and temperature conditions in the complex subsurface were not followed, as constant temperatures and pressures needed to be maintained for the experiment. The experiments were conducted at controlled room temperature with variability of $\pm 0.5^{\circ}$ C. Leachate samples were stored in a plastic bottle and refrigerated for future analysis.

3. RESULTS AND DISCUSSION

3.1 Soil Characterization

3.1.1 Soil Mineralogy

Fig.4 shows the results of the mineralogical composition for the soil sample tested by XRD analysis. Silicon dioxide (SiO₂), gypsum (CaSO₄ $2H_2O$), halite (NaCl) and calcite (CaCO₃) were the principal minerals in the sabkha soil sample with traces of aragonite (CaCO₃).



Fig.4 The XRD test result analysis of sabkha soil sample.

3.2 Physical Soil Properties

The grain-size distribution curves of the sabkha samples (Fig.5), indicate that the fines passing No, 200 sieve varied from 10 - 18 percentages and the sabkha samples consisted of sand and no gavel. The soil gradation analysis is shown in Table 1:

[26,14,15] reported results similar to those from this study's analysis. Table 1 shows the consistency limit values, that sabkha samples were low-plastic, resulting from the low fine contents and the lower amount of clay particles.

As stated sabkha soil samples are listed as poorly graded silly sand (SP-SM) by the USCS. Research from testing throughout the Gulf region, such as those by [13,19,14,15], have similar findings to those of this research testing.

The specific gravity of the sabkha soil samples was 2.8, lower than those of typical sand or silly sand values. According to [1], this can be related to the low oven temperature (60°C) and the sabkha soil high salt content.

pore volume (Table 2) were chemically analysed and the results are shown in Figs.7 and 8.

3.3 Compaction Characteristics

The modified proctor compaction test results for the tested soil samples (Fig.6) show a close range in the test parameters. MDD and OMC values, calculated from the compaction curves, are shown in Fig.1.



Fig.5 Grain size distribution curves for sabkha soil samples.

Table 1 Physical characteristics of sabkha soil samples.

Samples Location	D_{10}	D_{30}	D_{60}	C	C _c	Fine %	PL %	LL %	PI %	USC	GS	OMC %	MDD KN/m ³
*Sbk-1	0.065	0.125	0.28	4.3	0.9	11.0	18.0	21.5	3.5	SP-SM		10.30	19.04
*Sbk-2	0.017	0.125	0.28	16.5	3.3	20.0	17.0	19.5	2.5	SP-SM	·	8.80	19.07
*Sbk-3	0.018	0.14	0.3	16.7	3.6	18.0	19.5	22.5	3.0	SP-SM	2.79	9.65	18.70
*Sbk-4	0.038	0.16	0.3	7.9	2.2	12.0	14.5	16.5	2.0	SP-SM	ı	9.35	18.897

*Sbk means Sabkha.

The results of OMC and MDD values relate closely to those of sabkha soils studies conducted in Kuwait and other Gulf states [13,19].

3.4 Dissolution Characteristics

Leached chloride anions (Cl⁻), sulfates anions (SO₄²⁻), and TDS resulting from the percolated



Fig.6 Dry density versus moisture content for sabkha soil samples.

Table 2 Chemical	analysis	of l	eached	pore
volumes.				

PV	Chloride anions (Cl ⁻) (mg/l)	sulfate anions (SO ₄ ²⁻) (mg/l)	TDS
1	4100	3725	15558
5	2830	3129	11057
15	1295	2730	5864
20	920	2300	4417
25	195	1380	2096
30	53	720	930
40	10	215	301

A high concentration of corrosive ions, chlorides and sulfates are shown in the early stages of leaching in results from the leached pore volumes (Table 2).



Fig.7 Corrosive ions concentrations in effluents.



Fig.8 Variation in corrosive ions concentrations in effluents.

Chlorine and sulfates are shown to be the antons that add to the high effluent TDS levels. Concentrations of chloride (Cl⁻) and sulfate anions (SO_4^{2-}) were highest in the tested anions in the 20 leached pore volumes, resulting from gypsum being the main constituent in the sabkha samples, thereafter halite, as displayed in the XRD analysis. The dissolution of chloride (Cl⁻) anions diminishes after 25 pore volumes, while the leaching of sulfate anions (SO_4^{2-}) continues up to the 40 pore volumes. Table 3 shows the TDS and the ratio of corrosive anions dissolution, (Fig.9). TDS represent the sum of all common anions, for example, Na, K, Ca, Mg, Cl⁻, SO₄²⁻, and HCO³⁻, represent the TDS.

Table 3 Corrosive anions as a percentage of TDS in the leached pore volumes.

PV	(Cl ⁻) / TDS (%)	(SO4 ⁻²) / TDS (%)	Total Corrosive Ions (%)
1	26	24	50
5	26	28	54
15	22	47	69
20	21	52	73
25	9	66	75
30	6	77	83
40	3	71	75

The high ratio of the corrosive anion concentrations with respect to the total dissolved salts in the leached effluent. Are displayed in Table 3 and Fig.9. Table 3, which summarize the results appears to show the significant volume of leached corrosive anion concentrations in comparison to the total dissolved salts, the content of which was, in general, more than half the quantity of the total dissolved salts.



Fig. 9 Corrosive ion dissolution with respect to TDS along leached pore volume.

During their analysis of the collapsibility of sabkha soil, [27] observed a high dissolution of NaCl, where leaching was seen. They concluded that collapse is the primary ascribable to the dissolution of NaCl, soil grain adjustment and the leaching of calcium. Similar findings were reported by [28] in his leaching experiments with calcareous soils, that sulfate and chloride are among the highest dissolution salts. It was found that halite comprised 23% of the tested soil, which was confirmed by the XRD results.

Salt solubility and their concentration in the sabkha soil account for the variation in concentration, where the dissolution of powdered gypsum was 2 to 10 times faster than other forms as a result of both surface area and the presence of CaCo₃ impurity [29]. Representation of the ion dissolution in the tested soil sample (Figures 6 and 7) show a noticeable trait of reduction in the concentration of SO₄²⁻ and Cl⁻ with pore volume.

[27] reported similar results during their investigations on sabkha soils. They attributed the collapse to the calcareous nature of the leached soil samples. The quartz particles are left covered by a thin loose mat of illitic clay when large voids with dissolution and leaching of halite, gypsiferous and calcarenite cements occur, [2]. Gypsum has a solubility of (2g/l), in pure water, which is classified as a moderate soluble salt [29]. Normally its dissolution is more rapid in the presence of soil. This provides sinks for the Ca2+ and SO_4^{2-} ions released from the gypsum [29]. It should be reminded that current experiments were conducted at controlled room temperature with variability of $\pm 0.5^{\circ}$ [30], while gypsum solubility in the mixture increased by between 2 and 13% when mixing saturated waters at 10°C, and at temperatures ranging from 40 to 100°C.

4. CONCLUSIONS

This investigation aimed to examine the dissolution behaviour of corrosive anions namely

 Cl^{-} and SO_4^{2-} from sabkha soil from southern Kuwait. Selected sabkha soil sample was leached with distilled water for 40 pore volumes. The following results were deduced:

- 1- The effluent monitoring data show that chloride Cl⁻ and sulfate SO_4^{2-} anions potentially contribute to high effluent TDS levels where the two anions content was generally more than half the quantity of the total dissolved salts determined through the ion chromatography technique.
- 2- Higher leached concentrations of dissolved Cl⁻ and SO₄²⁻ anions in the first 20 pore volumes from sabkha soil samples, where the corrosive anions content was generally more than half the quantity of the total dissolved salts.
- 3- There was a clear trend of reduction in the concentration of SO₄²⁻ and Cl⁻ anions with continuous leaching.
- 4- Numerical criteria for specific anions such as chloride and sulfate are necessary to prevent underground structure corrosion.

5. FUTURE STUDY

There is a need for further investigation into the possible use of waterproof agents such as bitumen to reduce the dissolution of the corrosive ions from sabkha soil that participate in the progressive collapse of the soil structure and which affects the performance and durability of structures sited on or within such soil.

6. ACKNOWLEDGMENTS

The author is grateful to the support provided by the Ministry of Defense laboratory, Kuwait Institute for Scientific Research and Design Corner Engineering Consultants office. The author is also grateful to Eng/ Dhay F. Al-Otaibi for her technical support and for participating in effluent monitoring data research.

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