International Journal of GEOMATE, Feb., 2024 Vol.26, Issue 114, pp.42-49
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.114.3450
Geotechnique, Construction Materials and Environment

REDUCING CORROSIVE ANION DISSOLUTION IN SABKHA SOIL UNDER LONG-TERM LEACHING BY BITUMEN ADDITION

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ABSTRACT: Corrosive chloride (Cl^-) and sulfate (SO_4^{2-}) in sabkha are major environmental factors accelerating the deterioration of concrete structures with steel rebars or steel structures through long-term exposure. The dissolution of these corrosive anions from the surrounding soil must be reduced to increase the lifespan and durability and to ensure the protection of such structures. This study investigated the impact of bitumen addition on the amount of leached corrosive Cl^- and SO_4^{2-} in terms of quantity and rate as the percentage of total dissolved solids. Representative sabkha soil samples obtained from southern Kuwait were blended with various bitumen contents and leached with distilled water for more than 25 days, and the leached pore volumes were examined for the detected anions. Bitumen percentages of 0%, 4%, and 12% (by dry weight of sabkha) were selected as the mixing percentages based on geotechnical testing (density results obtained via modified Proctor tests) below and above the optimum bitumen contents. Results show that corrosive anion dissolution is reduced more in the bitumen-mixed sabkha than in the natural soil samples. The $SO_4^{2-}$and Cl^- concentrations almost diminish at the early leaching stages in the 12% bitumen-mixed sabkha sample, showing a strong reduction trend in the corrosive anion concentration. These findings highlight the importance of the waterproofing effect of bitumen in reducing corrosive anion dissolution from sabkha soil, which will reduce the impact of these soils on various structures, particularly buried gas, or oil steel pipes, and improve the effectiveness of other protective methods used for these structures.

Keywords: Sabkha, Corrosive anion dissolution, Bitumen, Sulfate, chloride, Leaching

1. INTRODUCTION

Sabkha is aggressive to concrete and steel structures owing to the presence of corrosive anions such as chloride (Cl^-), sulfate (SO_4^{2-}), and carbonate (CO_3^{2-}), which induce physical and chemical corrosion failure [1,2,3]. These ions along with other chemical constituents that induce sabkha soil leaching and influence its geotechnical properties [3,4,5,6] are particularly harmful because they originate from different sources [3]. The high concentration of these anions in sabkha sediments and their brines result in the corrosion of steel reinforcements and the deterioration of concrete [1,4,5,6], which are important causes of the degradation of various existing strengthened concrete structures [4]. The corrosion rate of steel gradually increases owing to a decrease in pH, increase in temperature, and high concentrations of corrosive anions, such as Cl^-, SO_4^{2-}, and HCO^{3-}, in the environment [1,5]; however, chloride is the primary source of reinforcement corrosion in some cases and concrete materials durability [4,5,6]. Moreover, crystallization and changes in the chloride crystal can lead to a change in its volume, thereby causing an expansive breakdown of mortar, concrete, and clay bricks [7]. The hot climate and high humidity of Kuwait may accelerate the physical and chemical weathering of building materials, which could cause the collapse and corrosion of reinforced concrete foundations built on sabkha soils [8,9]. Sulfate attack on cement stabilizers owing to a high gypsum content in the soil [1, 5] occurs via sulfate reactions with the cement hydration products, leading to continuous chemical expansion and corrosion, resulting in severe damage to structures composed of cement-based materials. The selection of appropriate materials and engineering practices for sabkha formations has long been a challenge, with [10] reporting major safety and serviceability issues in the infrastructure of newly built cities owing to inappropriate construction practices. The corrosion of steel pipelines in saline sandy soil indicates that SO_4^{2-} critically influences the initial corrosion behavior of pipeline steels, while the corrosion rate is influenced by the presence of Cl^- and HCO^{3-} [11]. The coating is a conventional method for protecting steel pipes. However, a corrosive saline environment reduces the effectiveness of the coating method [12].

Previous research has focused on the investigation of sabkha soil [13-14,15,16], reporting an increase in soil permeability with continuous salt dissolution. This increase in soil permeability owing to leaching causes a significant collapse of the soil skeleton because of the softening, dissolution, and effusion of salts from the sabkha soil skeleton [17]. Owing to the dissolution of these salts in water caused by the flooding of sabkha soil, building structures on such surfaces becomes challenging [17,18] because concrete and steel structures are vulnerable to degradation owing to corrosion, thus compromising their safety and service life.

Al-Otaibi [1] studied the dissolution rate of corrosive anions in sabkha soil obtained from southern Kuwait. The test findings of effluent data analysis revealed that corrosive ions, Cl^- and SO_4^{2-}, possibly contribute to high levels of effluent total dissolved salts (TDSs). The contribution of the dissolution rate of corrosive anions to the TDS at the end of the leaching process exceeded 75%. Al-Otaibi [1] reported that numerical criteria for certain anions, including Cl^- and SO_4^{2-}, should be considered to prevent the corrosion of underground structures.

2. RESEARCH SIGNIFICANCE

The two main corrosive anions, chloride (Cl^-) and sulfate (SO_4^{2-}) [1], highly influence the corrosion rate [6] and accelerate the deterioration of concrete structures with steel rebars under long-term exposure. Consequently, it would be extremely useful to explore the effect of employing waterproofing materials, such as bitumen, on reducing the dissolution rate of corrosive anions in sabkha soil samples during long-term water leaching. It is critical to reduce the dissolution of such harmful anions to minimize the corrosion rate of concrete structures, which will increase their lifespan and durability as well as increase the effectiveness of other protection methods. Laboratory leaching investigation results of this study and future research for both natural and stabilized sabkha can be employed to develop a conceptual leaching model that explains the leaching patterns of corrosive anions and specific control techniques.

3. MATERIALS AND METHODS

3.1 Soil Sampling

The sampling zone is a part of the sabkha that extends along the southern coastal area of Kuwait and was also the same location where the current author conducted a previous study [1]. Al-Otaibi [1] followed a soil sampling procedure to ensure that the chosen soil samples represented a uniform field area. The level of the high salt concentration layer for soil sampling was determined based on soil borehole test results conducted by [1] for the examined location. Soil samples were selected from one point since previous data for random points throughout the location and at 50 cm depth were assessed and recorded by [1].

The collected soil samples were thoroughly mixed and air-dried before each test and the required quantity was oven-dried to a maximum temperature of about 60°C to inhibit the transformation of gypsum-anhydrite phases [16,18,19]. The soils were gently separated using a rubber hammer, sieved using a 4.75-mm (4-mesh) stainless steel sieve, and stored in plastic bags for subsequent sample preparation and analysis.

Different specimens were air-dried, weighed, and mixed with 0%, 4%, and 12% of bitumen by weight. These percentages were selected according to previous investigations that revealed that optimum bitumen contents were lying from 3% to 12% [14,15]. The cut-back bitumen was made of a certain percentage of bitumen and an added percentage of kerosene, based on the manufacturer's specification.

The cut-back bitumen and sabkha soil were manually mixed to obtain an obvious quality homogeneous mixture. The mixture was remixed for one minute using a mechanical mixer. The mixture was then oven-dried to a maximum temperature of about 60°C for three days to simulate the field factor and to evaporate the material employed for the cut-back bitumen.

3.2 Experimental Tests

Various soil index tests were performed to assess the sabkha soil properties. Particle size distribution tests were performed according to ASTM D422. The effective grain size of the soil sample (D_{10}, D_{30}, and D_{60}), coefficient of uniformity (Cu), and coefficient of curvature (Cc) were determined. Furthermore, plasticity characteristics of the natural sabkha soil sample were carried out and the liquid limit (LL) and plastic limit (PL) for the natural sabkha soil samples were obtained based on ASTM D4318. The plasticity index (PI) was computed from these two values. Unified soil classification was employed to classify sabkha soil samples according to ASTM D2487. The specific gravity (Gs), or particle density of various soil samples, was determined considering ASTM D854.

The compaction test was conducted with the modified Proctor approach regarding ASTM D1557 to obtain their respective maximum dry density (MDD) and optimum moisture content (OMC).

3.3 Leaching Test

Leaching assessments were conducted on a wide variety of materials for regulatory purposes, waste management, environmental impact assessment, and scientific goals [20,21]. Previous investigations indicated that data from column leaching tests of various materials (contaminated soil, demolition waste, and waste incineration ash) of different compounds (heavy metals and polyaromatic hydrocarbons) related well with lysimeters and could be fitted reasonably with the advection-dispersion model [21]. The leaching process in the current study was performed using leaching tests described by [13,14] and the procedures proposed by [1] were employed for the evaluation of the results. The leached cell comprised a hollow plexiglass cylinder with a 3.0-mm-thick wall, an outer diameter of 110 mm, and a total length of 125 mm. Based on several previous works [14,15,16], distilled water was utilized in the leaching process since it has greater leaching capability than brackish water and a negligible concentration of ions to reduce the impact on the chemical analysis. The representative sabkha samples were prepared considering their compaction parameters obtained from the modified compaction assessments for the sabkha and bitumen-mixed sabkha soil samples.

The distilled water was initially allowed to percolate from the bottom at a lower pressure (1 psi) to ensure sample saturation. The sample was percolated the next day from the top to the bottom under a pressure of 5 psi (34.5 kPa). The applied pressure reflected a 3.5 m water head, selected based on the authors' knowledge of these soils to increase the leached pore volumes at a suitable time [1,15,16], The pore volume of the tested soil in the leached cell was determined by assuming that it was equal to the amount of water needed to fill the soil pores. This amount is equal to the product of the bulk volume and the total porosity. Temperature and pressure conditions common in the complex subsurface were not replicated to maintain constant temperature and pressure for this investigation. Experiments were conducted at a controlled room temperature with variability of ±0.5°C. The leachate for each pore volume was collected in separate 500-mL borosilicate glass bottles, which were stored in a refrigerator until further analysis. To examine the effects of bitumen treatment, chemical analyses were performed for chosen pore volume to identify the dissolution characteristics and variations for the tested sabkha soil samples. The collected pore volumes were analyzed for the corrosive Cl^- and SO_4^{2-} using the ion chromatography technique [22].

4. RESULTS AND DISCUSSION

4.1 Soil Characterization

4.1.1 Soil Mineralogy

Mineralogical composition results previously reported by [1] for soil samples obtained from the same location were evaluated using X-ray diffraction (XRD). The principal minerals in the sabkha soil were silicon dioxide (SiO2), calcite (CaCO3), gypsum (CaSO4·2H2O), aragonite (CaCO3), and halite (NaCl).

4.1.2 Physical Soil Properties

The grain size distribution curves resulted from the sieve and hydrometer tests of 0%, 4%, and 12% bitumen blended sabkha soils, as shown in Fig.1. As shown in Fig.1, bitumen-mixed sabkha soil samples become marginally coarser compared with the natural sabkha, where the 11% fines passing No of 200 sieves in the natural sabkha disappeared in the 4%, and 12% bitumen-mixed sabkha samples.

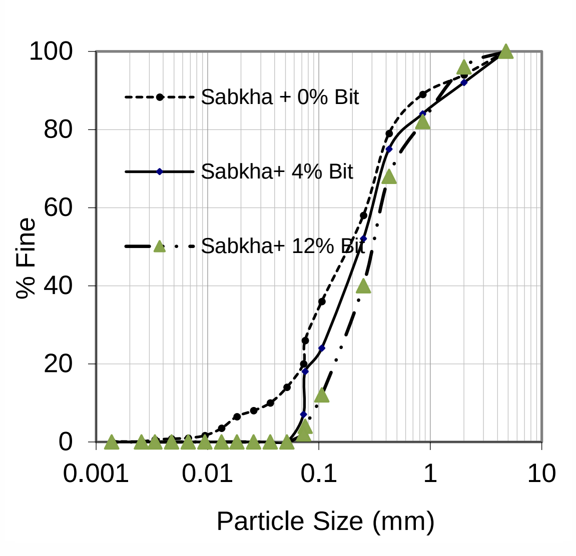

Fig.1: Grain size distribution curves for natural and bitumen mixed sabkha soil samples.

Soil aggregation is expected to be due to the effect of the adsorbed bitumen on the soil particle surfaces. Similar results have been observed in various studies on contaminated oil residue and bitumen-stabilized soils and have been attributed to an adsorbed viscous layer [14,15]. The plasticity properties of natural and bitumen-stabilized soil samples have been determined and presented in Table 1. LL and PL for the natural sabkha were 21.5 and 18, respectively. The bitumen-mixed sabkha soil samples were nonplastic; therefore, the liquid and PLs could not be assessed. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) values were calculated and summarized in Table 1. The Cu and Cc values indicate that the bitumen-mixed sabkha soils were classified according to the Unified Soil Classification System as poorly graded sand (SP), whereas the natural soil sample was classified as poorly graded sandy clay (SP–SCL).

Table 1 Physical characteristics of South Sabkha soil samples

	Sabkha Soil + 0% Bit	Sabkha Soil + 4% Bit	Sabkha Soil + 12% Bit
D_{10}	0.0365	0.075	0.1
D_{30}	0.085	0.14	0.185
D_{60}	0.275	0.3	0.362
Cu	7.5	4	3.62
Cc	0.72	0.87	0.95
FINE %	11	0	0
PL %	18	NP	NP
LL%	21.5	--	--
PI%	3.5	--	--
USC	SP–SCL	SP	SP
GS	2.79	NM	NM
OMC%	13	12.2	9.7
MDD kg/m3	1915	1938	1930

Therefore, soil classification of bitumen-mixed sabkha soil is expected to vary from that of natural soil due to changing soil gradation and consistency limits with bitumen addition. Previous results are in agreement with findings reported by [13] on his investigations of oil lake residue stabilized sabkha soils.

The sabkha soil sample's specific gravity value was 2.79. The sabkha soils' specific gravity values were lower in comparison with the typical sands' or salty sands' specific gravity values. This was meant to be caused by the combined impact of the specific gravity's low oven temperature (60°C) and the sabkha soils' high salt content [17] and may require corrections owing to the dissolution of the salts [23]. The specific gravity for the bitumen-mixed sabkha soil samples was not measured due to the difficulties reported by [13].

4.2 Compaction Characteristics

Modified Proctor compaction tests were performed on 0%, 4%, and 12% bitumen-mixed sabkha soil samples to develop their compaction parameter values for the range of bitumen addition. Results of compaction tests on natural and bitumen-mixed sabkha soil samples are displayed in Fig.2 and the MDD and the corresponding OMC values for various examined soil samples are summarized in Table 1.

The moisture content–dry density relation curves revealed an increase in the MDD value for the bitumen-mixed sabkha soil samples of 4% bitumen content, from 1915.0 kg/m^3 for natural sabkha to 1938.0 kg/m^3 of 4% bitumen-mixed sabkha soil sample. A reduction in the MDD value for the bitumen blended sabkha soil samples of 12% bitumen content and 1930.0 kg/m^3, was recorded. The increase in the MDD may be attributed to the higher compactness of the 4% bitumen mixed than the natural sabkha soil samples. The viscous bitumen layer facilitated the sliding of soil particles, and the denser soil was reached at lower moisture content, whereas the density reduced with further bitumen addition beyond the optimum bitumen content.

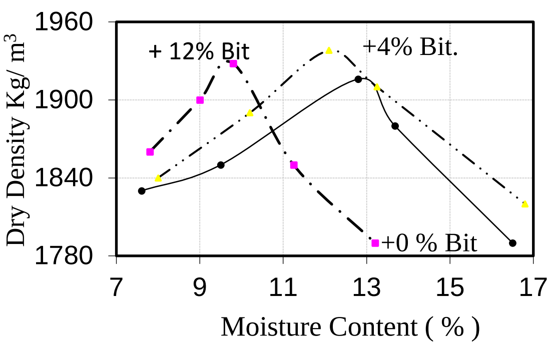

Fig.2 Dry density versus moisture content results

Compaction tests were carried out to establish the compaction parameter values for a range of bitumen addition, rather than to explore the relationship between the MDD values and the bitumen content according to [13] and [14]. Because the goal of this study was to assess the waterproofing effect of bitumen in reducing the corrosive ion dissolution, leaching examinations were carried out on the 0%, 4%, and 12% soil samples, regardless of the optimum.

4.3 Dissolution Characteristics

The percolated pore volumes resulted from leaching tests for the sabkha soil +0%, 4%, and 12% were chemically analyzed, and the amount of leached Cl^- and SO_4^{2-} are listed in Tables 2 and 3, respectively.

Table 2 Chloride anion (Cl^-) con. (mg/L) at PV

PV	Sabkha + 0% Bit	Sabkha + 4% Bit	Sabkha + 12% Bit
1	4100	2200	270
5	2830	1230	95
15	1295	315	45
20	920	35	0
25	195	0	0
30	53	0	0
40	10	0	0

The Cl^- dissolution concentration for 0%, 4%, and 12% bitumen content sabkha soil samples were (4100), (2200), and (270), respectively, which revealed a reduction in dissolute anion concentration values with further bitumen addition. Cl^- was not detected at 20 pore volumes in the 12% bitumen-mixed sabkha soil sample, indicating that the reduction increased with additional pore volumes.

Table 3 Sulfate anion (SO_4^{2-}) con. (mg/L) at PV

PV	Sabkha + 0% Bit	Sabkha + 4% Bit	Sabkha + 12% Bit
1	3725	1350	335
5	3129	1125	275
15	2730	995	165
20	2300	658	105
25	1380	370	45
30	720	65	0
40	215	0	0

Similarly, the SO_4^{2-} concentration readings in Table 3 continued to decrease in both bitumen-mixed sabkha soil samples. More reduction was recorded for the 12% bitumen-mixed sabkha soil sample, where the reading was over 20 pore volumes, which was very low.

The amount of dissolute corrosive anions is shown in Figs.3 and 4. An obvious reduction in the amount of corrosive anions dissolution is shown graphically, where an extremely low amount of corrosive anion dissolution after the 15-pore volume with 12% bitumen addition is indicated.

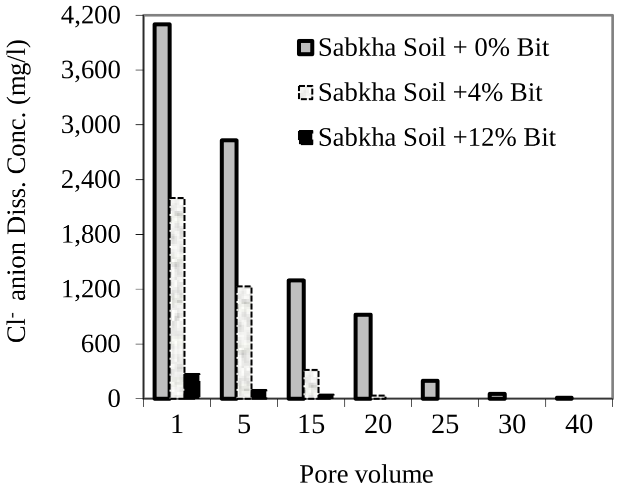

Fig.3 Chloride anion (Cl−) conc. vs. PV

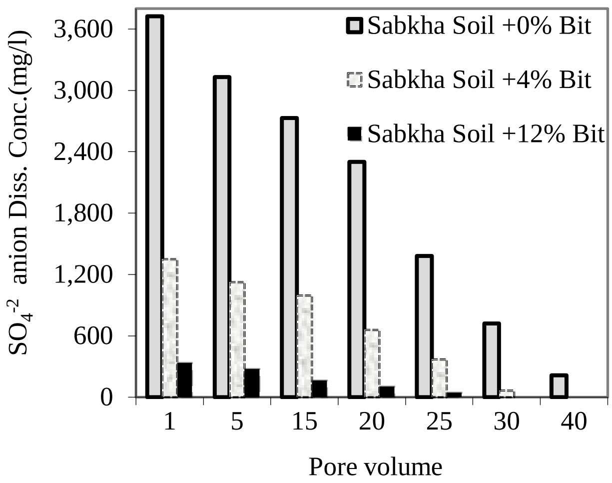

Fig.4 Sulfate anion (SO_4^{2-}) conc. vs. PV

The reduction rate of the corrosive anions is calculated and presented graphically in Figs.5 and 6.

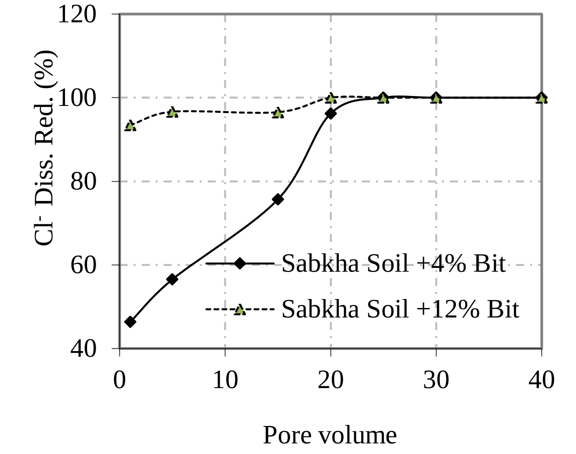

Fig.5 Chloride anion (Cl−) reduction rate vs. PV

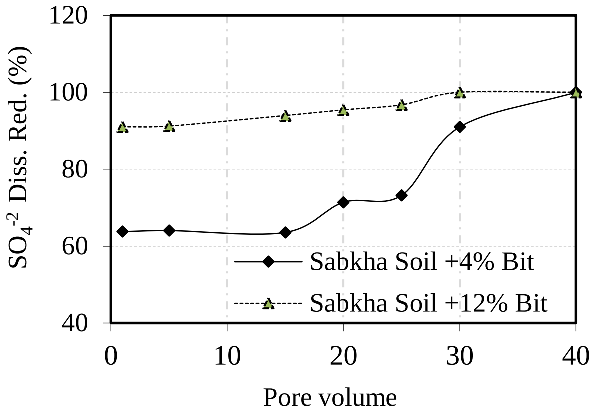

Fig.6 Sulfate anion (SO_4^{2-}) reduction rate vs. PV

The effect of bitumen addition on the reduction of corrosive anion dissolution concentration can be observed. A higher reduction occurred in the 12% bitumen-mixed sabkha soil samples. The reduction percentage of the corrosive Cl^- and SO_4^{2-} almost exceeded 90% for the 12% bitumen-mixed sabkha soil samples. Based on a previous study by [1], the main dissolution of corrosive anions in soil samples obtained from the current location as a ratio to the TDS is shown in Fig.7. TDS represents the total concentration of dissolved substances in water that contains inorganic salts. The TDS represents the sum of common ions such as magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^+), potassium (K^+), Cl^-, SO_4^{2-}, and bicarbonate (HCO^{3-}). It can be observed that SO_4^{2-} and Cl^- are the anions that probably contribute to high effluent TDS. The concentrations of SO_4^{2-} and Cl^- were the highest among the tested anions across the 20 leached pore volumes, which is likely because of the release of gypsum and halite minerals, indicated using XRD analysis.

The waterproofing impact of bitumen also reduced the high dissolution of NaCl leaching, which is expected to be the primary cause of sabkha soil collapse [24,25].

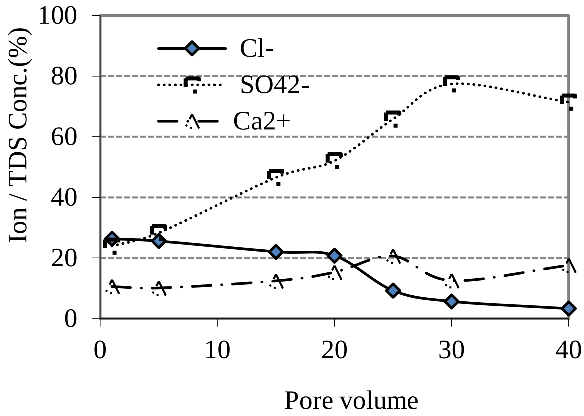

Fig.7 Main corrosive ion dissolution vs PV [1]

In general, the waterproofing impact of bituminous materials is expected to reduce the extent of gypsum dissolution in soil, which primarily increases the concentrations of Ca^{2+} or SO_4^{2-}) in the leached pore volumes of the natural sabkha soil [26]. Because gypsum is classified as a moderate soluble salt, the solubility of the hydrated gypsum in pure water was 2 g/L [27,28]. Dissolution of gypsum is generally faster in the presence of soil that provides sinks for Ca^{2+} and SO_4^{2-} released from the gypsum [27], and the waterproofing effect is expected to reduce the dissolution rate by minimizing the dissolution of these constituents. Moreover, the importance of reducing SO_4^{2-} and Cl^-, which were among the highest dissolved salts in calcareous soils in Kuwait [22], is expected to reduce steel pipe deterioration in sabkha, which is uncontrollable and unavoidable despite protective coatings like cathodic protection [6,28].

5. CONCLUSIONS

The goal of this study was to discover if the addition of bitumen may reduce the dissolution of corrosive anions, such as Cl^- and SO_4^{2-}, in Kuwait's southern sabkha soil samples. Sabkha soil samples mixed with 0%, 4%, and 12% bitumen were leached with distilled water for more than 35–40 pore volumes. Results obtained from this research reveal the following observations:

1. The effluent monitoring data demonstrates that Cl^- and SO_4^{2-} could be reduced with further bitumen addition.

2. A trend of reduction in the concentration of SO_4^{2-} and Cl^- with continuous leaching in 4% and 12% bitumen-mixed sabkha samples.
3. Higher reductions were observed in the 12% bitumen content detected in the first 5 pore volumes from the sabkha soil sample, where the corrosive anions content was high in the natural soil sample, where the leached concentrations of dissolved Cl^- and SO_4^{2-} practically declines.
4. Reducing the dissolution of anions, such as Cl^- and SO_4^{2-}, is predicted to reduce the corrosive environment, which will aid in the prevention of underground structures corrosion and soil collapse through various service protection mechanisms.

The heterogeneous nature of sabkha soils and the lack of information on their engineering properties and performance make it necessary to carry out additional investigations on sabkha soil behavior, mixed with bitumen to create a databank of information. It is also acknowledged that an in-depth investigation of chemical bonding mechanisms at the soil-bitumen-water interface is necessary for a better interpretation of the physical and geotechnical behavior of composite materials.

7. ACKNOWLEDGMENTS

The author wishes to acknowledge the Corner Design Office for assisting in the sampling process. The author would also like to express his thanks to Engineer Dhay F. Al-Otaibi for providing technical support and to Hessa F. Al-Otaibi for financial advice.

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