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IMPROVING THE CONSOLIDATION CHARACTERISTICS OF SALINE SABKHA SOIL BY ADDING BITUMEN

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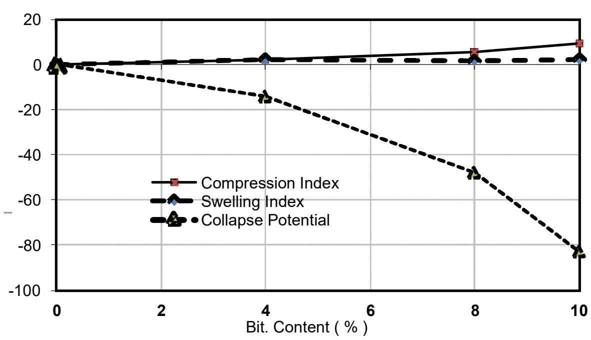
Graphical abstract



Abstract

The rapid economic and population growth, increase in constructions, and a small selection of appropriate soil resources in Kuwait have made it necessary to research soil stabilization methods because the existing soils are currently unsuitable in their natural conditions. In this study, the consolidation characteristics of sabkha soil samples in southern Kuwait mixed with 0%, 4%, 8%, and 10% bitumen with respect to soil dry weight were investigated. For this purpose, an experimental program, including soil characterization tests, modified Proctor compaction test, one-dimensional consolidation test, and collapsibility test, was executed. Results indicate that increasing the bitumen percentage improves the compressibility characteristics of sabkha soil. Upon the addition of 10% bitumen, the yield stress increased from 25 to 34 kPa, compression index slightly increased from 0.02774 to 0.03145, and swelling index decreased from 0.0119 to 0003. Further, there was a considerable reduction in the collapse potential from 1.192 to 0.301 upon the addition of 10% bitumen. Thus, it is evident that the disadvantageous characteristics of sabkha soil can be mitigated. The results support the possibility of recycling the sabkha soil, thereby contributing toward addressing the environmental issues associated with the disposal of excavated sabkha soil.

Keywords: Sabkha soil, compression index (Cc), swelling index (Cs), collapse potential (CP), oedometer test

1.0 INTRODUCTION

Large parts of surface deposits in the northern and southern coasts of Kuwait consist of salt-encrusted flats known as sabkha (Figure 1) [1]. The southern sabkha deposits are scattered and irregularly shaped, closed regions of different extents [2]. These flats are generally poorly graded fine sand to sandy silt with 5%–20% of fines and salty mixtures [3, 4, 5].

Sabkha flats are generally characterized by shallow groundwater table levels [6, 7, 8]. They are formed under the action of waves with low energy, which enables fine soil particles to settle and then be weakly cemented by saturated brines [9]. The unstable and collapsible conditions of the sabkha soils are attributed to a high content of salts, which can be leached [3, 4, 10]. Leaching can adversely affect the geotechnical characteristics of these soils [11] and make these flats susceptible to collapse [12, 13].

Thus, sabkha has complex and widely varying geotechnical properties, causing problems for the construction industry. Indeed, the sabkha soil is widely known as a waste material that has to be excavated to accommodate the building structure in question. The soil removed is then disposed of and replaced with clean sand.

Figure 1 Map of the study area in southern Kuwait [1]

Soil stabilization using bitumen is suggested as an effective treatment process for sabkha soil as bituminous materials will interact with the problematic salts in the soil [11, 14]. Bitumen can form a viscous, binding layer around soil particles, creating greater cohesion among particles, thereby ultimately and greatly improving the shear strength of the soil, as noted by Asi *et al.* [15] and Al-Otaibi and Aldaihani [11]. Nonetheless, the actual effect of bitumen treatment will be contingent on the type of the soil, salt compounds present in the soil, bitumen application method, and the additives present in the bituminous material [16, 17, 18, 19]. For instance, Al-Homoud *et al.* [20] discovered that in terms of reducing the swell potential, cutback asphalt (MC-70) was more effective than cement but less effective than lime. Several studies [3, 4, 11, 21, 22] reported the behavior of arid soils under the leaching effect. These studies reported the amounts of leached salts that can cause geotechnical deterioration that is expected to be reduced by waterproofing.

Although extensive literature is available on soil stabilization using bitumen, sabkha soil has special characteristics that make it different than other soils. With their highly variable characteristics, further research is necessary to realize a sustainable solution for the rapidly increasing sabkha soil waste accompanying urbanization in Kuwait, especially in the southern region with the scattered sabkha deposits in the coastal areas. A potential solution is to upgrade sabkha soil following a suitable stabilization process. This will be advantageous because, first, it reduces waste, and second, it is a cost-effective resource that can be used in future construction and contributes to a sustainable environment in the sabkha soil region, where the increasing frequency of dust storms is a potential health hazard for humans [23].

The purpose of this study was to examine the influence of bitumen treatment on sabkha soil characteristics, namely, its consolidation and collapsibility. To this end, a series of tests were conducted to study the soil gradation, compaction, Atterberg limits, and consolidation of sabkha soil treated with bitumen. Samples of sabkha soil were prepared by adding 0%, 4%, 8%, and 10% of bitumen and were tested according to the American Society for Testing and Material (ASTM) specifications. It was expected that waterproofing will reduce the tendency of the soil to expand or collapse upon wetting, thereby mitigating the geotechnical challenges related to sabkha soil.

The study results are expected to add a database for bitumen-sabkha soil mixture and to provide a reference for further investigations on using a combination of stabilizing materials such as bitumen and cement. The satisfactory bitumen waterproofing property effect is expected to protect the strength characteristics of cement stabilized sabkha. This will develop a sustainably stabilized soil that can be used in geotechnical engineering works using amply available waste materials.

2.0 METHODOLOGY

2.1 Soil Sampling

2.1.1 Sampling Location

In this study, the soil sampling field shown in Figure 1 is within the sabkha flats in southern Kuwait that have been explored and described in detail in previous works [11, 21, 22, 24].

2.1.2 Soil Sampling Method

Sabkha soil samples were collected in September 2020 when the groundwater table was at its lowest beneath the ground level. However, during the rainy seasons, the groundwater table can rise higher than the ground surface. September was chosen as the most appropriate time to collect the samples as the soil has the highest salt concentrations at this time, following the evaporation that occurs during the summer. Moreover, because of salt crystal cementation during this period, this month is predicted to have the most stable ground conditions for the sampling process.

From the data provided by an earlier soil survey [3, 4], a sampling plan based on a grid design was developed. At each point, four subsamples were randomly collected from 5- to 50-cm deep pits to obtain a composite sample. Next, a sample of 20 kg of composite sabkha soil was collected for representing layers of the soil profiles. Thus, four virgin soil samples identified as A, B, C, and D were obtained.

The samples were then dried in a laboratory for 3 days using ovens at temperatures not greater than 60°C. Controlling the temperature was critical, considering the effect of heat on soils containing salts [5]. Following the drying process, the soil particles were carefully and gently ground before sieving at 4.75 mm. The resultant products were then mixed well, homogenized, and stored at room temperature (25°C ± 0.5°C) for further analysis to identify the soil index properties.

The material was then air-dried, weighed, and separated into groups. To each group, a different amount of bitumen was added to obtain mixtures containing 0%, 4%, 8%, and 10% bitumen (percentages in reference to the dry weight). The 0% bitumen mixture represents the natural sabkha soil. These bitumen percentages were chosen after consulting the conclusions of previous studies that the most effective stabilization results are obtained for bitumen contents of 3%–12% [21, 22]. The cutback bitumen composite was obtained by adding kerosene to bitumen in accordance with ASTM (D2028-97) [25]. Kerosene was used as a solvent to reduce the viscosity of bitumen and to improve the bitumen workability while mixing with soil.

To apply the bituminous material to the soil, the two substances were mixed using hands until a visibly homogenous mixture was obtained, as shown in Figure 2.

Figure 2 Soil mixing

Subsequently, mechanical mixing was employed for 1 min to ensure thorough mixing, as previously described [24]. Finally, the mixture was dried for 3 days using an oven at approximately 60°C to simulate the field conditions existing in summer and to ensure that the cutback bitumen material evaporated.

2.2 Experimental Program

2.2.1 Index Properties

To evaluate the impact of bitumen addition on the distribution of the particle sizes in the tested soil samples, in this study, mechanical sieving and hydrometer analyses as per ASTM D 422 [26] were performed. The soil samples were also analyzed to determine their liquid and plastic limits as per ASTM D4318 [27]. Next, the samples were categorized based on the Unified Soil Classification System according to ASTM D2487 [28]. Further, ASTM D854 [29] tests were conducted to determine the specific gravity (G_s) or particle densities and modified Proctor compaction tests were conducted according to ASTM D1557-12 [30]. Chemical testing was conducted on one representative sabkha sample in the sampling location.

2.2.2 One-dimensional Consolidation Test

The oedometer was used to conduct several one-dimensional consolidation tests to determine the impact of the addition of bitumen on the sabkha soil in terms of its consolidation characteristics. Consolidation tests were conducted as per ASTM D2435-11 [31] on the samples of soil–bitumen mixtures prepared earlier, as described in Section 2.1. The test process was started by compressing each sample according to its compaction parameters, as mentioned in Section 2.2.1, in a stainless-steel ring of 70 mm in diameter and 20 mm in height. The interior of the stainless-steel ring was lubricated with silicone gel before each test to reduce friction. The upper and lower porous stones were soaked in distilled water for 24 h to prevent moisture absorption from the sample. Subsequently, the prepared sample was placed in the equipment for the consolidation test. Then, seating pressure was applied. When the monitored dial gauge reading versus time became asymptotic, the load was increased twofold.

2.2.3 Collapse Potential Test

The oedometer was used according to ASTM D 5333-96 [32] to determine the collapse potential (CP) of the sabkha soil samples. For this test, an incremental load up to a maximum of 200-kPa stress was applied to the samples, as reported by Day [33]. After equilibrium was achieved under that load, the soil sample was submerged in distilled water for another 24 h before additional vertical displacements were recorded using calibrated dial gauges. The final stage involved an additional cycle of loading.

Ultimately, the mean of two consolidation tests was used in the data to ensure the repeatability of the investigation.

3.0 RESULTS AND DISCUSSION

3.1 Soil Chemical Composition

The soil chemical composition was analyzed to assess the waterproofing effect of bitumen on the sabkha soil components. Sabkha soil sample chemical analysis results are shown in Figure 3. The principal component of the sabkha soil was found to be silicon dioxide, which made up 41.80% of the mixture. The next most common component was calcium carbonate (18.80%), followed by calcium oxide (16.60%) and sulfate (12.4%). These results are consistent with the results of previous investigations conducted in southern Kuwait [10, 21, 22]. Low silicate and high gypsum contents are a characteristic of coastal sabkha [34].

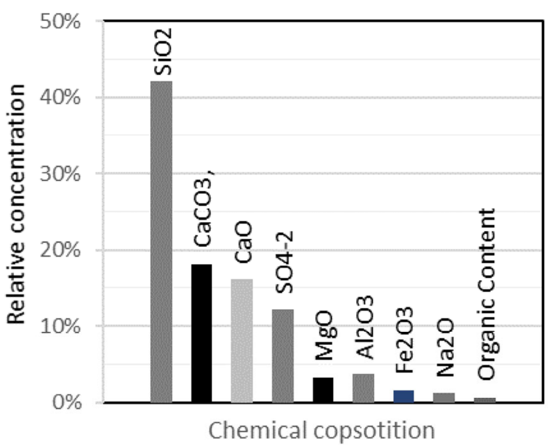


Figure 3 Sabkha soil chemical composition

3.2 Soil Physical Analysis

The grain size distribution curves of the four composite soil samples are shown in Figure 4, and the physical characteristics of the tested soil samples are listed in Table 1.

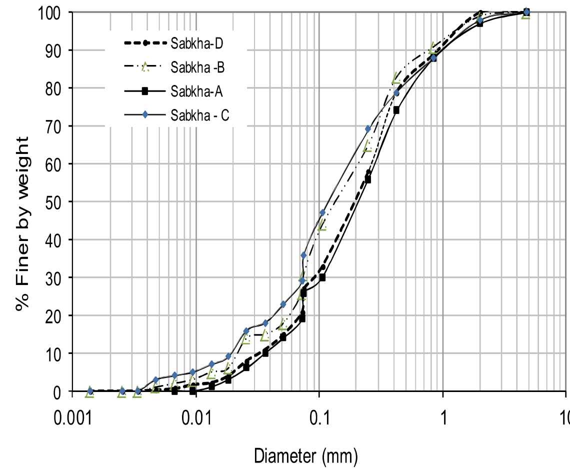


Figure 4 Grain size distribution curves of the tested soil samples

Table 1 Physical properties of the tested samples

	Sakha-A	Sakha-B	Sakha-C	Sakha-D
D_{10}	0.04	0.022	0.02	0.032
D_{30}	0.11	0.075	0.076	0.092
D_{60}	0.28	0.21	0.182	0.27
C_u	7	9	9.0	8
C_c	1.88	1.3	1.6	0.96
LL%	30	28	29	29
PL%	20	17	20	16
USC	SCL	SCL	SCL	SCL
G_s	2.7	2.7	2.7	2.7

The grain size results indicate that tested soil samples have almost similar gradation curves. The soil gradation results are in good agreement with the findings of earlier works [2, 3, 9, 22], which revealed that the sabkha soils in southern Kuwait have an average sand size content of 96%.

The plasticity results of the collected samples are summarized in Table 1, and these results show that all samples had a liquid limit considerably less than 30%. The liquid limit indicates that the sabkha soil has low plasticity and compressibility [35]. Similar results were reported [2, 3, 11] in earlier investigations on the properties of the soils in Kuwait.

The specific gravity of the soil was measured to be 2.7. This value is within the range of specific gravities of the sabkha soils in southern Kuwait [21, 22, 24].

Figure 5 shows the grain size distribution curves for natural and bitumen-mixed sabkha soil samples. Sabkha soil sample-D was used in the testing with bitumen addition.

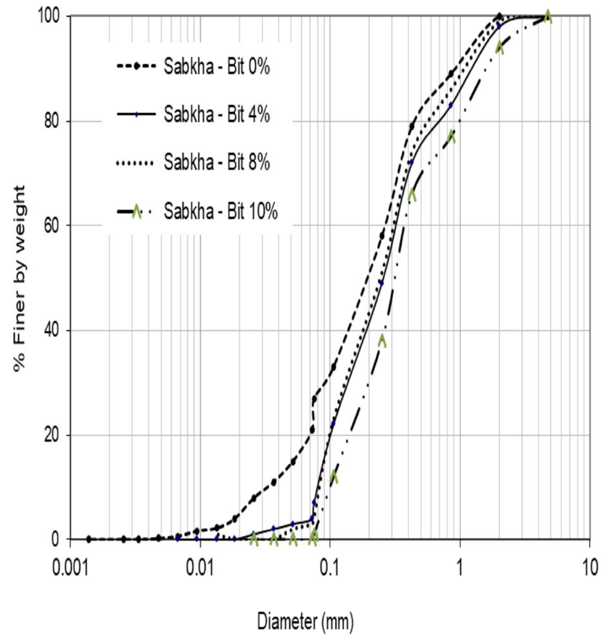


Figure 5 Grain size distribution curves of the tested soil samples

From Figure 5, it is clear that the bitumen-mixed sabkha soil samples had almost no fine contents and became increasingly coarse as the percentage of bitumen increased. This aggregative effect may be attributed to the viscous bitumen coat on the soil particles.

The liquid and plastic limits of the natural sabkha samples were found to be 29% and 16%, respectively. Because of the salinity of the soil, their consistency limits depend on the type of water used in the test [36].

The bitumen-mixed sabkha soil had no plastic elements. Hence, it could not be tested for liquid and plastic limits because of its low fine contents.

Further, according to the Unified Soil Classification System [28], the tested soil samples were classified; the natural sample was categorized as clayey sand of low plasticity (SCL), whereas the bitumen-mixed samples were identified as poorly graded sand (SP). The physical characteristics of the natural and bitumen-mixed samples are summarized in Table 2.

Table 2 Physical properties of the tested soil samples

	Bit-0%	Bit-4%	Bit-8%	Bit-10%
D_{10}	0.032	0.078	0.079	0.100
D_{30}	0.092	0.15	0.155	0.200
D_{60}	0.27	0.31	0.32	0.46
C_u	8.0	4.0	4.1	4.6
C_c	1.0	0.9	1.0	0.9
LL%	29	-	-	-
PL%	16	-	-	-
USC	SCL	SP	SP	SP
G_s	2.7	-	-	-
MDD	1.885	1.865	1.925	1.875
OMC	13.2	14.3	9.25	9.1

The measured physical characteristics are consistent with those reported in previous studies [2, 3, 21, 23].

3.3 Compaction Characteristics Results

Figure 6 shows the results of the modified Proctor compaction tests conducted on 0%, 4%, 8%, and 10% bitumen-mixed soil samples. Each data point represents the average of the two tests performed to check the repeatability of the data.

The figure shows the maximum dry density (MDD) with increasing bitumen content of the bitumen-mixed sabkha soil samples.

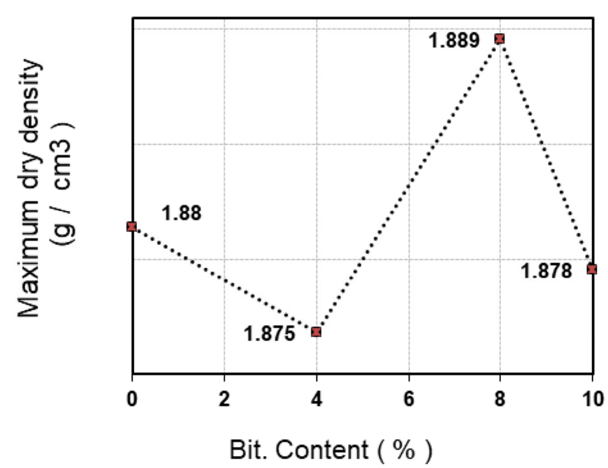


Figure 6 Maximum dry density–bitumen content relation

The MDD and optimum moisture content (OMC) of the tested soil samples listed in Table 2 show that the increase in the bitumen content by up to 8% had an impact on the compaction quality of sabkha soil; beyond this bitumen content, the MDD of the bitumen-mixed samples became less than that of the natural sabkha soil samples. The improvement of the bitumen-mixed sabkha soil sample compaction characteristics can be attributed to the bitumen viscosity that facilitates the sliding of soil particles on each other which increases soil compactness and reduce the voids more efficiently. Moreover, the bitumen-mixed sabkha soil had a greater density than normal sabkha soil because the moisture content decreased with the addition of bitumen, as shown in Figure 7. The decrease of MDD at 4% bitumen content is expected to be due to high salt dissolution as a result of the partial waterproofing effect of this percentage.

3.4 Consolidation Test

To draw inferences from the one-dimensional consolidation test, the variation of the logarithm of the applied stress (log σ) against the void ratio (e) of the natural and bitumen-mixed sabkha soil samples are plotted in Figure 8.

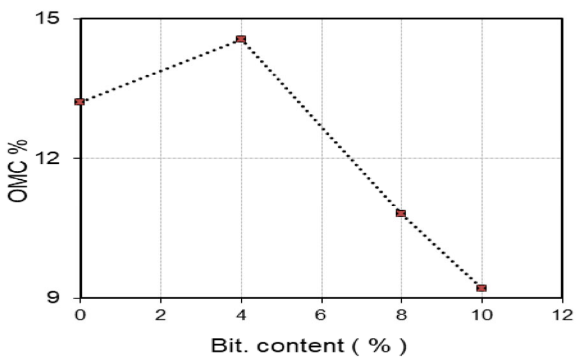


Figure 7 Optimum moisture content–bitumen content relation

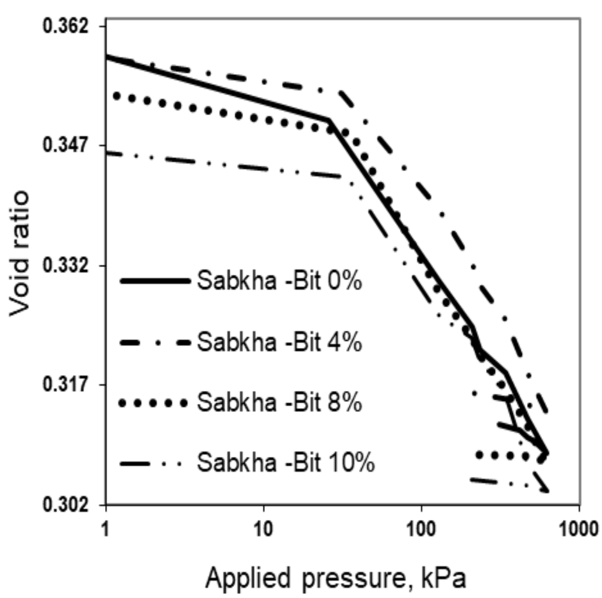


Figure 8 Pressure–void ratio relationship for tested soil samples

The bitumen-mixed soils had lower void ratios than the natural soil, and the void ratio decreased with increasing bitumen content. The measured void ratios for the samples with 0%, 4%, 8%, and 10% bitumen contents were 0.3638, 0.3609, 0.3566, and 0.348, respectively. This result is expected to be due to the permeation of bitumen particles through the spaces between soil particles. Moreover, as suggested in an earlier work [9], the nature of the bitumen may have enabled particles coated with bitumen to enter large pores and conduits between soil particles more easily, thereby reducing the overall porosity.

The calculated consolidation parameters are presented in Table 3.

Table 3 Consolidation parameters of the tested soil samples

	Bit-0%	Bit-4%	Bit-8%	Bit-10%
Yield stress (kPa)	25	31	36	34
Compression index (Cc)	0.02774	0.02979	0.03282	0.03145
Swelling index (Cs)	0.0119	0.0054	0.0027	0.0030
Collapse potential (CP)	1.192	0.542	0.271	0.301

From Figure 8 and Table 3, a positive correlation between yield pressure and bitumen concentration is observed, with yield pressure due to bitumen addition increasing from 25% to 40% as the bitumen content increases to 8%. This result may be attributed to the lubricating properties of bitumen, which minimizes the friction among soil particles. Hence, the compacted soil has a greater dry density, and in turn, greater stability and bearing capacity than the normal sabkha soil.

3.4.1 Compression Index (Cc)

Figure 8 shows the virgin compression line (VCL), which is defined as the slope of the linear part of a compression curve. The VCL is often used to represent the compressibility behavior of soil [37]. Compression rates of the samples were determined using the compression index (Cc), which was obtained by measuring the gradient of the VCL through the void ratio against the effective vertical stress curve for each tested soil sample. Cc remained relatively constant throughout the range of different pressures applied [38, 39]. The compression indices of the various soil samples calculated from Figure 8 are presented in Table 3.

For analyzing the impact of bitumen on compressibility, the relationship between the compression index and bitumen content is shown in Figure 9.

An overall positive correlation is observed from Figure 9, where compression indices were slightly higher for soil samples with 8% and 10% bitumen contents. The correlations were 0.038, 0.0388, 0.040, and 0.0415 for the samples with 0%, 4%, 8%, and 10% bitumen contents, respectively. The overall increase of the compression index is just about 5%. The slight increase in the compression index may be attributed to the increased lubrication provided by the bitumen adsorbed on the soil particle surfaces.

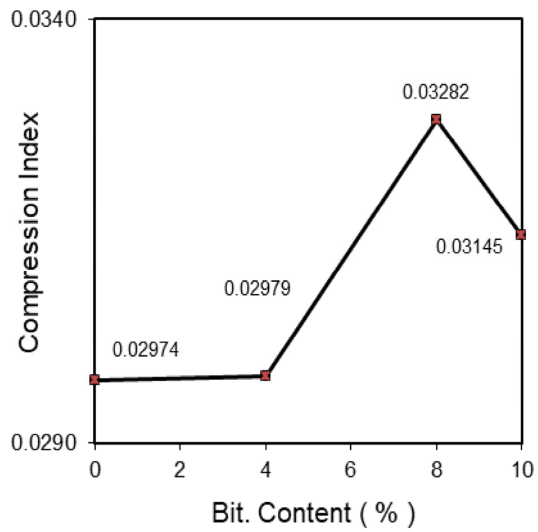


Figure 9 Variation of the compression index with the bitumen contents

3.4.2 Swelling Index

The gradient of the linear unloading area of the e–log pressure curve shown in Figure 10 was used to determine the swelling index, Cs, of each soil sample.

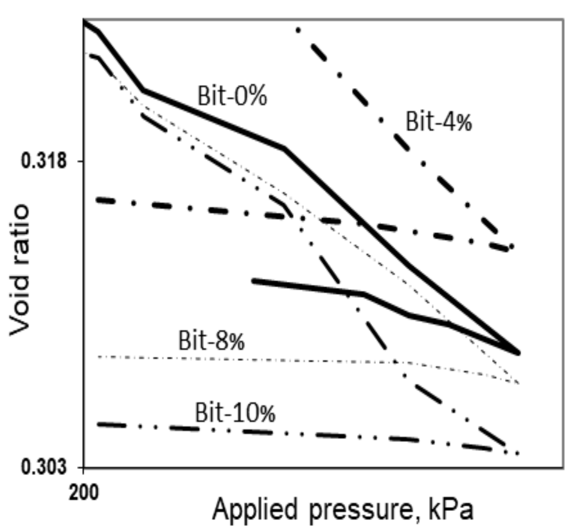


Figure 10 Pressure–void ratio relationship for tested soil samples

The swelling indices of the soil samples are presented in Table 3. Further, the bitumen content and swelling index relationship is plotted in Figure 11.

From Figure 11 and Table 3, the recorded swelling indices for the bitumen mixtures are clearly lower than those of the natural sabkha soil. Bitumen addition caused a 77% reduction in the swelling index of the 10% bitumen-mixed sabkha soil sample.

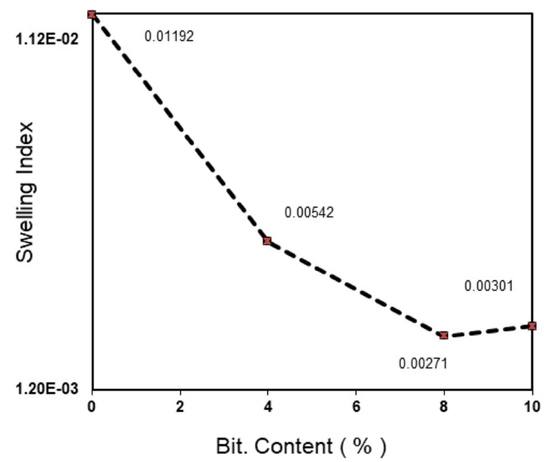


Figure 11 Swelling index–bitumen content relation

3.4.3 Collapse Potential Test Results

Jennings and Knight [40] defined the collapse potential (CP) as a percentage that represents the collapse strain of a sample affected by wetting while under a pressure of 200 kPa. To obtain the CP, the variation in settlement upon wetting was measured.

The results of the collapse test on the soil samples are shown in Figure 12. The figure shows the e–log p relationship at a normal pressure of 200 kPa.

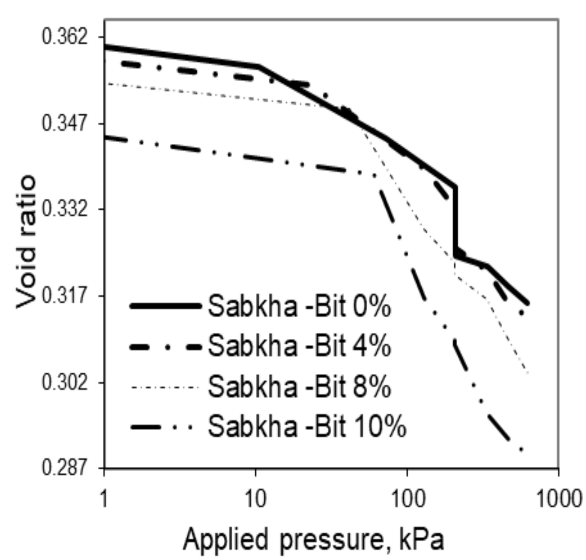


Figure 12 Pressure–void ratio relationship for tested soil samples

At the pressure-loading point of 207 kPa, the vertical line denotes the effect of a sudden application of pressure, and the length of this line reflects the degree of soil collapsibility, representing the values displayed in Figure 13.

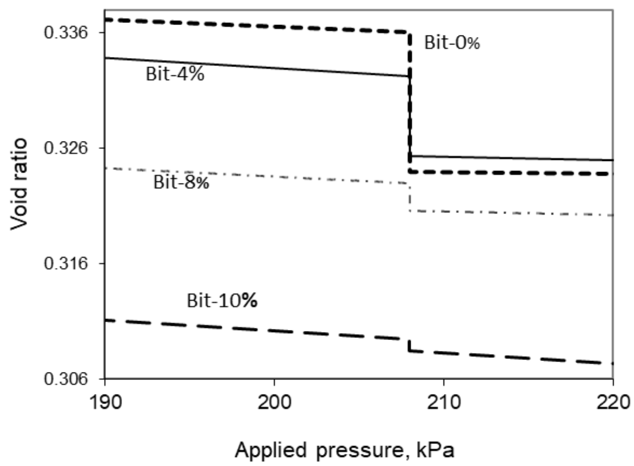


Figure 13 Soil collapsibility test results

Figure 13 clearly shows that compared to the natural sabkha soil, the soil with 10% bitumen content has a shorter vertical line at 200 kPa.

Table 3 lists the CP of the tested soil samples. The results are represented graphically in Figure 14. As observed from the table, an increase in the bitumen content results in a lower degree of collapsibility, and bitumen contents of 4%, 8%, and 10% correspond to collapsibility reduction percentages of 14%, 42%, and 82%, respectively. Thus, the measured CP values of the tested sabkha soil samples are within the suitable limits as identified by Jennings and Knight [40].

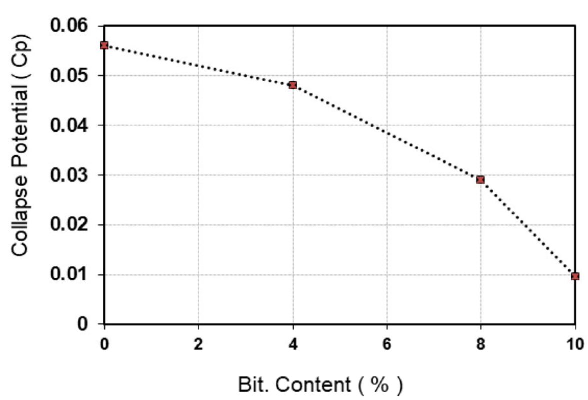


Figure 14 Collapse potential–bitumen content relation

The reduction in the CP resulting from an increased bitumen content is likely to occur due to the decrease in capillary tension and the dissolution effect of bitumen on salt particles. Furthermore, the collapse settlement did not occur immediately after bitumen inundation but rather developed steadily over several hours.

To summarize the impact of bitumen on compressibility parameters, the relationship between the variation percentages of compression indices and bitumen content is shown in Figure 15.

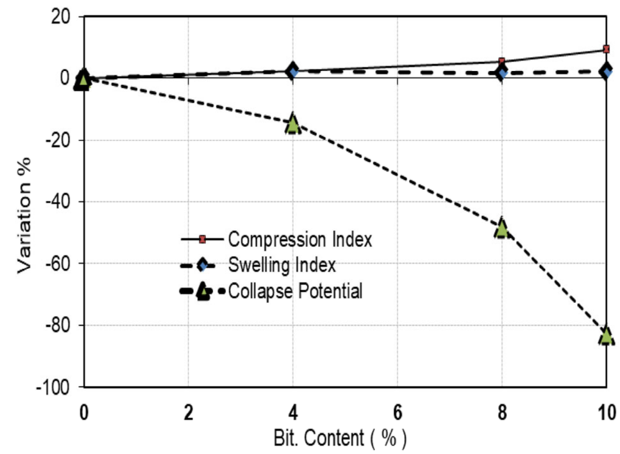


Figure 15 Percentage variation of consolidation parameters with bitumen content

The ability of sabkha soil to swell [13] increases its geotechnical challenges. The swelling characteristics increase with an increase in sodium and calcium contents [41]. Hence, sulfate saline soil will undergo subgrade swelling and cause cracking on pavements and slope loosening [42]. The waterproofing effect of bitumen is expected to minimize the effect of moisture on different salts during the soaking periods.

In general, sabkha soil is known to cause problems because of its collapsibility upon wetting due to the dissolution of cementing materials [12]. A slow collapse occurs because of chemical cementing bonding, and the collapse is a result of the dissolution or softening of the bonding agents [40], following the rearrangement of the grains in the coarse fraction [43]. Notably, mixing the sabkha soil with bitumen has previously been shown to reduce the hydraulic conductivity of soil [2, 4, 22], leading to a lower degree of water percolation. This, in turn, reduces the risk of salt dissolution in the soil matrix [11, 21, 24]. Thus, it is suggested that the optimum bitumen content of 10% significantly reduces the CP of sabkha soil because, at this point, bitumen has permeated the soil to fill the majority of the pore spaces. Moreover, this results in a denser and more stable structure of the soil, preventing the dissolution of salts by repelling water.

In the current study, the waterproofing effect of bitumen protected the weak cement bonding of sabkha soil, which minimizes its deterioration under soaked conditions. Further studies to confirm the long-term efficiency of the waterproofing effect of bitumen will encourage the use of a combination of stabilizing materials such as bitumen and cement.

Using cement in addition to bitumen as a stabilizer will modify the geotechnical sabkha soil properties to meet the subgrade and subbase construction standards and will also provide a waterproofing effect against the harsh corrosive sabkha environments.

4.0 CONCLUSION

Laboratory examinations were conducted to explore the effects of the addition of bitumen to sabkha soil samples collected from the southern coastal area of Kuwait. The compressibility values of soil samples with 0%, 4%, 8%, and 10% bitumen contents (by weight) were measured in standard oedometer tests.

From the results of the investigation carried out within the scope of the study, it can be concluded that sabkha soil compaction characteristics were modified up to a bitumen content of 8%. The compression index (Cc) is positively correlated with the addition of bitumen, while bitumen addition caused a significant decrease in the swelling index of the soil. Increasing the bitumen content resulted in a decrease of more than 85% in the CP; the CP was negligible in the sample with 10% bitumen.

Overall, the decreased value of the swelling indices and collapsibility of the bitumen-mixed sabkha soil samples suggest that bituminous materials can provide a suitable treatment process for the otherwise waste sabkha sand material. This is because the bitumen has a waterproofing effect, resulting in harder soil as well as reduced dissolution and effusion of the cementing salts in the sabkha soil.

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