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TESTING AND STABILIZATION OF SALINE SABKHA SOILS: A REVIEW

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ABSTRACT

Sabkha is one of the many types of evaporate regimes that exist around the globe. In addition to being distributed along the coasts, sabkha soils cover a number of continental depressions, both of which usually form in hot, arid climates and are associated with shallow groundwater tables. Sabkhas are well distributed locally and over the whole world. Sabkhas are characterized as being salt-full and water-sensitive soils. The presence of soluble salts makes the use of distilled water in testing these soils, as recommended by ASTM, etc., inappropriate. Further, sabkha soils possess low strength at their natural condition. Therefore, it would be imperative to stabilize the sabkha soil at the actual moisture content in the field. In this paper, the author reviews the modifications on some ASTM standard test methods in order to properly assess the geotechnical properties of sabkha soils. Moreover, two stabilizing programs of sabkha soil using lime and cement at various dosages are presented. The first program was concerned with stabilizing the sabkha at the optimum moisture content, while the second study was devoted to stabilize the sabkha at high (i.e., natural) moisture contents. The results of these studies indicate that sabkha (as a typical evaporitic soil) can be practically used by the construction industry in many field applications.

INTRODUCTION

The term "SABKHA" is originally an Arabic expression that has long been in use to denote indefinitely salt-encrusted flats underlain by sand, silt and/or clay. Scientifically speaking, there is no unanimous consensus on a "precise" definition of "sabkha", because these soils have been exposed to multi-disciplinary research by geologists, sedimentologists, hydrologists, environmentalists, chemists, civil engineers, etc. (Al-Amoudi, 1999). The definition of sabkha is further complicated by the considerable ramification of names for various types of high water-table situations in the Middle East (Fooks et al., 1986). The best "descriptive" definition for the sabkha system has been reported by Al-Amoudi and Asi (1991) as the large (in size or dimension), extremely flat (horizontal terrains with small, imperceptible slopes), saline, evaporative areas (due to the hot and dry environment), situated either along the coasts (i.e., called coastal sabkhas) or further inland (i.e., called continental or inland sabkhas) of many arid, semi-tropical countries. Ideally, a typical coastal sabkha terrain will be bordered on the seaward direction by a barrier (beach dune or a salt dome) and on the inland direction by a sand dune or a hill. Such a confinement increases the closure of sabkha terrains thereby augmenting their salinity. Table 1 depicts the chemical analysis of Ras Al-Ghar sabkha which is part of Ar-Riyyas sabkha, eastern Saudi Arabia, and compares it with the analysis of sea water from a nearby vicinity (Al-Amoudi, 1999). The data therein indicates that the sabkha brine is about three to six times more concentrated than sea water from the same vicinity.

Along the Arabian Gulf coasts, sabkha soils extend intermittently with varying inland extensions. The sedimentary features, mineralogical composition and the chemistry of the interstitial brines in such coastal sabkhas vary greatly in both the horizontal and vertical directions (Al-Amoudi, et al., 1992a). Horizontal variations are related to proximity from the shoreline, while vertical variations represent successive stages in the development of the sabkha cycle (Al-Amoudi, 1999). Surprisingly, the local people are still unaware of the whole spectrum of its hostile nature, and even engineers and researchers are still calling the sabkha a "special soil" (Stipho, 1989), despite the prevalence of sabkha soils in the Arabian Peninsula and in the world (Al-Amoudi, et al., 1992b), as shown in Figs. 1 and 2, respectively. Geotechnically, sabkha soils are considered to be highly variable in terms of grain size and shape, texture, degree of cementation, diagenetic minerals, layering, compaction, etc., due to the presence of alternating uncemented and cemented layers as well as lumps of quartz and/or carbonate sand. However, the principal cementing materials in sabkhas are aragonite, calcite, gypsum, anhydrite with halite (NaCl) being always present.

Table 1: Chemical analysis of the sabkha brine and seawater in mg/mL (i.e., parts per thousand)

Ions	Ras Al-Ghar Brine	KFUPM Beach Seawater
Na^+	78.8	20.7
Mg^{++}	10.32	2.30
K^+	3.06	0.73
Ca^{++}	1.45	0.76
Fe^{++}	Trace	Trace
Sr^{++}	0.029	0.013
Cl^-	157.2	36.9
Br^-	0.49	0.121
$(SO_4)^{--}$	5.45	5.12
$(HCO_3)^-$	0.087	0.128
PH	6.9	8.3
Conductivity*	208,000	46,200

*Microsiemens.

The variability of its geotechnical properties and the presence of highly concentrated brines make the sabkha a typical "salt-full" and "water-sensitive" environment, and pose many geotechnical problems to the construction industry in general and to the geotechnical engineers in particular. Despite these hostile attributes, very little has so far, been published on the geotechnical properties of sabkha soils except for their utilization in highway and sewerage projects, housing construction or for typical subsurface boring logs (Al-Amoudi, 1999). Recently, several "pilot" studies have been reported by local experts on classical testing and stabilization of sabkha soils (Owais and Bowman, 1981; Hossain and Sabtan, 1994; Abu Talem and Egeli, 1981; Akili and Torrance, 1981; Ghazali et al., 1985; Al-Shamrani and Dowian, 1997; Sabtan et al., 1995; Shehata et al., 1990; Al-Shamrani, 1998) without due consideration to the sabkha as being a "unique" soil. Among the major problems that the geotechnical engineer presently faces is the "appropriate" determination of some of the geotechnical properties of sabkha, which has not as yet been well addressed. For elucidation, the presence of soluble salts makes the use of distilled water (DW) in testing for grain-size distribution, for example, as recommended by international standards (i.e., ASTM, BS, DIN, etc.), inappropriate because DW tends to dissolve the readily soluble salts that are part of the sabkha soil (Al-Amoudi and Abduljauwad, 1994b).

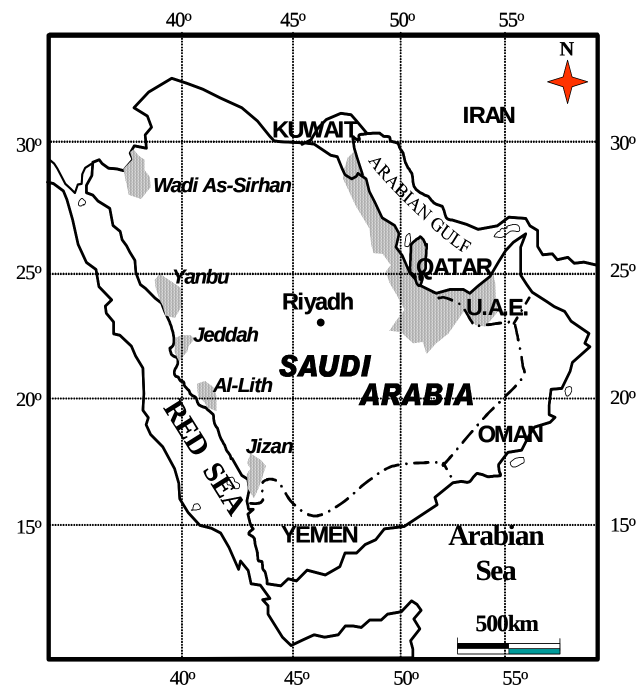

Fig. 1. Distribution of sabkhas in the Arabian Peninsula

In addition, naturally existing sabkha soils often possess low unconfined compression strength of only 20 kPa (≅ 3 psi) below the salt-encrusted layer and an SPT value of 0 to 10 (Al-Amoudi and Abduljauwad, 1995b). Furthermore, the collapse potential of these loose, low density and unstable soils presents an unacceptable risk in normal practice and calls for the improvement of their mechanical properties before any construction takes place (Al-Amoudi, 1994).

This paper presents a critical review of the standard and non-standard "modified" tests that are often used to test sabkha soils. Further, the paper summarizes the research conducted at King Fahd University of Petroleum and Minerals (KFUPM) on chemical stabilization of this "unusual" soil with the purpose of using the sabkha as a construction material.

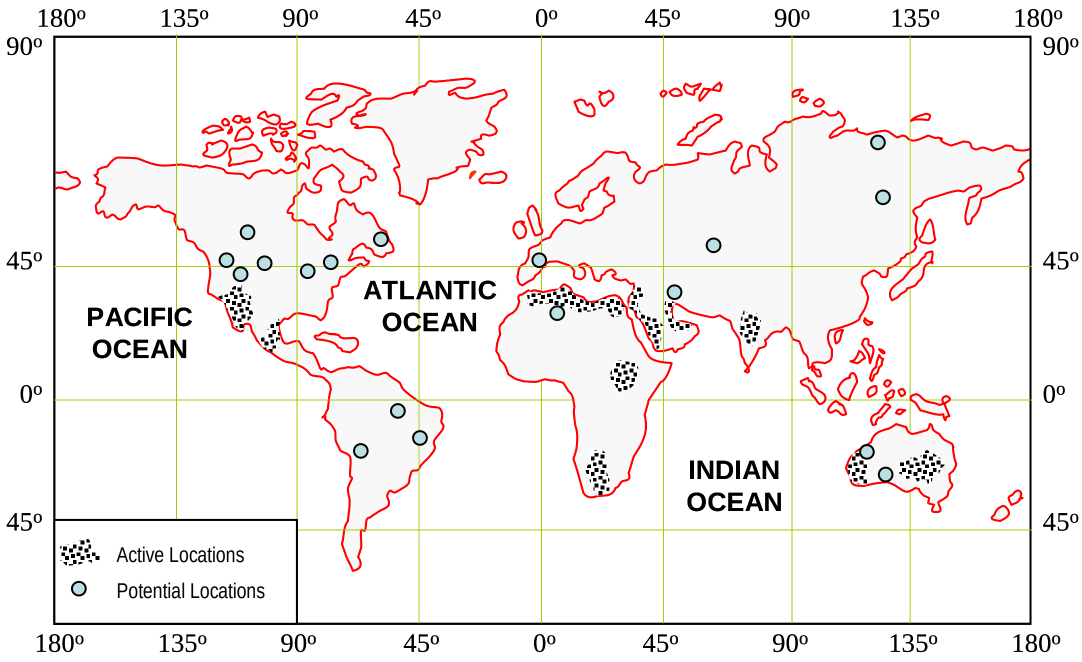

Fig. 2. World map showing active and potential locations of sabkha

EXPERIMENTAL PROGRAM

Sabkha Soil

Disturbed and undisturbed surficial sabkha soil samples were retrieved from Ras Al-Ghar site, which is located about 15 km southeast of Al-Jubail Industrial City, eastern Saudi Arabia, where the largest petrochemical industrial plants are situated. Disturbed samples were air-dried in the laboratory (22 ± 3 ^{o}C) and crushed gently using plastic hammers to break apart cemented particles to pass an ASTM No. 10-sized sieve (ASTM D 421). The soil was then thoroughly homogenized and stored in plastic drums till testing. Undisturbed specimens were obtained using thin-walled polyvinyl chloride (PVC) tubes with sharpened ends (Al-Amoudi and Abduljauwad, 1994b). Steel or brass moulds were not used to avoid corrosion-related problems. Each tube "specimen" was, thereafter, placed in a double nylon sheet along with a label indicating the date of sampling. As soon as the specimens were brought to the laboratory, they were uncovered from the nylon and their top and bottom ends sealed with wax and preserved until they were tested.

Testing Techniques

Grain-size tests were conducted using both dry (ASTM D 422) and wet techniques using three types of liquids: (1) distilled water (DW), (2) non-aqueous methylene chloride (MC), and (3) sabkha brine (SB) obtained from the same vicinity where the soil samples were collected. Materials passing the finest sieve (No. 200) were collected and prepared for hydrometer tests.

Though the Ras Al-Ghar sabkha doesn't possess any plasticity and the soil was classified as non-plastic (Al-Amoudi et al., 1992a), the plastic limit (w_p), liquid limit (w_L) and plasticity index (PI) should be determined for plastic sabkha soils in order to classify the soil according to AASHTO and USCS systems. Recent studies indicated that when determining these limits, SB should be used in place of DW in order to inhibit the dissolution of the diagenetic salts in sabkha soils (Al-Amoudi et al., 1997). In fact, large differences have been reported in w_p, w_L and PI when either DW or SB was used. The classification of sabkha should, therefore, be based on the usage of SB in these tests.

Two undisturbed specimens were subjected to constant head permeability tests performed in general accordance with ASTM D 2434 at a water-head of 177 cm. Two other similar specimens were tested using the variable head permeability test methods with a head differential of 100 cm (h_1 = 150 cm and h_2 = 50 cm). DW and SB were used during both types of permeability tests. The permeability coefficient was standardized at 20ºC.

To investigate the compressibility and collapse potential of sabkha, two types of oedometers were used. The first was the conventional oedometer (CO) (ASTM D 2435), while the second was an oedometer modified (MO) to permit water percolation through the consolidating specimen under a constant head (Al-Amoudi and Abduljauwad, 1994a; Al-Amoudi and Abduljauwad, 1995a). This was accomplished by making two holes below the consolidating specimen, an inlet and outlet for water supply and overflow of excess water, as shown schematically in Fig. 3. The undisturbed specimens used in both the CO and MO were tested under exactly the same laboratory conditions. In all tests, the specimens were first loaded to and held at the overburden pressure (σ_p') at the natural moisture content until no further settlement was observed. Except for the specimen tested all the way at its natural moisture content, all other specimens were then flooded with DW and maintained at the same σ_p' until the settlement ceased. For the MO test, the exit valve was opened, allowing water to percolate through the specimen under σ_p'. The pressure was, thereafter, incremented in a way similar to the standard consolidation test. It should be mentioned that water percolation was continued until the end of the test. In the second series of MO tests, the water percolation took place while the vertical pressure was 233 kPa. This was intended to investigate the collapse potential of sabkha under different pressures.

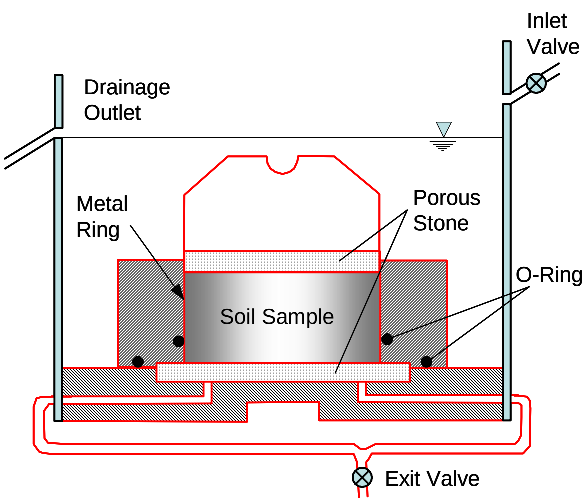

Fig. 3. Schematic diagram for the modified oedometer

In addition to the classical direct shear and CBR tests, various types of triaxial tests were conducted on undisturbed sabkha soils (Al-Amoudi and Abduljauwad, 1995b). These triaxial tests included the following:

(i) Consolidated-undrained (CU) tests: Whereby the specimens were saturated with either SB or DW with pore-water pressure measurements.

(ii) Consolidated-drained (CD) tests: Whereby the specimens were also saturated with SB or DW or without saturation (i.e. at the natural moisture content) with volume change measurements.

For the stabilization program, the effect of two inert (i.e. non-reactive) materials [crusher fines (i.e. limestone dust) and marl] and three chemical stabilizers (i.e. emulsified asphalt, lime and cement) at five dosages (0, 2.5, 5, 7.5 and 10% by weight of dry soil) on the density and unconfined confined compressive strength was investigated in the first study. ASTM D 698 standard Proctor tests were conducted to establish the dry density and moisture content relationship for both untreated and treated sabkha mixtures. For the unconfined compressive strength, small moulds of 50×100 mm were used to prepare the specimens at similar densities to those developed by the Proctor test, as detailed in Al-Amoudi et al. (1995) and the 7-day cured specimens were prepared at moisture contents either lower or around the optimum obtained from the standard Proctor tests.

Since the actual *in-situ* moisture content of all sabkhas is more than the optimum obtained from the Proctor test (Al-Amoudi et al., 1997), another stabilization program was conducted in which the sabkha specimens were prepared at high moisture contents of 16% and 22%, confining the range of natural moisture content (Al-Amoudi, 1994). Only cement and lime were used in the second program and the unconfined compressive strength was determined at 7 and 90 days of laboratory curing in order to study the effect of curing period on the strength. Specimens size and preparation followed the same procedure as in the first study.

EXPERIMENTAL RESULTS AND DISCUSSION

Results on Testing Program

The results of the grain-analysis test results are presented in Figure 4. The data therein indicate that the ASTM D 422 "dry sieving" standard test produced 2% passing the No. 200 sieve, while the wet sieving using DW resulted in 31% passing the same sieve. The 29% difference between the two "standard" techniques appears to be the result of salt dissolution in these "salt-full" soils. This difference illustrates the need to specify the test technique to be used. While the dry sieving (ASTM D 422) is definitely inappropriate because the cemented particles are not broken down to their actual sizes, thereby causing the gradation of the soil to appear coarser than it is, washing the sabkha sample with distilled water tends to dissolve the salts that are considered part of the soil (Al-Amoudi and

Abduljauwad, 1994b). These findings elucidate the need to use a liquid that does not dissolve any of the sabkha materials.

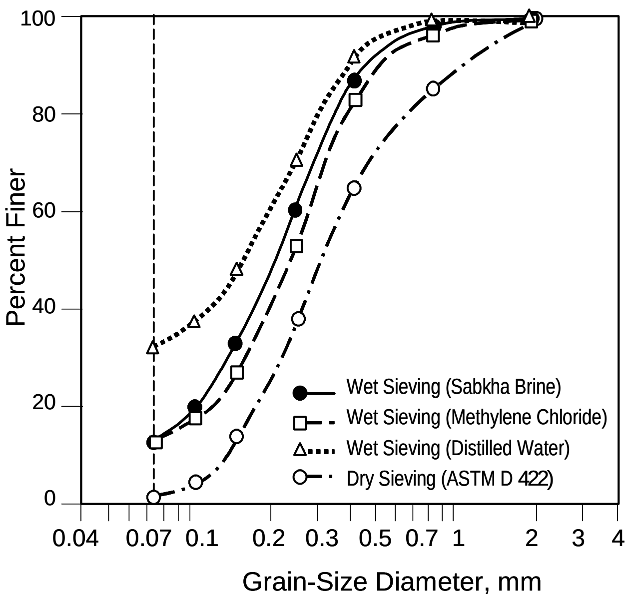

Fig. 4. Summary of various sieve analysis test results

The use of both MC and SB was intended to address the problem of salt dissolution (Al-Amoudi and Abduljauwad, 1994b). Figure 4 indicates that both the MC and SB curves seem to be similar and fall midway between the extremes defined by the two "standards" indicating no fundamental difference between them. However, the following disadvantages are associated with the use of MC (Al-Amoudi and Abduljauwad, 1994b). This liquid is irritant, expensive, volatile, toxic and damaging to some laboratory plexiglass equipment. On the other hand, SB could be obtained very easily from the same site from which the soil is retrieved. Therefore, SB is highly recommended for appropriately determining the grain-size characteristics of sabkha soils.

A complementary test, yet very essential for fine-grained soils, is the hydrometer technique. For sabkha soils, this technique is inappropriate because the hydrometer test is solely calibrated to be used with DW of a specific gravity that varies with ambient temperature. The use of the hydrometer test to measure the grain sizes of evaporitic soils will therefore cause dissolution of soluble salts, thereby dynamically changing the specific gravity of the soil and liquid (Abduljauwad et al., 1994).

The results of the permeability (*k*) test are presented in Figs. 5 and 6 for constant and falling head techniques, respectively. For both tests, when DW was used, the increase in *k* with the volume of percolated liquid (i.e. test repetition) was solely attributed to salt dissolution, which causes more channels to form, thereby increasing *k*. When SB was used, *k* tended to stabilize, whether the constant or falling head test was used, as evidenced in Figs. 5 and 6.

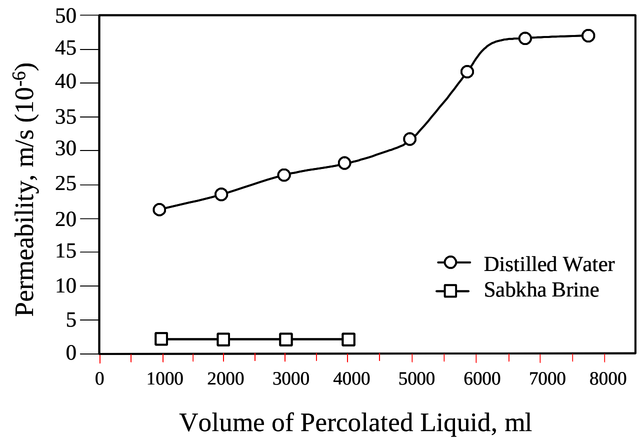

Fig. 5. Constant head permeability test result

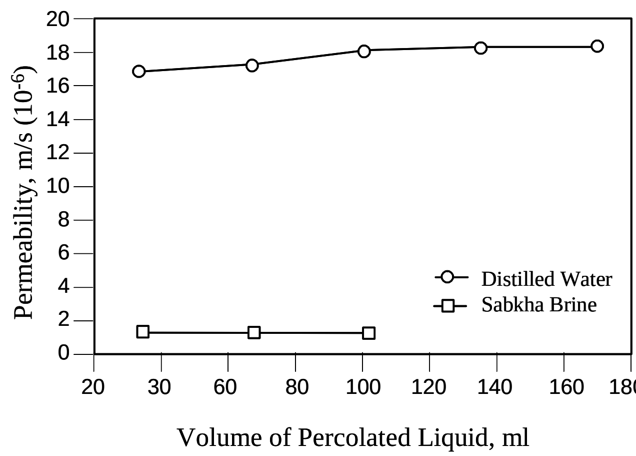

Fig. 6. Falling head permeability test result

Comparison of the constant head with variable head techniques indicates that the magnitude of *k* from the first test was higher than that determined from the latter test for both DW and SB. In addition, permeability to DW was observed to be about 10 to 14 times greater than the permeability to SB for both tests, respectively. These facts imply that if the permeability test is intended to simulate groundwater flow, SB should be used irrespective of the rather well-known shortcomings of the laboratory permeability testing. If, however, the test is planned to assess seepage of rain water percolation, the usage of DW is recommended. It is to be noted that the values of *k* in Figs. 5 and 6 for SB compare relatively well with the field test results reported by James and

Little (1994) and others whereby the coefficient of horizontal permeability for an eastern Saudi sabkha is in the range of 10^{-6} to 10^{-5} m/s.

Consolidation test results using both CO and MO are depicted in Figs. 7 and 8. The CO data included the one tested at the natural moisture content without inundation (denoted as Conventional Oedometer 1) and the one in which the specimen was flooded with DW at the overburden pressure (denoted as Conventional Oedometer 2). Figures 7 and 8 indicate that the least change in void ratio (0.233) was observed for the specimen tested at the natural moisture content, followed by the specimen tested under flooded condition. Furthermore, flooding the sabkha specimen with DW at the beginning of the test resulted only in a marginal decrease in void ratio (0.006), even though the specimen was kept submerged for two days. This minimal reduction in void ratio indicates that collapse hasn't been induced (as expected), which could be attributed to the profuse cementation and desiccation (Al-Amoudi and Abduljauwad, 1994a).

On the other hand, the MO test results indicated that DW percolation through sabkha specimens induced significant salt dissolution, thereby resulting in a remarkable reduction in void ratio, as shown in Figs. 7 and 8. Comparison of the total reduction in void ratio due to water percolation indicates that the reduction in void ratio increases significantly with increasing the sustained pressure (Al-Amoudi and Abduljauwad, 1995a), as could be noted by comparing the reduction in void ratio at the overburden pressure and at 233 kPa in Figs. 7 and 8, respectively.

The data developed using both CO and MO indicate that the compression and swelling indices remained almost unchanged with DW percolation at about 0.19 and 0.018, respectively, regardless of the saturation condition, percolating fluid (i.e. whether DW or SB is percolating) or oedometer type. Based on the values of these indices, it can, therefore, be concluded that the arid, saline sabkha soil possesses low to moderate compressibility (Al-Amoudi and Abduljauwad, 1995a) in spite of the high salt content in these types of soil.

In summary, the analysis of the data in Figs. 7 and 8 indicate the following observations: (i) flooding the sabkha specimens in the CO resulted only in marginal collapse potential compared to that obtained by the MO, when the specimens were loaded under the same σ_p'; (ii) for the case of MO results, the specimen tested under a pressure of 233 kPa exhibited a relatively higher collapse potential (as reflected by the large reduction in void ratio) compared to the one tested under σ_p'. Accordingly, an appropriate pressure should be chosen if and when the collapse potential is to be determined, which should be based on the foundation pressure. Therefore, the use of the MO testing technique was capable of genuinely assessing the collapse potential due to its ability to dissolve the salts in the sabkha matrix; and (iii) the collapse potential of sabkha has been classified as "trouble" (Al-Amoudi and Abduljauwad, 1995a), not due to the destruction of its bulky structural and meta-stable fabric but due to the dissolution of salt. Hence, the fear of collapse upon the exposure of sabkha to water, rather than the compressibility of the sabkha per se, should be of prime consideration to the geotechnical engineer. Therefore, provision for water drainage should be warranted to avoid such a collapse.

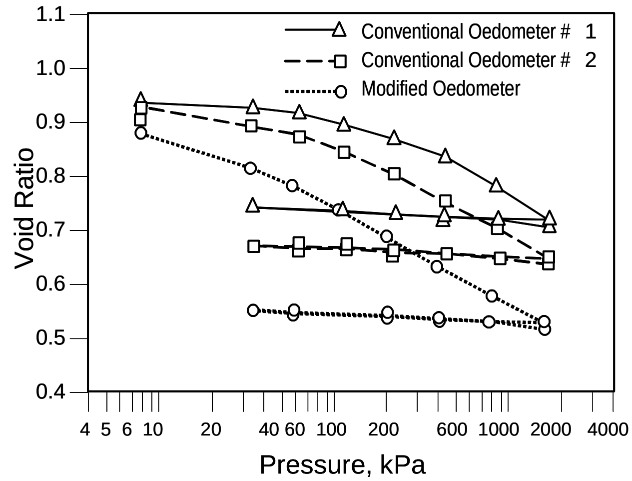

Fig. 7. Consolidation test result using the conventional oedometers (Percolation of Distilled Water at the Overburden Pressure)

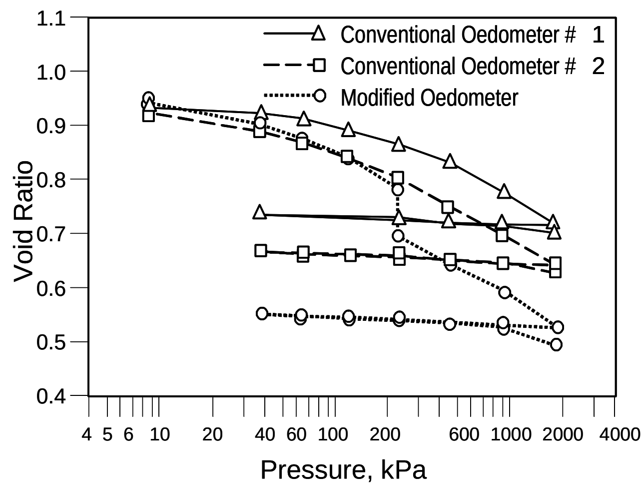

Fig. 8. Consolidation test result using the conventional and modified oedometers (Percolation and Distilled Water at 233 kPa)

The strength test results are presented in Table 2. Only the following summary of the findings is presented. Details of these tests are presented elsewhere (Al-Amoudi and Abduljauwad, 1995b).

- The effective shear strength parameters, namely the angle of internal friction and cohesion (ϕ' and c'), determined by the direct shear tests are relatively marginally larger than those determined by the triaxial tests due to the confining effect by the metal shear box.

Table 2: Summary of various triaxial and direct shear test results

Triaxial Test	Saturation With	Parameter Measured	Shear Strength Parameters			
			ϕ', deg.	c', kPa	ϕ, deg.	c, kPa
CD*	No Saturation	None	34.5	14	-	-
CD*	Distilled Water	Volume Change	27	10	-	-
CD*	Sabkha Brine	Volume Change	34	0	-	-
CU**	Distilled Water	Pore-Water Pressure	34	0	24	3
CU**	Sabkha Brine	Pore-Water Pressure	33	16	25	12
Direct Shear Test			36	50	-	-

*CD = Consolidated-drained triaxial test
**CU = Consolidated-undrained triaxial test

- The effect of saturation on the total and effective shear strength parameters (ϕ, ϕ', c and c') is only marginal indicating that saturation with DW in the CD triaxial tests reduced both ϕ' and c'. However, when the sabkha soil was saturated with SB, only a reduction in cohesion was observed because DW induces both dissolution of salts and wetting, while SB results only in wetting.

- The CBR and unconfined compression tests on undisturbed specimens are observed to better assess the low strength characteristic of surficial sabkha soils in their natural state (Al-Amoudi, 1999). This is in contrast to both the direct shear and triaxial tests where the applied confining pressures were higher than the prevailing σ_p' in the field. Hence, the strength parameters obtained from the direct shear and triaxial tests were overestimated. Furthermore, these latter tests do not reflect the collapse and water sensitivity of shabka soils due to saturation as there is no big difference between the effective and total shear strength parameters shown in Table 2. In fact, our test results indicate that the CBR strength will reduce by as much as 50% when the sabkha specimens are tested under soaked CBR test. Accordingly, the CBR (and unconfined compression) tests are more appropriate to assess the sabkha strength under various conditions (Al-Amoudi, 1999).

Results on Stabilization Program

Results of the density-moisture content (compaction) tests and the stabilization program with various stabilizing agents are summarized in Tables 3 and 4, respectively. Further, comparison of the effect of moisture content on the compaction and unconfined compression test results is schematically presented in Fig. 9. Based on these data, the following observations have been noted:

- The maximum dry density $(\gamma_{d_{max}})$ for the control sabkha soil (i.e. with DW) is 1.896 Mg/m^3 (Table 3 and Fig. 9) as compared with 1.602 Mg/m^3 for the *in-situ* density. This results in a relative compaction of 84%, which is relatively low. Further, the sabkha soil becomes spongy around the optimum moisture content (w_{opt}) and it is very cumbersome to compact the soil on the wet-side of w_{opt} for the control and all the other treated sabkha mixtures.

- The data in Table 3 indicate that the variation in $\gamma_{d_{max}}$ and w_{opt} with the addition of various stabilizing agents was marginal. $\gamma_{d_{max}}$ varied from 1.825 Mg/m^3 for 7.5% emulsion addition to 1.960 Mg/m^3 for 10% cement addition. The higher density for cement-stabilized sabkha is ascribed to the higher specific gravity of cement as compared with the sabkha soil (i.e. 3.15 compared with 2.73). Similarly, w_{opt} varied over the marginal range of 12.3% to 13.5%).

- As shown in Fig. 9, the optimum moisture content (w'_{opt}) obtained from the unconfined compression strength (q_u) is attained at a much lower water content than w_{opt}. Such a trend can be easily observed by comparing w_{opt} with w'_{opt} in Tables 3 and 4, respectively, for the untreated and treated sabkha mixtures with all the stabilizing agents. The same trend having a lower w'_{opt} than w_{opt} has been observed when determining the maximum CBR when stabilizing twenty different sabkha soils from eastern Saudi Arabia (Al-Amoudi et al., 1997, 2002).

- The usage of sabkha brine in place of water didn't bring about any remarkable change in w_{opt} and γd_{max} (Table 3). However, q_u has increased from 70.1 to 103.0 kPa with an improvement of 47% (Table 4) the growth of salt crystal (Al-Amoudi et al., 1945).

Table 3: Effect of additives in sabkha soils on standard Proctor test results

Agent	% added (by weight of soil)	Optimum moisture content (%)	Maximum dry density (Mg/m^3)
Control	0	12.5	1.896
Brine	0	12.4	1.904
Limestone dust	2.5	12.3	1.896
Limestone dust	5.0	12.3	1.899
Limestone dust	7.5	12.3	1.907
Limestone dust	10.0	11.8	1.936
Marl	2.5	13.4	1.901
Marl	5.0	13.5	1.904
Marl	7.5	13.5	1.901
Marl	10.0	13.4	1.907
Emulsion	2.5	13.0	1.857
Emulsion	5.0	12.9	1.848
Emulsion	7.5	12.7	1.825
Cement	2.5	12.8	1.878
Cement	5.0	13.1	1.902
Cement	7.5	12.1	1.917
Cement	10.0	12.4	1.960
Lime	2.5	12.7	1.864
Lime	5.0	12.7	1.891
Lime	7.5	13.0	1.886
Lime	10.0	12.4	1.904

- The data in Table 4 vividly indicate that significant improvements were attained for only the cement and lime stabilizers. The average q_u was increased from 70.1 kPa for the control (untreated) specimens to 271 to 1,391 kPa and to 246 to 1,600 kPa for the 2.5 to 10% cement- and lime-stabilized specimens, respectively. Such improvements ranged from 250 to 2,200% compared to the control sabkha soil. Such improvements were ascribed to the development of chemical binders by the reactions between cement and/or lime with water and the sabkha ingredients (Al-Amoudi et al., 1995). This is evidenced by the increase in q_u with the increase in the dosage of cement and lime.

- All the other three stabilizers (i.e. limestone dust, marl and emulsion) as well as the sabkha brine could not increase the unconfined compressive strength beyond 47% as compared with the control sabkha specimens (Table 4). Therefore, these stabilizers were not successful in improving the sabkha soils to meet the demand of constructional projects.

- As the natural moisture content of sabkha is much higher than w'_{opt} (and w_{opt}), stabilization of these soils in the field would require lowering the moisture content before any stabilization program commenced, which would be neither feasible nor economical (Al-Amoudi, 1994). Therefore, it would be advisable to conduct a study to stabilize the same sabkha at high moisture content (i.e., 16% and 22%) to envisage the effect of cement and lime on q_u of sabkha at high moisture contents (Al-Amoudi, 1994).

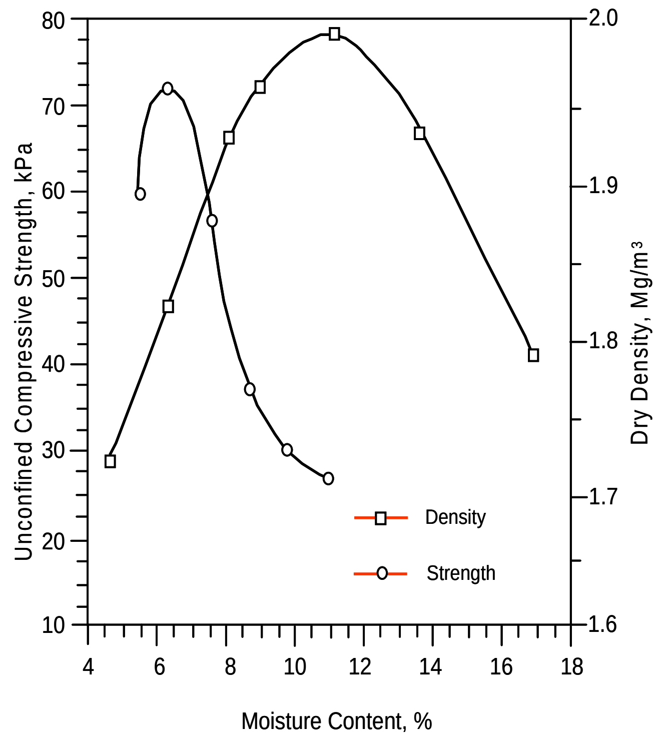

Fig. 9. Comparison of optimum moisture content from compaction and strength tests

- In contrast to the results in Table 4, the data in Table 5 indicate that only cement was efficient in enhancing the strength at high *w* simulating the range of natural *w*. As shown in Table 5, the 90-day strength of these specimens at all cement additions (i.e. 2.5, 5, 7.5 and 10%), particularly those prepared at w = 16%, was higher than the 7-day of the specimens prepared at the optimum moisture content (Table 4).

- Contrary to the superior performance of lime at w'_{opt} (Table 4), the high moisture content has significantly lessened the initial (7-day) and ultimate (90-day) strength of lime-stabilized sabkha specimens indicating the deleterious consequence in stabilizing sabkha soils at high *w* simulating the *in-situ* moisture content.

- In order to assess and assure the long-term performance of cement-stabilized sabkha soil, recent studies on the evaluation of the durability characteristics of this stabilized soils have indicated their excellent performance when exposed to water, as per the slake durability test of ASTM D 4644 (Aiban et al., 2006).

Table 4: Summary of the unconfined compression test results

Agent	Addition (%)	OMC* (%)	q_u** (kPa)	Improvement+ (%)
Control	0	7.1	70.1	--
Brine	0	6.4	103.0	47
Crusher Fine	2.5	6.2	84.8	21
Crusher Fine	5.0	6.3	93.0	33
Crusher Fine	7.5	6.2	81.8	17
Crusher Fine	10.0	6.7	74.8	7
Marl	2.5	7.0	65.0	-7
Marl	5.0	7.0	69.6	-7
Marl	7.5	6.7	72.0	3
Marl	10.0	6.8	73.5	5
Emulsion	2.5	7.4	47.2	-33
Emulsion	5.0	7.2	45.0	-36
Emulsion	7.5	6.9	53.2	-24
Cement	2.5	10.7	271.0	287
Cement	5.0	10.5	736.0	960
Cement	7.5	10.8	1180.0	1583
Cement	10.0	10.7	1391.2	1884
Lime	2.5	5.8	246.0	251
Lime	5.0	8.4	792.0	1030
Lime	7.5	8.5	1226.0	1649
Lime	10.0	8.7	1600.0	2182

*Optimum moisture content from strength data
**Unconfined compressive strength
+With reference to the control

Table 5: Comparison of maximum strength for stabilized sabkha at optimum and high moisture content

Stabilizing Agent	% Addition	Maximum Strength and Optimum Moisture Content		Maximum Strength (kPa) at:			
		w_{opt} (%)	q_u (kPa)	16% Moisture Content		22% Moisture Content	
				7 days	90 days	7 days	90 days
Cement	2.5	10.7	271	127	322	99	196
Cement	5.0	10.5	7.36	388	801	197	520
Cement	7.5	10.8	1,180	766	1,993	485	901
Cement	10.0	10.7	1,391	804	2,682	664	1,316
Lime	2.5	5.8	246	43	130	15	107
Lime	5.0	8.4	792	66	197	21	153
Lime	7.5	8.5	1,226	95	256	27	192
Lime	10.0	8.7	1,600	119	345	68	271

Summarizing the results of the two stabilizing programs, the data in Tables 4 and 5 indicate that only cement can be effectively used to stabilize the evaporitic sabkha soils at both the optimum moisture content and high moisture content simulating the *in-situ* conditions.

CONCLUSIONS

Sabkha is a salt-encrusted soil that prevails in arid and semi-tropical regions. These soils are associated with several geotechnical problems that principally emerge from the heterogeneous nature of the soil and its high salt content. In this investigation, a typical eastern Saudi sabkha soil was tested using ASTM standard and non-standard tests and using five improved different stabilizing agents at various dosages. The conclusions drawn from the data developed in this study are:

1. The standard ASTM D 422 test cannot be used to determine appropriately the grain-size characteristics of arid soils. The use of washed sieving with DW is also not appropriate. SB should be used to measure the grain sizes of these soils.

2. The present hydrometer testing technique seems to be inappropriate.

3. The use of SB in the constant head and variable head permeability tests resulted in a permeability coefficient that was ten to fourteen times less than when DW was used. SB should be used if the test is to be conducted to simulate groundwater seepage.

4. The compression and swelling indices reveal that the sabkha soil used in this investigation possessed low to moderate compressibility. These two indices were not affected by either flooding with or percolation of DW.

5. Flooding tests using conventional oedometers were incapable of predicting the collapse potential of this type of sabkha soil due to the profuse cementation and desiccation.

6. Percolation of DW through sabkha soils induced a significant reduction in void ratio, thereby leading to a collapse potential higher than that determined by flooding only.

7. The unconfined compression and CBR tests are the best techniques for the assessment of the actual strength of natural sabkha soils.

8. The maximum dry density can not be used as a criterion to assess the stabilization potential of sabkha soils.

9. The optimum moisture content of sabkha soil as obtained from Proctor test (ASTM D 698) was high than the optimum moisture content obtained from q_u-w tests.

10. Through cement and lime significantly improved the strength of sabkha at normal moisture contents, only cement succeeded to stabilize the sabkha soil at high moisture contents simulating the field conditions.

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