Chemical Stabilization of Al-Qurayyah
Eastern Saudi Sabkha Soil

by

Eissa Shayei Al-Ayedi

A Thesis Presented to the
FACULTY OF THE COLLEGE OF GRADUATE STUDIES
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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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DEPARTMENT OF CIVIL ENGINEERING

This Master of Engineering Report written by EISSA SHAYEI. AL-AYEDI under the direction of his Advisor and approved by his Report Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of MASTER OF ENGINEERING IN CIVIL ENGINEERING (Geotechnical).

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Dr. Ala H. Al-Rabeh
Dean, College of Graduate Studies:
أهدي هذا العمل المتواضع إلى:
- زوجتي الغالية (أيسمار).
- ولديي (بسام ومحمد).
- ابنتي (هديل).

وذلك لوقوفهم بجانبي أثناء دراستي وخلال بحثي في رسالة الماجستير، مما كان له من أثر طيب ساعدني كثيرًا في تحقيق هدفي وإنجاز عملي في الوقت المحدد ووفقًا لما أصبر إليه، نجواهم الله عني خير الجزاء في الدنيا والآخرة، ووفقني الله عز وجل لرد هذا الجميل.
This Work is Dedicated to:

To my family members for their moral support, patience, encouragement, and prayers throughout my studies.
Especially:

- My wife (umm-Bassam)
- My sons (Bassam and Mohammed)
- My daughter (Hadeel)
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Nomenclature

AASHTO  American Association for State Highway and Transportation Officials
ACI      American Concrete Institute
ASTM    American Society for Testing and Materials
CBR     California Bearing Ratio (%)
CIV     Clegg Impact Value
LVDT    Linear Variable Differential Transducer
MR      Resilient Modulus (MPa)
OMC     Optimum Moisture Content (%)
UCS     Unconfined Compressive Strength (kPa)
USACE   United States Army Corps of Engineers
USCS    Unified Soil Classification System
XRD     X-ray Diffraction
φ       Angle of Internal Friction (degrees)
γdmax   Maximum Dry Density
μ       Poisson’s ratio
ملخص الرسالة

اسم الطالب: عيسى بن شايع العابدي

العنوان الرسالة: تشتت التربة الكيميائي لتراب التربة السبخية في شرق المملكة العربية السعودية.

ال/address: هندسة مدنية (فيزفيكا التربة وهندسة الأساتذة).


تشير مراجعات البحوث المنشورة أن هذه الأنواع من التربة تم تحليلها في بلدان مختلفة، وخاصة على طول المناطق الساحلية. وتشير مراجعة البحوث المنشورة أن هذه الأنواع من التربة تم تحليلها في بلدان مختلفة، وخاصة على طول المناطق الساحلية. وتشير مراجعة البحوث المنشورة أن هذه الأنواع من التربة تم تحليلها في بلدان مختلفة، وخاصة على طول المناطق الساحلية.

تم في هذا البحث دراسة عينات من التربة السبخية من موقع مقرية بالمنطقة الشرقية للملكة العربية السعودية، وركزت الدراسة على الأمور الآتية: (1) تشتت التربة، (2) تشتت التربة، (3) تشتت التربة، (4) تشتت التربة، (5) تشتت التربة، (6) تشتت التربة، (7) تشتت التربة، (8) تشتت التربة، (9) تشتت التربة، (10) تشتت التربة، (11) تشتت التربة، (12) تشتت التربة، (13) تشتت التربة، (14) تشتت التربة، (15) تشتت التربة، (16) تشتت التربة، (17) تشتت التربة، (18) تشتت التربة، (19) تشتت التربة، (20) تشتت التربة، (21) تشتت التربة، (22) تشتت التربة، (23) تشتت التربة، (24) تشتت التربة.

يتم استخدام مقياس التربة لقياس القوة المحمولة (CBR) في هذا البحث، والذي يشير إلى قوة تشتت التربة السبخية في موقع التربة. وتم استخدام مقياس القوة المحمولة (CBR) في هذا البحث، والذي يشير إلى قوة تشتت التربة السبخية في موقع التربة.

وتم استخدام مقياس التربة لقياس القوة المحمولة (CBR) في هذا البحث، والذي يشير إلى قوة تشتت التربة السبخية في موقع التربة.

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ABSTRACT

Name: Eissa Shaye Al-Ayedi

Title: Chemical Stabilization of Al-Qurayyah Eastern Saudi Sabkha Soil

Major Field: Civil Engineering (Geotechnical)

Date of Degree: July, 1996

Despite the extensive distribution of sabkha soil in many countries in the Arabian Gulf and the Middle East, particularly along the coastal areas, a review of the published literature indicates that these types of soil have received little attention from the geotechnical community to improve their inferior properties. There exist some “pilot” studies, however, they can not be generalized to all sabkhas due to the heterogeneous nature of these soils.

In this research program, a “selected” sabkha soil from Al-Qurayyah, eastern Saudi Arabia, was researched for: (i) characterization, (ii) preliminary stabilization using chemical additives, namely cement and lime, and (iii) detailed stabilization program using one of the stabilizers only. The test results indicated that lime did not bring about significant improvement and therefore was excluded in the detailed stabilization of Al-Qurayyah sabkha. However, the 7% cement content by weight of dry soil improved the strength of Al-Qurayyah sabkha soil significantly. Many tests were conducted including compaction, CBR, unconfined compressive strength, resilient modulus and durability.

The parameters studied in the detailed stabilization program using cement were: (i) cement content, (ii) exposure conditions, (iii) moisture content, (iv) exposure period, (v) delay in compaction, and (vi) exposure temperature.

The results of this investigation indicated that cement addition has proven to be feasible, economical and the stabilized soil has satisfied both the strength and durability requirements. Furthermore, cement addition increased the strength of Al-Qurayyah sabkha soil sharply and gave over 500% improvement compared to the untreated sabkha soil. However, this stabilized sabkha soil can be used as subbase or subgrade in roads and other constructions.

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Chapter 1

INTRODUCTION

Sabkha soils are vastly distributed in the Arabian Gulf region. Their presence is very extensive in few parts of Saudi Arabia, especially along the coastal areas. Previous experience with sabkha soil in Saudi Arabia and elsewhere indicates that sabkha is a highly variable material and has caused many problems to highways and structures built over sabkha terrain. Typical problems encountered in highways built over sabkha beds include cracking, formation of huge potholes and rutting. A review of the literature reveals that the main geotechnical problems in sabkha media could be ascribable to one or more of the following (Al-Amoudi, 1992): (i) periodic changes in moisture content; (ii) presence of diagenetic minerals; (iii) shallowness of groundwater table; (iv) presence of highly corrosive brines; and (v) very low and variable strength at the sabkha natural conditions.

The above summary of problems indicates that there is an urgent need to find an easy, feasible and cost effective methodology for improving and stabilizing these types of soil. One of the best methods is through the use of chemical additives (i.e. Portland cement and lime) and, although this technique has been used extensively worldwide to stabilize almost all soils, there is only meager data on the performance of sabkha soils when stabilized with chemical additives (Al-Amoudi, 1994b). The available data indicates that when sabkha is stabilized with lime or cement, the potential improvement
could be significant. Unfortunately, these studies were few and concerned with only one sabkha soil, i.e. the "Ras Al-Ghar eastern Saudi sabkha", and the assessment criterion followed therein was totally based on the unconfined compression tests using small "51x102 mm" cylindrical specimens.

As sabkha soils exhibit variable characteristics and the exposure conditions, in terms of temperature, moisture content, repeated/static loading, etc., vary significantly from one region to another, it is rational to expect that the response of each sabkha to stabilization is unique. Consequently, this investigation was conducted with the cardinal objective to stabilize an eastern Saudi sabkha soil using chemical additives.

1.1 Objectives of this Investigation

The following are the primary objectives of this investigation:

(i) To characterize the behavior of a genuine sabkha soil from the Eastern Province (Al-Qurayyah sabkha).

(ii) To stabilize the selected sabkha soil with cement and lime. The potential type of the stabilizing agent will thereafter be selected on the basis of the maximum strength achieved.

(iii) To optimize the chemical stabilization of the selected sabkha taking into account the following factors:

- Strength.
- Curing temperature.
- Curing period.
- Delay in compaction.
- Resilient modules ($M_R$).
- Durability.

1.2 Organization of this Report

In order to accomplish the above-stated objectives, a thorough survey of the published literature to provide a fundamental basis of this research work was presented in Chapter Two. It mainly focuses on previous experimental results related to geotechnical properties and stabilization of sabkha soils in general and those in the Arabian Gulf in particular. Chapter Three, devoted to the experimental program, presents the laboratory investigation program and discusses the procedures and methodologies of the different testing techniques carried out during the experimental part of the report.

Chapter Four outlines the results obtained from the laboratory testing on the one hand and reviews and explains these results critically on the other hand. This Chapter is entitled “Results and Discussion”. Lastly, Chapter Five summarizes the main conclusions that can be derived from the findings of this research program. It also gives some recommendations for future work in this subject area.
Chapter 2

LITERATURE REVIEW

2.1 Definition of Sabkha Soil

Sabkhas can be defined as saline flats underlain by clay, silt and/or sand and are often encrusted with salt (Al-Amoudi and Asi, 1991). They are equilibrium surfaces whose level is largely controlled by the local ground water table (Johnson et al, 1978). A more formal definition of sabkha is given in a glossary of desert terms produced by the Military Engineering Experimental Establishment (1969) as follows:

"Sabkha: Bottom of a closed depression, zone of evaporation for accumulated runoff from a shallow subterranean water-table, characterized by the presence of salt deposits and absence of vegetation usually consists of fine textured materials and is soft when wet. Can also be used for salt marshes or marine lagoons."

Since sabkha is associated with brine evaporation, many types of evaporitic terrains are expected to exist. Local names of these evaporitic associations are many and indeed highly bewildering (Fookes and Collis, 1975). Ellis (1973) presented the variations in regional nomenclature in many countries as shown in Table 2.1. On the other hand, Fookes and Collis (1975) reduced these nomenclatures, at the risk of over-
Table 2.1: Summary of Sabkha/Playa Nomenclature (Ellis, 1973)

<table>
<thead>
<tr>
<th>Location</th>
<th>General Terms</th>
<th>Clay-Silt Playas</th>
<th>Saline Playas</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>Playa, dry lake, alkali flat</td>
<td>Dry playa, clay playa</td>
<td>Salt flat, salt marsh, salina</td>
</tr>
<tr>
<td>Mexico</td>
<td>Laguna, salina</td>
<td>Laguna</td>
<td>Salina</td>
</tr>
<tr>
<td>Chile</td>
<td>-</td>
<td>-</td>
<td>Salina (moderate salt)</td>
</tr>
<tr>
<td>Australia</td>
<td>Playa, lake</td>
<td>Clay pan</td>
<td>Salar (much salt)</td>
</tr>
<tr>
<td>Russia</td>
<td>Pliazh</td>
<td>Takir</td>
<td>Salt pan, salina</td>
</tr>
<tr>
<td>Mongolia</td>
<td>Gobi, nor</td>
<td>Takyk</td>
<td>Tsakal, nor</td>
</tr>
<tr>
<td>Iran</td>
<td>Daryacheh</td>
<td>Dayq</td>
<td>Kavir</td>
</tr>
<tr>
<td>South Africa</td>
<td>Pan, vloer mbuga</td>
<td>Clay pan</td>
<td>Salt pan, kalahari</td>
</tr>
<tr>
<td>North Africa</td>
<td>Sebkha</td>
<td>Garoet, qavat</td>
<td>Sebkha, chott</td>
</tr>
<tr>
<td>Arabia</td>
<td>-</td>
<td>Khabra</td>
<td>Marnelah (salt flat)</td>
</tr>
<tr>
<td>Jordan</td>
<td>Ghor</td>
<td>Qa</td>
<td>Sabkhal (coastal salt flat)</td>
</tr>
<tr>
<td>Iraq</td>
<td>Hawr</td>
<td>Foydat</td>
<td>-</td>
</tr>
<tr>
<td>India</td>
<td>Rei</td>
<td>-</td>
<td>Sakhar</td>
</tr>
<tr>
<td>Pakistan</td>
<td>Hamum</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
simplification and for engineering classification, to: (i) sabkha (coastal salt marsh); (ii) playa (an ephemeral lake flat); (iii) salt playa (as playa but with a saline surface due to evaporation of saline lake waters); and (iv) saline (a local depression with a high water table and capillary rise reaching the surface; with the formation of a salt crust). Al-Amoudi (1995b) has recently defined these terms from geotechnical perspectives as:

Playa: It is a dry flat area at the center of an undrained desert basin, where water accumulates after rain and is evaporated to leave behind a thin layer of encrusted salt.

Salina: It is a salt pit, salt mine, salt pan, salt flat, salt marsh, lake, or any other place, where crystalline salt deposits are formed. Sabkha: It is a supratidal environment where sedimentation is formed under arid or semi-arid conditions on restricted coastal or continental plains.

2.2 Types of Sabkha Soils

Many researchers have reported two main types of sabkhas, namely, coastal and continental sabkhas. Coastal sabkhas are supertidal surfaces which have developed as a result of a sedimentation sequence that appears to have started several thousands of years ago with the Arabian Gulf waters transgressing over sand dunes that formed during the Pleistocene age. This sea encroachment has resulted in lagoons separated from the Gulf water by barrier islands. After this transgression and subsequent morphological changes, the depositional environment appears to have shifted from subaerial to subaqueous causing extensive carbonate sedimentation in lagoons which led to gradual widening of
the sabkha plain and eventual progradation of the coastline (Akili, 1981). Following the deposition of the primary material sediments and continuing even at present are diagenetic processes which result in the formation of new materials. Argonite, calcite, gypsum, anhydrite, magnesite, dolomite, halite and a few other minerals form in response to the physical and chemical conditions that prevail in the sabkha environment (Akili, 1981). Figure 2.1 shows a generalized cross section of a coastal sabkha from the Arabian Gulf water to the inland margin where the sabkha plain may abut sand dunes or rock outcrops.

The continental or inland sabkhas are saline deposits of inland areas that do not have a hydrological link with the sea or ocean; therefore, replenishment of their ground water is not from the sea (Akili and Torrance, 1981). They may abut the coastal sabkha as does the Matti sabkha in Abu Dhabi or they may occur further inland. They tend to occur in areas that are dominated by dune sands and derive their evaporative minerals through the concentration of ground water by an evaporative mechanism or by saline continental ground waters. These waters flow through deep permeable strata to the Miocene formation which underlies the continental sabkha and then rise to replace the evaporated ground water (Kinsman, 1969). The continental sabkhas are dominated by wind-blown sands and aeolian agencies which are primarily responsible for transporting mineral grains into and out of the sabkha. The continental sabkhas contain relatively little carbonate and what is present has usually been derived by erosion of merely carbonate outcrops or by
Fig. 2.1: Generalized Cross Section Across a Coastal Sabkha with Typical Surface Features (Akili, 1981)
aeolian transport from the coastal areas. Gypsum and anhydrite are the most abundant minerals in the sabkha (Akili and Torrance, 1981).

2.3 Distribution of Sabkha Soils

Saudi Arabia has a large number of sabkhas, both coastal and inland. A summary of these sabkhas in the coastal plains of the Eastern Province, based mainly on reconnaissance visits, has been reported by Johnson et al. (1978). Along the western shores of Saudi Arabia, coastal sabkhas also exist at Obhor, Al-Lith (250 km south of Jeddah) and Yanbu (Al-Amoudi et al, 1992b). In south-western Saudi Arabia, near the town of Jizan, a coastal sabkha is reported to exist surrounding a salt dome. In the North, continental sabkhas are reported to exist in Wadi As-Sirhan. A schematic diagram showing the distribution of sabkhas in Saudi Arabia is shown in Fig. 2.2.

The sabkha distribution along the southern and southwestern shores of the Arabian Gulf is well documented. Figure 2.3 gives a typical presentation of the prevalence of sabkha along the Arabian Gulf (Fookes and Higginbottom, 1980). The presence of sabkhas in Saudi Arabia and in the other Arabian Gulf States is shown to be quite extensive, especially in the well-populated cities along the Arabian Gulf and Red Sea coasts.

A review of the global distribution of sabkha (Renfro, 1971; Al-Amoudi et al, 1991; Al-Amoudi et al, 1992b) indicates its prevalence in the Middle East, including
Fig. 2.2: Distribution of Sabkhas in the Arabian Peninsula  
(Al-Amoudi et al., 1992)
Fig. 2.3: Distribution of Sabkhas in the Arabian Gulf (Fookes and Higginbottom, 1980)
Egypt, Sudan, Libya, Tunisia, Algeria and Ethiopia. Sabkha also exists in India, Australia and Southern Africa. Sabkha and sabkha-like sediments occur in relatively cold climates, such as in Mexico, California, Utah and Texas in the U.S.A. The active and potential locations of sabkha around the world are depicted in Fig. 2.4, where the potential locations include some sites in North and South America as well as in what was previously called the Soviet Union (Al-Amoudi, 1994a).

2.4 Factors Affecting Sabkha Formation

Numerous factors influence the formation of sabkhas. These factors are shown in Fig. 2.5 and have recently been discussed by Al-Amoudi (1992). As for the present investigation, only the climatic factors will be outlined below, because these factors are more clearly documented in the geotechnical literature compared with the other factors summarized in Figure 2.5.

2.4.1 Climatic factors

These primary climatic factors affecting the formation of sabkha include rainfall, temperature, relative humidity and prevailing winds. These factors are discussed below.

(a) Rainfall

It is one of the three main water resources to and/or from the sabkha system (i.e. rainfall or precipitation, water evaporation and flow of ground water). Butler (1969) quotes an average annual rainfall for the Arabian Gulf sabkhas of less than 5 cm; however, it is probably mainly between 3 and 4 cm; compared to an average
Fig. 2.4: World Map Showing Locations of Active and Potential Sabkhas (Al-Amoudi, 1994a)
Fig. 2.5: Summary of the Factors Controlling the Sabkha Formation (Al-Amoudi, 1992).
annual rate of evaporation of approximately 125 cm from the Arabian Gulf waters. The net evaporation rate is estimated to be 6 cm/year of groundwater, which is relatively low compared to the 125 cm/year for the Arabian Gulf open waters.

The effect of rainfall on sabkha is that it tends to dissolve the precipitated salts at or near the surface and to raise the water table level (Al-Amoudi, 1995a). The salt dissolution tends to increase the permeability of sabkha and may ultimately induce collapse. The rise of ground water tables may have many geotechnical impacts (Al-Sanad and Shaqour, 1991) amongst which are:

(i) reduction in effective stresses as a consequence of increased pore-water pressure, which reduces the shear strength of granular soils;

(ii) flooding of improperly water-proofed basements, which will cause significant disturbance, both functional and, in the long-term, structural; and

(iii) settlements of buildings becomes imminent due to the wetting of sabkha or due to the compressibility of dewatered, loose, sandy soils.

(b) Temperature

Temperature is one of the main driving factors for the evaporative pumping mechanisms of the sabkhas. As the temperature increases, the evaporation rate will increase thereby leading to high precipitation of salt and other diagenetic minerals in the strata above the ground water tables (Al-Amoudi, 1994b).
(c) **Relative Humidity**

Although this factor is the least reported in the literature, the relative humidity is proposed as a constraint on the final salinity of a brine and, hence, on the ultimate evaporite mineral facies (see Al-Amoudi, 1992). It is shown that different evaporate minerals will be precipitated at different activities of water (i.e. relative humidity) as follows:

at $H_2O = 0.93$ to $0.76$ - Sulfate minerals will precipitate.

at $H_2O = 0.76$ to $0.67$ - Halite will precipitate.

at $H_2O = <0.67$ - Potash minerals will precipitate.

For the coastal evaporite areas of the Arabian Gulf, the mean relative humidities ranging from 70% to 80% which are mainly suitable for sulfate mineral precipitation.

(d) **Prevailing Winds**

Their persistence, seasonality and direction all play important roles in the genesis of sabkha in the Arabian Gulf. For example, shimal winds can transport huge quantities of aeolian sands onto and across the sabkha flats. Moreover, another type of wind, called monsoon, are north to northwest in direction and can
cause flooding of the sabkha surfaces and provide critical replenishment of the sabkha ground water (Al-Amoudi, 1994b).

2.5 Previous Experience with Improvement of Sabkha Soils

In this part of the report, an attempt is made to review the previous work carried out to improve the geotechnical properties of sabkha soils, with more emphasis on chemical stabilization of sabkha.

2.5.1 Mechanical improvement of sabkha soils

Russell (1974) conducted an investigation to study the chemical and physical properties of sabkha-type materials in the United Arab Emirates with a view to determining the suitability of sabkhas for unpaved roads. He suggested tentative criteria for the selection of sabkha for road construction on the basis of its chemical composition and particle size distribution.

Khan and Hasnain (1981) investigated the engineering properties of sabkhas in the Benghazi plain, Libya and construction problems associated with these soils. They stated that several buildings constructed on sabkha soils showed tilting and cracks. The cause of this trouble was traced to the special characteristics of sabkha soils. They suggested that improved mix design and dense concrete should be used so as to make concrete in the foundation materials impermeable and durable.
Akili (1981) reported an investigation on one of the sandy sabkhas in eastern Saudi Arabia. In his study, the field result confirmed the fact that sabkha sediments along the Eastern Province of Saudi Arabia were variable in both lateral and vertical extents. He concluded that calcium sulphate and calcium carbonate were the two main cementing agents of sabkha sands. Moreover, it was shown that one of the main geotechnical problems that may arise from the reduction in strength and stability was attributed to flooding of sands cemented by relatively soluble salts.

Akili and Torrance (1981) carried out preliminary “model” experiments on laboratory static penetration resistance of cemented sands. One of their conclusions was that some of the major problems of sabkha as bearing materials are attributed to the high soluble salt content that exists and continues to form within the host sediments. Furthermore, a common occurrence in the upper zone (0.5 to 2 m) of coastal sabkhas is the instability and sudden decrease in strength when the soluble salts acting as cementing agents dissolve, due to either a rise in the ground water table or to the percolation of surface water during wet periods. The static penetration tests that were performed on these cemented sand samples confirmed what one would intuitively expect; cementation by calcium carbonate and calcium sulfate causes a substantial increase in the resistance to penetration, and the greater the concentration of the cementing agent (calcium carbonate or calcium sulphate), the higher is the penetration resistance. It was also inferred from the limited experiments performed that the pattern of distribution of the precipitate within the penetrated layer has a marked effect on the measured penetration resistance. In a similar
study. Akili and Torrance (1980) further supported the use of static cone penetrometers in
the field to assess strength and layering of sabkha sediments.

Abduljauwad et al. (1994) studied the influence of geotextiles on the static and
dynamic performance of saline sabkha soils. Their results indicated that the use of
geotextiles significantly enhances the inferior properties of sabkha subgrade, particularly
when the soil-fabric-aggregate (SFA) system is saturated. The contribution of geotextiles
to the performance of SFA systems diminishes when the subbase thickness increases.

Akili and Ahmed (1986) reported that the particular difficulties that are often noted
in sabkha have included the high degree of variability of sabkha which makes the sabkha
particularly susceptible to differential settlement. Furthermore, the adverse chemical
reactions that are likely to occur between the sabkha brines, the sediments and the
foundation structures include the potential leaching of carbonates in high carbonate soils
and the potential volume changes that may occur in gypsum-dominated layers. The
authors concluded that the vibroflotation technique has been successfully used to densify
sabkha soils in eastern Saudi Arabia down to a depth of about 6 meters. However, the
presence of silt or cemented sand-silt layers has locally affected the densification process.

Abou Al-Heija and Shehata (1986) studied the engineering properties of Al-Lith
sabkha of western Saudi Arabia. They reported that the top layers which vary in depth
from 0.5 to 2.0 m exhibited firm-stiff to very stiff characteristics unless the surface is
inundated with water and this situation usually creates loose density conditioning.
Furthermore, they recommended the use of ASTM C 150 Type V cement due to the high percentage of sulfates in both the soil and the groundwater in Al-Lith sabkha.

Ellis (1973) conducted a study on the engineering properties of sabkha soil in the United Arab Emirates. He reported that sabkha is a very variable material and thus its performance in road bases is likewise bound to be very variable. It was also stated that if sabkha is used as a base material, the road surface should be at least 1 meter above the highest water table. Further, he concluded that standard laboratory tests do not necessarily provide adequate prediction of field behavior and, consequently, field trials remain the most reliable method of assessing the performance of sabkha soil as a road-building material.

Stipho (1983) performed a study to determine the engineering properties of salt bearing soils and reported that the main initial strength of salt-bearing desert sand is due to the enhanced cohesion developed by the cementation bonding of the salt precipitation. Furthermore, he concluded that the salt content affects the effective angle of friction ($\phi'$) of desert sand ($\phi'$ varies between 30 and 38°, with a range of salt content in the samples tested).

Juillie and Sherwood (1983) carried out several field investigations on the improvement of sabkha soils of the Arabian Gulf coast. They reported that the sabkha soil can be improved and stabilized using different techniques such as vibroflotation, vibroreplacement (i.e. stone columns) and heavy tamping. Furthermore, stone column
may result in a significant decrease in sabkha strength if silt and clay constitute more than 25% of the sabkha soil. The dynamic compaction technique was used to stabilize a loose sabkha site for a sea water canal in Jubail, eastern Saudi Arabia. They also reported that the dynamic consolidation technique was used to stabilize a sabkha site (power and desalination plant housing compound) in Jubail. Furthermore, and based on their experience with sabkha soils, the authors reported that a combined technique of both dynamic replacement and dynamic consolidation could be an effective in-situ stabilization methodology for sabkha.

Abu-Taleb and Egeli (1981) reported that vibroflotation techniques were successfully adopted without disturbing the lightly-loaded strip footings that were already in place when improving the properties of coastal, shelly sands in Jubai, eastern Saudi Arabia. Similarly, Akili and Ahmed (1986) depicted significant improvement in the sabkha site at Rahirma, eastern Saudi Arabia, when using the vibroflotation technique.

Clough and French (1982) indicated that geotextiles were used for several applications associated with saline soils in some of the Middle East countries including the United Arab Emirates, Egypt, Kuwait, Iraq and Saudi Arabia. Further, the use of geotextile was implemented in cultivating sabkha sites along the Red Sea and the Arabian Gulf coasts. A typical example was the Al-Khobar Meridian Hotel in eastern Saudi Arabia.
French et al. (1982) carried out some preliminary laboratory studies on simulated-sabkha soils and indicated some success with the use of "Filtram" geotextile to prevent the rise of both salt and water and to prevent water infiltrating from above penetrating the fabric.

Shehata et al. (1990) reported a review on the potential sabkha hazards in Saudi Arabia. They cited that the sabkha hazards may include soil subsidence due to hydrocompaction, corrosive actions of both soil and groundwater on reinforced concrete substructures, possible heave due to salt recrystallization and potential flooding due to the low infiltration rates of sabkha soils. Many of those hazards were observed at various locations in Saudi Arabia. They concluded that several remedial measures, such as soil replacement, soil densification, groundwater control, deep foundations and use of suitable construction materials, in the afflicted areas.

Ismael (1993) performed laboratory and field leaching tests on sabkha soils. He reported that a comparison between the soil properties of laboratory specimens before and after leaching and indicated that leaching resulted in a reduced unit weight, plasticity, specific gravity and a significant increase in the percent of fines. The latter was attributed to the breaking of particles containing gypsum crystals of low mineral hardness. Leaching under very low confining pressure resulted in an increased permeability and void ratio. Furthermore, leaching leads to increased compressibility and a minor reduction in shear
strength parameters. It also caused a modest reduction of the pre-consolidation pressure due to the removal of some cementation bonds.

2.5.2 Previous experience with chemical stabilization of sabkha

In order to set up the experimental program for the present investigation, a thorough review of the literature was searched, with the primary objective to underline the previous experience on stabilization of sabkha soils in particular and of arid, saline soils in general. Following is the main findings of the literature review.

Akpokodje (1985) stabilized three arid-zone soils using cement and lime. He concluded that cement is a more effective stabilizing agent than lime in all the soils examined although an addition of 2 to 4% lime was required in the case of a clayey soil in order to improve mixing with cement. The strength developed by soil-cement mixtures was mainly dependent on the texture and the overall mineralogy (clay and non-clay) of the soil. Furthermore, the high content of gypsum and bassanite in the sandy soils rendered them unamenable to cement and lime stabilization. In addition, the high contents of clay (smectite) and gypsum/bassanite result in large strength reduction of the cement-stabilized soils upon soaking in water, whereas the abundance of illite and carbonate tend to produce an opposite effect.

Farwana and Majidzadeh (1988) carried out an investigation on the use of emulsified asphalt in the stabilization of sandy sabkha. They observed some improvement in strength and stability that was sufficient to withstand wet-dry cycles. They also stated
that the bitumen provides the sand particles with cohesion and water-proofing to the clay constituents that may exist in the sand. Furthermore, the bitumen seemed to serve as a protection against water intrusion in the sabkha domain.

Stipho (1989) investigated the engineering properties of stabilized saline soil. He stabilized two simulated-saline sabkhas using cement for the coarser-grained samples and lime for fine-grained ones. He concluded that the saline soil which was treated with Portland cement improved the maximum dry density and cone penetration resistance, and changed the optimum moisture content. However, for the saline soil which was treated with lime, the shearing resistance and cohesion of fine-grained soil have been improved. Despite such improvements, it is very difficult to state whether the same behavior could be obtained for "genuine" sabkha soils or not. Further, the artificial method to create the cementation and the cementing agents themselves in no way resembles the field conditions (Akili and Torrance, 1981; Aiban, 1994). Moreover, sabkha soils usually consist of a mixture encompassing silty sands, sandy silts, and/or clayey sands, and the separation of fine-grained and coarse-grained soils does not represent the actual conditions (Al-Amoudi, 1994b).

Al-Abdul Wahhab and Abduljauwad (1989) performed a study on sabkha-soil stabilization in the Eastern Province of Saudi Arabia using three stabilizers, namely lime, cement, emulsified asphalt with two additions of 2% and 4% of lime and cement. Their results showed that stabilization of sabkha by lime or cement is effective in increasing the
shear strength of dry compacted samples. Moreover, the addition of lime to emulsion treated-sabkha mixtures improved the shear strength slightly, and this effect was reduced when lime was increased from 2% to 4%.

Al-Amoudi and Asi (1991) as well as Al-Abdul Wahhab et al. (1994) conducted two investigations; both studies indicated that the use of liquid asphalt alone in stabilizing sabkha soils did not bring about any improvement in strength. However, the properties of sabkha, as evaluated by the shear strength parameters (φ and c) were improved significantly by the addition of cement to the emulsified asphalt-sabkha mixtures. The properties of sabkha were improved to a lesser extent when lime and emulsified asphalt were conjointly used (Al-Abdul Wahhab et al. 1994)

Al-Amoudi and Asi (1991) performed a preliminary investigation on the improvement of sabkha properties using three different stabilizers, namely cement, emulsified asphalt and fly ash, at five percentages, 0, 2.5, 5, 7.5 and 10%. Their results indicated that the maximum strength was attained at a lower moisture content than the optimum. Furthermore, the emulsified asphalt reduced the maximum dry density and increased the moisture content; the cement and fly ash, however, increased the maximum dry density and decreased the optimum moisture content at 5% and higher additions due to their ability to act as a filler. The emulsified asphalt reduced the unconfined compressive strength of sabkha for all the percentages implemented in that investigation. However, the fly ash increased the strength marginally. The use of cement resulted in
considerable improvements. As low as only 2.5% of cement addition was able to increase the strength three times that of the plain soil, while the 10% cement addition attained as high as about 20 times (Al-Amoudi et al., 1995b). This significant improvement is due to the ability of the hydration products to produce cementitious materials that bind sabkha soil particles together. However, the output of this investigation, although to be considered as preliminary, highlights the potential of using cement as a stabilizing agent to improve the inferior properties of sabkha soils.

Al-Amoudi (1994b) has recently conducted a chemical stabilization program on sabkha soil at high moisture contents of 16% and 22% confining the range of natural moisture content of sabkha in the field. Cement and lime were only used at five percentages (0, 2.5, 5, 7.5 and 10%). His results indicated that only cement was efficient in enhancing the strength at high moisture contents simulating the range of natural moisture content. The 90-day strength of these specimens, particularly those prepared at 16% moisture content, was higher than the 7-day strength of the specimens prepared at the optimum moisture content. The high moisture content, however, significantly lessened the initial and ultimate strength of lime-stabilized sabkha specimens.

Al-Amoudi, et al. (1995) have recently conducted an extensive stabilization program on the effect of inert materials (i.e. non-reactive, including crusher fines, marl) and chemical stabilizers (cement, lime and emulsified asphalt) at five additions (0, 2.5, 5, 7.5 and 10%) on the unconfined compressive strength of an eastern Saudi sabkha. The 7-
day cured specimens were prepared at moisture contents either lower or around the optimum moisture content obtained from the standard Proctor tests. The results indicated that significant improvements were only observed for the cement and lime stabilizers. The average maximum strength was improved from 70.1 kPa for the control (untreated) specimens to 271 to 1391 kPa and 246 to 1600 kPa for the 2.5 to 10% cement and lime stabilized specimens, respectively. Such improvements ranged from about 250% to 2200% compared with the control specimens. What is important and relevant is the fact that the optimum moisture content from strength perspectives was around 10.7% and 8.5% for the cement and lime-stabilized sabkha mixtures compared to about 12.5% for the compaction tests.

2.6 Significance of This Research

The present review of the literature, mostly cited in this Chapter, indicates that several studies have been conducted to study the properties of sabkha soil. However, these soils are highly heterogeneous and, therefore, the response of each sabkha to chemical stabilization may be unique. Further, only meager data is available on the performance of sabkha soils when stabilized with chemical additives. Moreover, the usefulness of chemical additives, namely cement and lime, in improving the sabkha soil in the hot-weather conditions of the Arabian Gulf was not fully elucidated. Similarly, the performance of stabilized sabkha soils when exposed to different curing temperatures, curing conditions (sealed vs. exposed), curing period, delay in compaction, modulus of resilience, and the wetting and drying cycles, was not adequately investigated.
Chapter 3

EXPERIMENTAL PROGRAM

This Chapter outlines the procedures and test methods which were followed to fulfill the objectives of this investigation. The experimental program consisted of five stages, as shown in Fig. 3.1. The first phase was to select a site in the Eastern Province of Saudi Arabia that represents an original sabkha. In the second phase, the sabkha sample was retrieved from the selected sabkha site. In continuation of the second phase, the third phase was to characterize the sabkha sample in the laboratory using ASTM standards. Chemical stabilization of the selected sabkha soil using cement and lime was pursued in the fourth phase. Only unsoaked CBR tests were conducted to select the appropriate stabilizer. Based on the results obtained in the fourth phase, the sabkha soil was thereafter subjected to a detailed stabilization program in the fifth phase. All phases of the experimental program are discussed thoroughly in the following paragraphs.

3.1 Site Selection

The first phase of this investigation was to select a site in the Eastern Province that represents a "genuine" sabkha. Many sites located at Ar-Riyas, Jubail and Al-Qurayyah were surveyed (Fig. 3.2). Reconnaissance visits to each of these regions were based on visual observation of the surficial layers above groundwater table. Salt-encrusted surface, sandy nature of the layers, presence of diagenetic minerals
Fig. 3.1: Flow Chart for the Experimental Program of Stabilization of Al-Qurayyah Sabkha
Fig. 3.2: Vicinity Map Showing the Location of Al-Qurayyah Sabkha Site (Aiban et al., 1995)
such as gypsum, halite and anhydrite were the symptoms considered. It is noteworthy to mention that the characterization of 20 sabkha sites from eastern Saudi Arabia has recently been reported by a KFUPM-research group (Aiban et al. 1995). Their preliminary characterization was the basis of this selection. After visiting some of the two regions and observing many pits, it was decided that Ar-Riyas sabkha be excluded since previous investigations were carried out on that sabkha. For this reason, Al-Qurayyah sabkha was selected for characterization and stabilization and this selection was supported by the following reasons:

1. No previous geotechnical investigation was conducted on this sabkha.
2. The potential importance of this sabkha is ascribable to its location beside Al-Qurayyah power plant (an existing facility).

3.2 Collection of Al-Qurayyah Sabkha Soil

The sabkha soil used in this investigation was collected from Al-Qurayyah sabkha which is located approximately 80 kilometers from Dhahran city and east of Abqaiq city, beside Al-Qurayyah power plant where the Saudi-ARAMCO's beach is located, as shown in Fig. 3.2. The materials were collected from all the layers above the water table excluding the crust. The pit consisted predominantly of two types of sandy layers in addition to the salt-encrusted surficial soil. These layers composed of relatively coarse-grained and fine-grained sands. The deeper fine-grained soil contained some silt with no plasticity, as shown in Plates 3.1 and 3.2. At a depth of
Plate 3.1: Layering characteristics in Al-Qurayyah sabkha soil.
Plate 3.2: A presentation Showing Calcitic Sand in Al-Qurayyah sabkha.
38 cm, an anhydrite layer of about 11 cm thickness was encountered. The anhydrite layer is supported by the presence of gypsum and silty fines of about 16 cm, probably reflecting the coastal nature of Al-Qurayyah sabkha, as shown in Plate 3.1. It worths mentioning that huge salt ponds were found on the whole sabkha flats as shown in Plate 3.3. In some areas, the salt was so extensive that it was taken from these ponds using a back-hoe (Plate 3.4). A sufficient and representative quantity of Al-Qurayyah sabkha soil was retrieved. The soil was placed in plastic bags and labeled in the site and thereafter transported to the Geotechnical Laboratory at KFUPM.

3.2.1 Preparation of sabkha soils

The materials which were brought to the Geotechnical Laboratory were spread on plastic sheets outside the laboratory (i.e. in the open air) for air drying. Once the materials were air-dried, they were thoroughly mixed and plastic hammers were used to gently break down the crystals and pockets and allowing all the sabkha soil to pass ASTM Sieve # 4. The materials were again thoroughly mixed and stored in plastic drums till testing.

3.3 Preliminary Characterization of Al-Qurayyah Sabkha Soil

The preliminary characterization of Al-Qurayyah sabkha soil was evaluated as per standard indices and strength parameters. The response of this sabkha soil to different tests was meant to forecast its behavior in the field to check its potential usage as a construction material by itself, or some improvement techniques are needed
Plate 3.3: Documentation showing the presence of salt ponds in Al-Qurayyah sabkha.
Plate 3.4: Documentation of collecting salt from Al-Qurayyah sabkha.
to make it suitable for construction. For this purpose, sabkha samples were subjected to preliminary soil classification using grain-size analysis and Atterberg limits. In addition, the compaction and strength characteristics, using the modified Procter compaction and California bearing ratio tests, were investigated. Specific gravity test was also included as part of the preliminary tests.

3.3.1 Specific gravity test

This test was conducted on four representative disturbed samples passing ASTM Sieve # 4. The test was performed in accordance with ASTM D854, however, oven drying was maintained at 70°C, as recomended by Al-Amoudi (1995a) so as to inhibit the transformation of diagenetic phases. The average of the four samples was taken as the specific gravity value of Al-Quarayyah sabkha soil.

3.3.2 Atterberg limits tests

Liquid limit and plastic limit tests were conducted on the material passing ASTM Sieve No. 40 using distilled water and sabkha brine. The two tests were performed in general accordance with ASTM D 423 and ASTM D 424, respectively. For this sabkha soil, it was not possible to get the required number of blows for the liquid limit test, therefore, the liquid limit was reported as nil. The soil also could not be rolled to a thread of 1/8-in (3.18 mm), therefore, the soil was classified as nonplastic.
3.3.3 Grain-size distribution tests

This test is a basic requirement in any soil investigation. It is also essential in almost all soil classification systems. Wet sieving was carried out using distilled water and sabkha brine on the material passing ASTM Sieve No. 4, as recommended by ASTM D 422. The sabkha brine was brought from the same pit from which Al-Qurayyah sabkha soil was retrieved.

In the wet sieving method, the fluid was allowed to flow into the top sieve from a Plexiglas reservoir which was placed at a height of about 130 cm. Based on preliminary trials (Al-Amoudi and Abduljauwad, 1994), about one cubic foot (0.028 m³) liquid was used during the wet sieving test, which was enough to make the passing fluid clear. The soil portions retained on each sieve as well as that passing the No. 200 sieve were dried in the oven and then weighed. The difference in weights of the (sieves + dry soil) and the (empty sieves) was used to determine the percentage passing for each sieve, as elucidated in ASTM D 422.

3.3.4 Moisture-density test

The purpose of any moisture-density test, commonly called the compaction test, is to determine the optimum moisture content at which the maximum dry density of the soil is attained. It is generally desirable to increase the density in the field in order to increase the strength of the soil. Two types of compaction tests were used in
practice; standard Proctor compaction test (ASTM D 698) and modified Proctor compaction test (ASTM D 1557).

In this investigation, the modified Proctor compaction test with 18 lb (8.18 kg) hammer weight and 18 in (45.7 mm) fall height was conducted on disturbed samples to identify the maximum dry density and the optimum moisture content. Compaction was made in five layers in the CBR mold. The CBR mold has a height of 5 in (127 mm) and a diameter of 6 in (152 mm) and the number of blows per layer was 56.

When compacting the mixtures of sabkha soil with cement (or lime) and water, the following procedure was followed: The required amount of sabkha soil was placed in Hobort mixer (0.3 m³ capacity), the dosage of cement was added by weight of oven-dry (105°C) sabkha soil. Mixing was thereafter started in a dry state for 1 minute, the water was then added to the mixture and mixing was continued for about another 3 minutes till the whole mixture was fully mixed and the final product was completely homogeneous. The same procedure was followed for lime-sabkha mixtures.

3.3.5 Unsoaked CBR and Clegg hammer tests

California bearing ratio (CBR) test was originally developed in California, USA, as a means to evaluate the suitability of a soil to be used as a subgrade material in pavements and, thereafter, adapted by the engineering communities as a test to
empirically measure the strength of a soil under controlled moisture and density conditions. This test is recognized worldwide because of the absence of better alternatives, and of its great deal of reliable data as well. Therefore, it can easily be used to evaluate the materials for use in pavement construction.

In this investigation, CBR tests were conducted in compliance with ASTM D 1883. As stated above, all the samples prepared for the moisture-density relationship were subjected to CBR testing procedure. The samples were tested soon after preparation so that no moisture loss was permitted. For this part of the characterization, only unsoaked CBR tests were performed.

Clegg impact hammer test was performed on the same samples used in the CBR tests in order to get a correlation between CBR and Clegg impact value (CIV). This test is considered to be a practical alternative to the CBR test as it can be easily conducted in both the laboratory and the field (Khan, et al., 1995). Furthermore, it can be used for quality control purposes in the field. Also, this test is easy to operate and cost effective. The device consists of a compaction hammer with size and shape similar to the one use in the modified Proctor test, equipped with piezoelectric accelerometer, and attached to a digital measuring device (Asi et al., 1992), as schematically shown in Plate 3.5. It measures the Clegg Impact Value (CIV) by means of dynamic rebound of the soil against a standard weight falling from a standard height and it measures the strength of the material (Khan et al., 1995). At the
end of the CBR test, the Clegg impact hammer was used on the bottom "undisturbed"
face of the CBR samples to get the corresponding CIV.

3.3.6 Unconfined compression test

The unconfined compressive strength ($q_u$) test was used to assess the strength characteristics of chemically-stabilized soil specimens as well as the untreated ones. $q_u$ test is frequently used in many standards and codes for stabilized earth materials. Usually, a minimum $q_u$ value is specified for different applications. It was therefore adopted as a basic test in this investigation where a comparative study of the effects of different parameters such as curing conditions, curing period, and the effect of delay in compaction on the strength gain of stabilized sabkha soil mixtures are to be studied.

In this investigation, $q_u$ test is performed on cylindrical specimens with a height to diameter ratio ($h/d$) of 2. According to ASTM D 559, soil cement specimens for unconfined compressive testing can have $h/d$ values in the range of 1.15 to 2.0, however, $q_u$ values have to be corrected to an $h/d$ ratio of 1.15. Correction factors for $h/d$ ratios are supplemented in ASTM D 559.
Plate 3.5: The Clegg impact hammer
Cylindrical specimens of 71 mm (2.8 in.) diameter and 142 mm (5.6 in.) height (h/d = 2.0) were prepared for all unconfined compressive testing. The required sabkha soil and additive content were mixed first and then the corresponding moisture content was added and mixed thoroughly in a mechanical mixer for 3 minutes. The mixture was then compacted in a mold to the maximum dry density based on the modified Proctor compaction test. The mixture was compacted in 3 equal layers. The number of blows was adjusted to obtain the required dry density. On the average, these blows came out to be around 40 blows/layer. The mold used was of a split type with a longitudinal slit along its axis. The slit was tightened or opened with the help of bolts. After compacting each layer, a mechanical key between the three layers was made by scratching the surface of the preceding layer before placing the successive layer on top of it. After compaction, the specimen was removed from the mold by loosening the bolts and then immediately jacking out of the mold. Two types of curing regime were used; the sealed specimens and exposed ones. In the exposed curing regime, the specimens were cured as taken from the molds while in the sealed curing regime, the specimens were wrapped in three layers of nylon sheets in order to inhibit any loss of moisture from the specimens. The exposed and sealed samples were then put on the table in the laboratory and kept to cure for different periods at the laboratory temperature (23 ± 2°C). On the other hand, some other samples were allowed to cure at different temperatures (i.e. 35, 50 and 70°C) for different curing periods of 1, 3, 7, 14, and 28 days.
3.3.7 Resilient modulus test

The resilient modulus (MR) test is basically a repetitive type of loading test using the stress distribution principle of indirect tensile test (Haas and Hudson, 1978). It is used to investigate the behavior of certain pavement materials under repeated loading. The main advantage of this test procedure is its simplicity as well as its ability to test soil specimens similar in size to those used in the widely known Marshal and Hveem tests. The MR test has been adopted by AASHTO (AASHTO T 274) for the design of pavement layers, and its dynamic nature simulates the response of pavement layers to the impulse loading produced by the moving wheels of vehicles.

The diametral type of MR test was adopted in this investigation to evaluate the behavior of stabilized sabkha mixtures under repeated loading. Stabilized soil specimens of 4 inches (101.6 mm) in diameter and 2.5 inches (63.5 mm) in height were prepared, and the samples were compacted in one layer. The number of blows was adjusted in order to attain the required maximum dry density based on the modified Proctor test, these blows came out to be 84 blows for the single layer (i.e. specimen). After compaction, the samples were taken out from the mold and subjected to the different curing regimes similar to those used in the unconfined compression test discussed above. The curing period was, however, maintained at 28 days for all MR samples. At the end of curing period, the samples were subjected to diametral MR testing. The mold containing the sample was fixed in the resilient modulus device in position by applying a seating load of 150 lb (667 N). The mold
has two transducers (LVDT's) installed on two opposite ends that were fixed on the sides of the sample. In each test, a static load of 150 lb (667 N) was first applied normal to the direction of the installed LVDT's in order to hold the sample in place. LVDT's were used to measure the diametrical resilient tensile strain produced by the application of the impulse loads. The resilient tensile strain at the end of the 100 cycles was used in calculating the resilient modulus ($M_R$) of the specimen. The maximum load applied and the horizontal tensile deformation were recorded using a computer connected to the $M_R$ device. Therefore, the resilient modulus $M_R$ can be computed according to the following formula (Yoder and Witczak, 1975):

$$M_R = \left( \frac{P(\mu + 0.2734)}{(t \Delta h)} \right)$$  \hspace{1cm} (3.1)

where:

- $p =$ the applied dynamic load (lb);
- $\mu =$ poisson's ratio;
- $t =$ specimen thickness (inches);
- $\Delta h =$ total deformation (inches).

The $M_R$ value depends on many variables including soil type, molding water content, density, stress level and duration, and environment (Haas and Hudson, 1978).

3.3.8 Durability tests (wetting and drying)

Two different tests were performed to evaluate the durability of stabilized sabkha soil since stabilized sabkha specimens are often subjected to repeated wetting
and drying due to moisture variation in the field. Rise and fall of water
table, leakage from adjacent utilities, septic tanks, irrigation water, and seasonal
variation of rainfall are responsible for these wetting and drying cycles. These cycles
induce tensile and compressive stresses in the stabilized and untreated soils.

In this investigation, the durability of soil-cement samples was evaluated using
both the standard ASTM D 559 method and another proposed slake durability test.
The latter was originally used for testing rocks (Goodman, 1980) but has recently been
modified by Aiban et al. (1995) in order to accommodate the cement-stabilized soil
specimens with specific sizes.

3.3.8.1 Standard durability test (ASTM D 559)

Soil-cement samples were prepared with different percentages (3, 5, 7 and
10%) of cement. The mold used to prepare the soil samples was 4 in. (101.6 mm) in
diameter and 4.6 in. (116.8 mm) in height. Each specimen was compacted in 3 layers
to its modified Proctor maximum dry density. After demoulding, all the specimens
were cured for 7 days at a temperature of 23 ± 2°C and 100 % relative humidity. Four
specimens were prepared for each cement content. Two of these specimens were
designated as weight loss specimens while the other two were designated as volume
change specimens. For the volume change criterion, the volume of each specimen
was initially determined by measuring its height and diameter. After the curing period,
the specimens were placed in a water tank for 5 hours at the room temperature (23°C)
and then transferred to an oven at 71°C and kept there for 42 hours. This constitutes of one wet-dry cycle for the soil-cement specimens. At the end of this cycle, the specimens designated as volume change were dimensioned using a vernier caliper, and were weighed. The other two specimens were brushed using a standard brush with two strokes on the whole surface with a force of about 3 lb (13.3 N). In order to apply the 3 lb force, each specimen was placed on a balance and then brushed while watching the specified force on the scale of the balance. The weight of the specimens before and after brushing was taken. Similar measurements were taken for the remaining 11 cycles thus subjecting each specimen to a total of 12 cycles according to the standard procedures (ASTM D 559). At the end of each cycle, the weight loss and volume change were determined for the respective specimens. At the end of the 12th cycle, the samples were dried to a constant weight at 110°C. Therefore, the change volume and weight loss were determined according to the following equations (ASTM D 559):

i) Volume change (VC):

\[
VC \text{ (%)} = \left( \frac{V_i - V_f}{V_i} \right) \times 100
\]  

(3.2)

ii) Weight loss (WL):

\[
WL \text{ (%)} = \left( \frac{W_i - W_f}{W_i} \right) \times 100
\]  

(3.3)
where:

\[ \text{VC} = \text{volume change of the specimen after } t \text{ cycles (\%)}; \]
\[ V_i = \text{initial volume of the specimen (cm}^3\text{)}; \]
\[ V_f = \text{final volume of the specimen (cm}^3\text{)}; \]

\[ \text{WL} = \text{weight loss of the specimen after } t \text{ cycles (\%)}; \]
\[ W_i = \text{initial calculated oven-dry weight (kg); and} \]
\[ W_f = \text{final corrected oven-dry weight (kg).} \]

Moreover, it worths mentioning that a correction was applied on the oven dry weight, which could be determined according to the following equation (ASTM D 559):

\[
\text{Corrected oven-dry weight} = \frac{A}{B} \times 100 \quad (3.4)
\]

where:

\[ A = \text{oven-dry weight after drying at } 230^\circ\text{F (110}^\circ\text{C); and} \]
\[ B = \text{percentage of water retained on specimen plus 100.} \]

3.3.8.2 Slake Durability Test

This test is basically used to determine the slake durability of rocks. A certain weight (500 gm) of rock pieces is placed in a drum made of 2 mm stainless steel mesh. The drum is 140 mm in diameter and 100 mm in length. The drum is rotated at a speed of 20 rpm, while being partially soaked in water. The weight loss after 10
min. of rotation is considered as a measure of the durability of the rock (Goodman, 1980).

In this investigation, the above test was adopted for the soil-cement specimens with some modifications (Aiban et al. 1995). The length and diameter of the drum were increased to 152.4 mm (6 inch) and 304.8 mm (12 inch), respectively. In order to allow the soil-cement specimens to travel the same distance as by the rock pieces in the original test, the number of revolutions was accordingly adjusted to accommodate the change in dimensions. The revolution time was decreased from 10 to 4.6 min. This change would give a total travel distance of 88 m similar that of the original test. The set-up for slake durability testing is shown in Plate 3.6.

Two additional samples were compacted for each percentage of cement. These samples were subjected to the same wet and dry cycles as for the samples tested using ASTM D 559 durability test. At the end of each cycle, each sample was tested for slake durability using the modified apparatus. After slaking, the surface of the sample was cleaned with a dry absorbent cloth and then weighed. Weight loss for each sample was observed by taking the weight before and after the slaking test. After 12 cycles, the samples were oven dried at 110°C in order to get the dry weight of samples.
Plate 3.6: The set-up for slake durability testing (Aiban et al., 1995).
3.4 Chemical Stabilization of Al-Qurayyah Sabkha Soil

Chemical stabilization is the most feasible, economic and cheapest technique when sabkha is to be used as a construction material. Chemically-stabilized sabkhas have various applications such as in backfilling, paving slopes, embankment protection, highway embankments, airport runways, etc. (Al-Amoudi, 1994b). Properly chemically-stabilized sabkha soils are known to have higher strength, more erosion resistance, markedly high volume change stability against swelling and shrinkage, and generally improved workability and durability. Furthermore, the chemical stabilization technique is considered to be relatively more economical and cheaper than many other techniques and requires less expertise and tools. Despite all the mentioned advantages associated with chemical stabilization, the presence of diagenetic minerals, such as halite, gypsum, aragonite, etc., in the sabkha system may significantly change the response of sabkha to chemical stabilization (Al-Amoudi, 1994b). Therefore, previous experience with normal soils or other sabkhas can not be directly duplicated. The above-cited points necessitate that each sabkha be dealt with as a "single case study".

In this investigation, Portland (i.e. ASTM C 150 Type V sulfate resisting) cement and hydrated lime were initially used as chemical additives for the present Al-Qurayyah sabkha soil. Out of these two additives, the suitable chemical additive (i.e. the one producing high strength using the CBR test), would be chosen.
3.4.1 Optimization of sabkha soil stabilization

Chemical stabilization improves the quality and general properties of soils. The required level of improvement is different from soil to soil and from project to project. The improvement does not depend only on the type and amount of stabilizer but also on the environmental conditions associated with a specific site and the construction procedures as well as on the properties of the soil itself. Considering all the conditions which positively or negatively influence the properties of stabilized-sabkha mixtures, an optimum dosage of the chemical stabilizer should be determined which should also be economical and satisfy the minimum requirements of strength and durability.

The objective of this investigation is to make the sabkha soil suitable to be used as a construction material for foundations, and as sub-bases and subgrades for pavements. For these structures, strength, settlement and durability are the main concerns. Strength of stabilized soils can be expressed in terms of the unconfined compressive strength, CBR or resilient modulus and can be improved using chemical additives. However, there are specific ranges of moisture content and curing temperature and exposure conditions for which these parameters can be maximized. As it is well known, strength is frequently the primary criterion to be optimized and durability and compressibility are considered thereafter. Therefore, to optimize (i.e.
maximize) the strength of Al-Qurayyah sabkha soil, the following parameters were investigated:

1. Additive content (i.e. cement and lime).
2. Molding moisture content.
3. Curing regime (i.e. sealed and exposed).
4. Curing temperature (i.e. 23, 35, 50, and 70°C).
5. Curing period (i.e. 1, 3, 7, 14, and 28 days).
6. Delay in compaction (i.e. ½, 1, 2, and 4 hours).

The effects of either all or some of these six parameters on strength and durability were assessed using one or more of the following tests:

1. Compaction.
2. Unconfined compressive strength.
3. California bearing ratio (CBR) & Clegg impact hammer.
4. Resilient modulus.
5. Durability.

Figure 3.1 depicts the general optimization procedures. These parameters along with their beneficial impacts on the optimization process are discussed thoroughly in the following paragraphs.
3.4.2 Additive content

Additive content is defined, in this research, as the percentage by weight of additive to that of the (oven-dry soil plus additive). Since additives are often expensive materials, it is therefore important to determine an optimum value, which is dependent on the soil type and the intended objective. Apart from the economic point of view, the injudicious increase in additive content may sometimes lead to negative effects (i.e. increase in cement content causes shrinkage cracks). Initial results of this investigation indicated that lime is not efficient in stabilizing Al-Quarayyah sabkha soil when compared to cement. Therefore, cement was selected as the best candidate for this sabkha soil. However, a review of the literature reveals that cement stabilization is generally most suitable for granular soils since they do not require any pulverization and thus they mix well with cement and need less quantity of cement due to their small specific surface (ACI Committee, 1990), although the strength of the cement-treated sand is relatively low (Aiban et al. 1995). On the other hand, fine-grained soils frequently require high percentages of cement due to their large specific surface. For highly plastic soils, it is often advisable to pretreat these soils with lime in order to reduce the plasticity and therefore the high dosage of cement. Normally, the optimum cement content ranges from 4 to 16% by dry weight of soil (ACI Committee, 1990), however, a feasible range of 5 to 10% is frequently dosed for all practical applications.
In this investigation, four different percentages (3, 5, 7 and 10%) of cement in addition to the untreated (0% cement) soil were used to optimize the cement content for Al-Qurayyah sabkha soil. These percentages were used to determine the moisture-density relationship for each soil-cement mixture. The desired cement content was chosen based on the results of the unconfined compressive strength of cement-stabilized specimens as well as on economy requirements.

3.4.3 Curing conditions

Cement hydration takes place when Portland cement reacts with water to produce cementitious matters, known as cementing gel. In the presence of sufficient amount of moisture, the hydration reactions are fast in the beginning; the rate of hydration, however, decreases with time and depends primarily on the curing conditions and ambient temperature.

In the field, different curing methods are applied in order to preserve the moisture content of cement-soil mixtures. One of the popular methods is to cover the exposed surface of the stabilized soil by either a wet layer of sand, burlap, etc., or seal the surface by spraying curing compounds such as emulsified asphalt. Water is consistently sprinkled to supplement the moisture loss from the soil and to enhance the hydration reactions of cement.

In order to simulate the field conditions, the stabilized samples in this investigation were subjected to different curing conditions. The moisture conditions
were controlled either by keeping the samples unwrapped (i.e. exposed to laboratory conditions) or by sealing the samples in nylon wrap or by leaving the samples in a very humid environment above water in a curing tank. The sealed samples were covered with about 5 layers of nylon sheet to make sure that no moisture loss takes place. The samples for the exposed conditions were not sealed at all as well as for the samples that were kept above water in the curing tank.

According to the literature review, it was found that the average maximum "ambient" temperature in Dhahran and Al-Hasa areas of the Eastern Province has been recorded to be 46.3°C and 47.6°, respectively. Due to solar radiation, the temperature of pavement and concrete surfaces may be as high as 65 to 75°C during a typical summer day (Al-Amoudi et al., 1995a). Therefore, in order to evaluate the strength gain of the soil-cement samples with the variation in temperature, the specimens for the unconfined compressive testing were exposed to various curing temperatures (including room temperature 23°C), 35, 50 and 70°C. Therefore, the samples were placed in ovens to cure at constant temperatures of 35, 50 and 70°C under both the sealed and exposed conditions.
3.4.4 Curing period

Theoretically, the hydration of cement will continue indefinitely, however, its rate decreases with time. This process is responsible for the strength gain with time for cement-stabilized soils. Usually, the 7-day unconfined compressive strength is used as a criterion for design purposes (Bahtia, 967), while 3-day strength is used for quality control purposes during field construction. Strength after 28 days of curing can also be used to assess the bearing capacity of an existing pavement, for example. However, to speed-up construction, the 24-hour strength is sometimes used.

In this investigation, five different curing periods, namely 1, 3, 7, 14 and 28 days, were used at the various exposure temperatures 23, 35, 50, and 70°C. This is essential to study the effect of curing period and exposure temperature on the strength of stabilized sabkha soil.

3.4.5 Delay in compaction

In order to assess the strength development of soil-cement mixtures, it is important to have not only adequate compaction of the mix but also the hydration kinetics of the cement should continue to produce high and appropriate strength within the early days of construction. If the elapsed time between the mixing process and compaction stage is more than some specific duration, detrimental effects may occur because the cement will hydrate before compaction. Delay in compaction therefore results in the formation of clods of cemented soil and this will minimize the
particle rearrangement during compaction thereby leading to lower density as well as lower initial and ultimate strengths. With the delay in compaction, there will be less amount of cement available for binding the soil material after compaction, and the bonds will be weaker. All this will lead to lower strength and less durability.

In the field, construction of soil-cement mixtures is associated with time-consuming processes. These processes include the pulverization of soil to the required degree of fineness, dry mixing of cement with soil, adding water to get the desired moisture content, appropriate mixing of soil-water-cement system, compaction, and lastly curing. In order to have a uniform mixing of cement with water in the entire soil to be treated, a period of approximately 2 to 4 hours is usually practically needed before compaction. Moreover, the hydration of cement begins soon after mixing with wet soil. In addition, if compaction of the soil and cement mixtures is delayed after mixing, then loss of strength and durability will occur if and only if the delay time is equal to or greater than the initial setting period of cement (Habib-ur-Rahman, 1995). It is to be noted that the initial setting time for the sulfate resisting cement (Type V) used in this research program was approximately three hours.

In this investigation, the effect of delay in compaction of 1/2, 1, 2 and 4 hours on the strength of Al-Qurayyah sabkha-cement mixtures was studied. Moreover, curing periods of 3, 7, 14 and 28 days, were considered in the evaluation of delay
effect. After the prescribed periods of delay, the soil-cement samples for unconfined compressive test were prepared. During the delay time, the mix was sealed in nylon sheets to inhibit any loss of moisture. In the field, however, sealing the treated soil may not be easy, although there is a practice of adding some additional moisture to the soil-cement mixtures during compaction, to make up the moisture loss during the delay.
Chapter 4

RESULTS AND DISCUSSION

This Chapter presents the data generated during the course of this work in order to fulfill the report objectives. Appropriate interpretations are thereafter forwarded to explain the reasoning for the behavior of Al-Qurayyah sabkha before and after stabilization.

4.1 Characterization of Al-Qurayyah Sabkha Soil Results

The characterization tests are basically conducted according to ASTM and AASHTO standards in order to identify Al-Qurayyah eastern Saudi sabkha soil with regard to its particle shape and size, its plasticity and its suitability as a bearing soil for foundation, roads and highways. Although, there were minor deviations from the standards for some of the tests. Characterization tests in this research program encompass specific gravity of the solid grains, grain-size distribution and plasticity tests.

4.1.1 Specific gravity test results

Four specific gravity tests were conducted and yielded 2.52, 2.52, 2.51 and 2.52 with an average value of 2.52 for Al-Qurayyah sabkha soil. The test results were consistent since the variation from the average was minimal. Despite the low value of the specific gravity, the 2.52 value does fall within the range of sabkha soils of eastern Saudi Arabia (i.e. 2.51-2.82), as reported by Abu-Taleb and Egeli (1981). It should be
mentioned that the drying process was conducted at 70°C, as recommended by Al-Amoudi (1995). This could be the main reason for the low specific gravity value of Al-Qurayyah sabkha soil. It worths mentioning that when oven drying was carried out at 105°C, the average specific gravity was increased to 2.89.

4.1.2 Plasticity Tests

Liquid and plastic limit tests were performed in accordance with ASTM D 423 and ASTM D 424, respectively. For this sabkha soil, it was not possible to get the number of blows for the liquid limit test, therefore, the liquid limit was reported as nil. The soil also could not be rolled to a thread of 1/8-in (3.18 mm), therefore, the soil was classified as non-plastic.

4.1.3 Grain-size distribution test results

The grain-size distribution curves are depicted in Fig. 4.1. This Figure indicates that the % passing Sieve No. 200 is 24.3 and 41.3 when sabkha brine and distilled water were used in the sieving process, respectively; the difference being 17%. The sediments in Al-Qurayyah sabkha soil were non-plastic, hence, the soil could be classified as SM according to the USCS system, however, according to the AASHTO soil classification system, the soil could be classified as A-2-4 and A-4 for sabkha brine and distilled water washing, respectively.

At first glance on Fig. 4.1, both sabkha brine and distilled water sieve analysis curves exhibit a slight difference which is attributed to the potential salt content in the
Fig. 4.1: Grain-Size Distribution of Al-Qurayyah Sabkha Soil
sabkha soil. Distilled water tends to dissolve the salts which are considered part of the solid matrix; that is why the grain-size curve obtained when using distilled water was consistently above the one when sabkha brine was used. Therefore, the use of sabkha brine has been recommended to replace distilled water in the wet sieving technique because sabkha brine does not cause any salt dissolution (Al-Amoudi, 1994a).

4.2 Chemical Analysis of Sabkha Brine

The chemical analysis of Al-Qurayyah sabkha brine is presented in Table 4.1. The analysis of seawater is also included therein for the sake of relative comparison. Based on the total dissolved solids, as reflected by the conductivity test results, Al-Qurayyah sabkha brine is almost 6.8 times more concentrated than that of a typical seawater obtained from the same vicinity. These results reveal the presence of a potential salt content in Al-Qurayyah sabkha soil. This is also evidenced by the current situation in the field where salt is mined at different places in Al-Qurayyah vicinity (see Plates 3.3 and 3.4). Table 4.1 also compares the chemical analysis of Al-Qurayyah sabkha brine with other sabkha brines from different locations in the Eastern Province such as Ar-Riyas, Ju‘aymah, and Ras Al-Ghar as well as the average values reported by Johnson et al. (1978). This data indicates that Al-Qurayyah sabkha brine is relatively more saline than the other brines in eastern Saudi Arabia.
Table 4.1: Chemical Analysis of Sabkha Brines and Seawater in g/l (i.e. parts per thousand)

<table>
<thead>
<tr>
<th>Ions</th>
<th>Al-Quwayyah Brine</th>
<th>Ar-Riyas Brine</th>
<th>Ju‘aymah Brine</th>
<th>Ras Al-Ghar Brine+</th>
<th>Reported Average++</th>
<th>KFUPM Beach Sea Water+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>99.6</td>
<td>99</td>
<td>41.4</td>
<td>78.8</td>
<td>79.8</td>
<td>20.7</td>
</tr>
<tr>
<td>Mg⁺</td>
<td>13.4</td>
<td>10.5</td>
<td>4.53</td>
<td>10.32</td>
<td>7.33</td>
<td>2.30</td>
</tr>
<tr>
<td>K⁺</td>
<td>8.1</td>
<td>6.8</td>
<td>1.40</td>
<td>3.06</td>
<td>2.69</td>
<td>0.73</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>7.1</td>
<td>5.0</td>
<td>1.34</td>
<td>1.45</td>
<td>1.86</td>
<td>0.76</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.16</td>
<td>0.15</td>
<td>Trace</td>
<td>Trace</td>
<td>—**</td>
<td>—**</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>—**</td>
<td>—**</td>
<td>0.031</td>
<td>0.029</td>
<td>—**</td>
<td>0.013</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>179.9</td>
<td>175</td>
<td>76.8</td>
<td>157.2</td>
<td>158.2</td>
<td>36.9</td>
</tr>
<tr>
<td>Br⁻</td>
<td>—**</td>
<td>—**</td>
<td>0.22</td>
<td>0.49</td>
<td>—**</td>
<td>0.121</td>
</tr>
<tr>
<td>(SO₄)²⁻</td>
<td>7.03</td>
<td>6.8</td>
<td>8.43</td>
<td>5.45</td>
<td>5.24</td>
<td>5.12</td>
</tr>
<tr>
<td>(HCO₃)⁻</td>
<td>0.191</td>
<td>0.182</td>
<td>0.114</td>
<td>0.087</td>
<td>0.056</td>
<td>0.128</td>
</tr>
<tr>
<td>pH</td>
<td>6.1</td>
<td>5.6</td>
<td>7.2</td>
<td>6.9</td>
<td>6.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Conductivity*</td>
<td>315,300</td>
<td>303,300</td>
<td>152,000</td>
<td>208,000</td>
<td>—**</td>
<td>46,200</td>
</tr>
</tbody>
</table>

* Microsiemen
** Not reported
-- Reported by Al-Amoudi et al. (1992a)
--- From Johnson et al. (1978)
4.3 Compaction Test Results

Compaction tests were performed on plain (0% additive) as well as on sabkha-cement and sabkha-lime mixtures with additive contents in the range from 3 to 10%. The results, presented in typical plots of water content versus dry density ($\gamma_d$), are presented in Figures 4.2 and 4.3 for cement and lime additions, respectively. These results indicate that an increase in the cement content is associated with a marginal increase in the maximum dry density ($\gamma_d_{(\text{max})}$). However, in the case of lime addition, the trend is reversed, whereby an increase in the lime content resulted in a decrease in $\gamma_d_{(\text{max})}$. The increase in $\gamma_d_{(\text{max})}$ with cement addition is attributed to the fact that cement has a higher specific gravity than sabkha soil ($G_s$ for cement is 3.15 compared to 2.52 for sabkha). A similar increase in the maximum dry density with cement addition has recently been reported by Al-Amoudi et al. (1995b).

Regarding the optimum moisture content ($w_{\text{opt}}$), there was no fundamental difference in the $w_{\text{opt}}$ when cement was used in the range of 0 to 7%. There was, however, a slight increase in $w_{\text{opt}}$ when 10% cement was used. In the case of lime-sabkha mixtures, there was an increase in $w_{\text{opt}}$ from about 17% in the case of 0 and 3% lime contents to about 20% for 5, 7 and 10% lime contents.

4.3.1 CBR test results

CBR tests are generally used to evaluate the suitability of a soil to be used as a subgrade material in pavements. Clegg impact hammer test is currently considered a
Fig. 4.2: Effect of Cement Addition on Moisture-Density Relationship for Al-Qurayyah Sabkha Soil
Fig. 4.3: Effect of Lime Addition on Moisture-Density Relationship for Al-Qurayyah Sabkha Soil
potential alternative to the CBR test because it can be easily conducted in both the laboratory and the field (Khan, et al., 1995).

Figure 4.4 shows the moisture-density CBR relationship for untreated sabkha soil (0% additive). It can be seen that the maximum dry density $\gamma_{d(max)}$ was 1.79 g/cm$^3$ at an optimum moisture content of 18.0%. It can be also observed that the compaction curve follows the typical $\gamma_d$-w relations whereby $\gamma_d$ increases initially with increasing the moisture content until it reaches the maximum dry density ($\gamma_{d(max)}$) at the optimum moisture content ($w_{opt}$). Further increase in the moisture content resulted in a reduction in dry density. On the other hand, for the CBR curve, the maximum CBR value was 111 at a moisture content of 14.9%. As can be noted from Fig. 4.4, the CBR values increased initially with increasing the moisture content until the maximum CBR value was attained at a moisture content of 14.9%. Further increase in the moisture content would lead to a substantial reduction in the CBR value reaching a complete loss of strength (CBR is almost zero) at a moisture content of about 20%.

The results from CBR curve indicate that the moisture content giving the maximum CBR is approximately 14.9% for plain sabkha. This moisture content is well below the optimum moisture content obtained from the dry density-moisture content relationship, which was about 18.0%. This is in consensus with the findings that have been reported by Al-Amoudi et al (1992a) and Aiban et al (1995).
Fig. 4.4: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (0% Additive)
Figure 4.5 presents the moisture-density-CBR relationship for stabilized sabkha soil with 3% cement. The results from $\gamma_d$-$w$ curve indicate that the $\gamma_{d(\text{max})}$ was 1.81 g/cm³ at an $w_{\text{opt}}$ of 17.5%. For the CBR-moisture curve, however, the maximum CBR value was 300 at a moisture content of 15.4%. Comparison of the data in Figure 4.5 with that in Figure 4.4 indicates that there was an increase in the $\gamma_{d(\text{max})}$ as well as the maximum CBR value when 3% cement was added to the sabkha soil mixtures. Furthermore, for the CBR curve, with 3% cement addition, the CBR value increases initially with increasing the moisture content until it reaches the maximum CBR value. Further increase in the moisture content leads to a sharp reduction in the CBR value reaching a CBR value of about 85 at moisture content of about 22%. It can be observed that despite this high moisture content (22%), the addition of 3% cement to Al-Qurayyah sabkha did not exhibit complete loss of strength as it was observed in the untreated (0% cement) soil (Fig. 4.4). Therefore, the introduction of cement to the sabkha soil has dual beneficial effects: (i) it increases the maximum CBR value, and (ii) the sabkha soil at high moisture contents did not exhibit complete strength loss.

Figure 4.6 depicts the moisture-density-CBR relationship for the 5% cement stabilized sabkha soil mixture. The results indicate that the maximum dry density $\{\gamma_{d(\text{max})}\}$ was 1.82 g/cm³ at an $w_{\text{opt}}$ of 17.9%. On the other hand, for the CBR-moisture curve, the maximum CBR value was 395 at a moisture content of 15.4%. Comparison of the data in Figures 4.6 and 4.5 indicates that there was a similarity in the shape of the $\gamma_d$-$w$ and CBR-$w$ curves. In addition, there was an increase in the $\gamma_{d(\text{max})}$ as well as in the maximum CBR
Fig. 4.5: Moisture-Density-CBR Relationship of Al-Qurayyah Sabkha Soil (3% Cement)
Fig. 4.6: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (5% Cement)
value when 5% cement by weight of dry soil was added to the sabkha soil. Furthermore, for the CBR curve, with 5% cement addition, the CBR value at a moisture content of about 22% was 110 compared with only 85 at the same moisture content when 3% cement was added (Fig. 4.5).

Figure 4.7 presents the moisture-density-CBR relationship for the stabilized sabkha soil with 7% cement addition. It can be seen that the $\gamma_{d(max)}$ was 1.82 g/cm$^3$ at an $w_{opt}$ of 17.2%. On the other hand, the maximum CBR value was 417 value at a moisture content of 17.2%. Again, there was a similar trend between the curves with those reported in Fig. 4.7. In addition, there was an increase in the maximum CBR value when the 7% cement was added. Furthermore, the ultimate CBR value at a moisture content of about 22% was 175 compared with 110 in the case of 5% cement addition (Fig. 4.6). It can be observed that the $\gamma_{d(max)}$ as well as the maximum CBR value were attained at a moisture content of 17.2%.

Figure 4.8 presents the moisture-density-CBR relationship for the 10% cement-sabkha mixture. It can be observed that the $\gamma_{d(max)}$ was 1.84 g/cm$^3$ while the maximum CBR was 533; both were attained at an optimum moisture content of 18.9%. Comparison of the curves in Figure 4.8 with the curves in Figure 4.7 indicates that there was an increase in the $\gamma_{d(max)}$ as well as in the maximum CBR value when 10% cement was added, however, the increase in $\gamma_{d(max)}$ was negligible. Furthermore, the ultimate CBR
Fig. 4.7: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (7% Cement)
Fig. 4.8: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (10% Cement)
value at a moisture content of 22%, the CBR value increased significantly to 280 compared with 175 when the 7% cement was added to Al-Qurayyah sabkha soil.

Figure 4.9 summarizes the CBR test results for cement stabilized-sabkha mixtures. The data therein indicates that the CBR value increased from 111 for 0% (untreated soil) to 300, 395, 417, and 533 when 3, 5, 7 and 10% cement by weight of dry soil, respectively, were added to Al-Qurayyah sabkha soil. Such a significant increase in the CBR values corresponds to an improvement ratio of 2.7, 3.6, 3.8 and 4.8 times that of the untreated sabkha soil.

It can be observed that the CBR curves for 3, 5, 7 and 10% cement additions indicate that the moisture content for maximum CBR values of the stabilized sabkha soil is generally higher than that for the untreated soil (0% additive). This higher moisture is attributed to the fact that the hydration kinetics of the cement-sabkha soil system requires an amount of water sufficient to fulfill two functions: It is firstly required for the proper compaction, more or less similar to plain sabkha mixtures; and the second is to provide extra water for the cement hydration during the curing period (Al-Arnoudi et al., 1995b).

Figure 4.10 depicts the moisture content-density-CBR relationship for stabilized the Al-Qurayyah sabkha soil with 3% lime. It can be noticed that the maximum dry density $\gamma_{d(max)}$ was 1.79 g/cm$^3$ at an optimum moisture content of 17.5%. On the other hand, the maximum CBR value was 123 at a moisture content of 15.2%. Comparison of the curves of Fig. 4.10 with the curves in Figure 4.4 for untreated sabkha soil indicates
Fig. 4.9: Effect of Moisture and Cement Contents on CBR for Al-Qurayyah Sabkha Soil.
Fig. 4.10: Moisture-Density-CBR Relationship for Al-Quaryyah Sabkha Soil (3% Lime)
that there was no improvement in $\gamma_{d(max)}$ over the non-stabilized specimens. Similarly, there was just a little increase in the maximum CBR value over the untreated soil which can be considered marginal. It can also be observed that there is a significant reduction in the CBR values when the moisture content increased and the CBR was significantly reduced (CBR is almost zero at about 21%). This behavior is more or less similar to that of the untreated sabkha (Figure 4.4).

Figure 4.11 shows the moisture-density-CBR relationship for stabilized sabkha soil with 5% lime. It can be observed that the $\gamma_{d(max)}$ was 1.77 g/cm³ at a $w_{opt}$ of 20%. Similarly, the maximum CBR value was 138 at a moisture content of 18.3%. Comparison of the data in Figure 4.11 and Figure 4.10 indicates that there was a negligible decrease in $\gamma_{d(max)}$ and there was just a little increase in the maximum CBR value. Figure 4.11 also indicates that at high moisture contents, there was a significant reduction in strength; at $w = 24\%$ the CBR value came to be around zero. This indicates that the 5% lime dosage could not improve the sabkha strength at high moisture contents.

Figure 4.12 depicts the moisture-density-CBR relationship for stabilized sabkha soil with 7% lime. It can be seen that the $\gamma_{d(max)}$ was 1.74 g/cm³ at $w_{opt}$ of 20.3%. On the other hand, the maximum CBR value was 150 at a $w$ of 17.6%. Again, the data in Figure 4.12 indicates that there was a decrease in the $\gamma_{d(max)}$ and there was a little increase in the maximum CBR value when 7% lime was added to the sabkha soil mixtures.
Fig. 4.11: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (5% Lime)
Fig. 4.12: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (7% Lime)
Figure 4.13 presents the moisture-density-CBR relationship for sabkha stabilized with 10% lime. It can be noticed that the \( \gamma_{d(\text{max})} \) was 1.70 g/cm\(^3\) at \( w_{\text{opt}} \) of 19.4%. The maximum CBR value was 164 at a moisture content of 19.4%. Comparison of the data in Figure 4.13 and Figure 4.12 indicates that there was again a decrease in the \( \gamma_{d(\text{max})} \) but there was a little increase in the maximum CBR value which can be considered marginal when 10% lime was added to the sabkha soil mixtures. The data in Figures 4.12 and 4.13 indicates that the 7 and 10% lime additions are not suitable for improving the CBR values neither at the \( w_{\text{opt}} \) nor at high moisture contents.

Figure 4.14 summarizes the CBR test results for lime stabilized-sabkha mixtures. It can be seen that in the case of these mixtures, the improvement was only marginal; the CBR value of lime-sabkha mixture being increased from 111 to about 160 when the lime content was increased from 3 to 10%. Such an improvement, which corresponds to an increase of only 44%, can be considered negligible for practical purposes, especially if one knows that lime costs more than cement in the Saudi market. Furthermore, the optimum moisture content for the various lime-sabkha mixtures was higher than that for the untreated soil (0% additive). This higher moisture is more or less similar to that observed in the case of cement-stabilized sabkha mixtures. Al-Amoudi et al. (1995b) have recently attributed such an increase in \( w_{\text{opt}} \) to the same reasons mentioned previously for cement. In addition, lime requires more water due to the higher heat generated during its hydration with water.
Fig. 4.13: Moisture-Density-CBR Relationship for Al-Qurayyah Sabkha Soil (10% Lime)
Fig. 4.14: Effect of Moisture and Lime Contents on CBR for Al-Qurayyah Sabkha Soil
4.3.2 Clegg impact hammer results

In this investigation, the soil specimens prepared for the CBR test were also tested using the Clegg impact hammer. Clegg hammer test was conducted on the other end of the samples tested for CBR. Figures 4.15 and 4.16 depict the Clegg impact values (CIV) for cement and lime-sabkha mixtures, respectively. With regard to moisture content, the CIV results seem to be somewhat similar to the CBR results for both cement and lime additions, particularly with regard to the moisture contents at which the maximum CIV's were obtained.

The Clegg Impact Values (CIV) were plotted against the corresponding CBR, as shown in Fig. 4.17 and Fig. 4.18 for cement- and lime-sabkha mixtures, respectively. These plots are helpful in predicting the CBR values in the field using the Clegg hammer which is relatively quick and easy. The best correlations developed between CBR and CIV can be expressed in the following form:

\[
\text{CBR} = 1.96033 \times \text{CIV} - 11.4858 \quad \text{(for cement)} \quad \text{for CIV} \leq 98
\]

\[
\text{CBR} = 77.375 \times \text{CIV} - 7400.62 \quad \text{(for cement)} \quad \text{for CIV} > 98
\]

\[
\text{CBR} = 2.27732 \times \text{CIV} + 25.441 \quad \text{(for lime)}
\]

It is well known that correlations between any two variables are considered reliable if the \( R^2 \) is generally greater than 0.75 (Montgomery, 1991). The statistical relationships above can be considered reliable, as the values of \( R^2 \) are (0.80),(0.53) and (0.93) for cement and lime, respectively.
Fig. 4.15: Effect of Moisture and Cement Contents on Clegg Impact Value (CIV) for Al-Qurayyah Sabkha Soil
Fig. 4.16: Effect of Moisture and Lime Contents on Clegg Impact Value (CIV) for Al-Qurayyah Sabkha Soil
CBR (1) = 1.96033 * CIV - 11.4858
CBR (2) = 77.375 * CIV - 7400.62
R^2(1) = 0.7984
R^2(2) = 0.5283

Fig. 4.17: Correlation Between CBR and CIV for Cement-Sabkha Mixtures
Fig. 4.18: Correlation Between CBR and CIV for Lime-Sabkha Mixtures

CBR = 2.27732 \times CIV - 25.441

R^2 = 0.928565
Again, using the correlations which were developed between CBR and CIV, the predicted CBR values were calculated for cement. Furthermore, the measured CBR values as well as the predicted CBR values were plotted in order to get the relationship between them as shown in figure 4.19.

4.3.3 Unconfined compression test results

Although the compaction test results have already been presented with the CBR test results (Figures 4.4 to 4.14), it is traditional in the field of soil mechanics to present the compaction test results with the unconfined compressive strength ($q_u$) data, and that what was done herein.

4.3.3.1 Cement-sabkha mixtures

Figure 4.20 depicts the moisture-density-strength relationship for untreated sabkha soil (0% additive). For the $q_u$ curve, the $q_u(\text{max})$ was 809 kPa at a moisture content of 13.9%. The $q_u$ data indicates that there is a substantial reduction in strength with the increase in moisture content in a way more or less similar to the CBR results. Strength value of about 100 kPa was obtained at a moisture content of about 22%.

The moisture content at the maximum strength is about 13.9% for plain sabkha. This moisture is less than the optimum moisture content obtained from the $\gamma_d$-$w$ curve which was about 18% (Fig. 4.20). It should be mentioned that similar findings have been reported by Al-Amoudi et al. (1992a).
Fig. 4.19: Correlation Between Measured CBR and Predicted CBR for Cement-Sabkha Mixtures
Fig. 4.20: Moisture-Density-Unconfined Strength Relationship for Al-Qurayyah Sabkha Soil (0% Additive)
Figure 4.21 shows the moisture-density-strength relationship for stabilized sabkha soil with 3% cement. These results indicate that a maximum strength ($q_u(\text{max})$) of 2667 kPa was obtained at a moisture content of 15.4%. Comparison of the data in Figure 4.21 with the data in Figure 4.20 indicates there is a significant increase in $q_u$ when only 3% cement was added to the sabkha soil; the increase being 230%. Again, the moisture content at $q_u(\text{max})$ was 15.4% compared with 17.5% from the $\gamma_d$-w curve. This behavior is similar to that observed in the CBR-w relationship. Furthermore, at high moisture contents, there was a significant reduction in strength. For example, at a moisture content of 22%, the $q_u$ value was about 800 kPa.

Figure 4.22 presents the moisture-density-strength relationship for sabkha soil stabilized with 5% cement. The $q_u(\text{max})$ was 2766 kPa at a moisture content of 15.4%. Again, at a high moisture content of about 22%, the $q_u$ was about 900 kPa, which is much smaller than $q_u(\text{max})$. Similarly, the moisture content at $q_u(\text{max})$ was 15.4% compared with 17.9% obtained from the $\gamma_d$-w curve; indicating the reduction in moisture content with cement addition.

The moisture-density-strength relationship for sabkha soil stabilized with 7% cement is depicted in Figure 4.23. From the data therein, the $q_u(\text{max})$ was 3939 kPa at an optimum moisture content of 17.2%. The significantly high $q_u$ value indicates that an increase in the cement content tend to enhance the strength of Al-Qurayyah sabkha soil. However,
Fig. 4.21: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (3% Cement)
Fig. 4.22: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (5% Cement)
Fig. 4.23: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (7% Cement)
the \( w_{opt} \) is almost the same as that obtained from the \( \gamma_d-w \) curve. The data in Figures 4.23 indicates that at a high moisture content of 22\%, the \( q_u \) was over 2000 kPa, which is very high. The same behavior has been observed by Al-Arnoudi (1994) when stabilizing the Ras Al-Ghar eastern Saudi sabkha.

The moisture-density-strength relationship for sabkha soil stabilized with 10\% cement addition is depicted in Figure 4.24. The \( q_{u(max)} \) was 5005 kPa at a moisture content of 18.9\%. This increase in \( q_u \) corresponds to over 600\% improvement compared with the untreated soil. Again, the \( w_{opt} \) from \( q_u \) perspective was 18.9\%, which is similar to the \( w_{opt} \) from the \( \gamma_d-w \) data. This behavior is more or less similar to that observed from the 7\% cement-sabkha mixtures (Figure 4.23). Figure 4.24 indicates that the \( q_u \) was about 3000 kPa at a moisture content of about 22\%. This is similar to that mentioned previously in the case of 7\% cement addition (Fig. 4.23)

A summary of the \( q_u \) results is presented in Figure 4.25 for cement-sabkha mixtures. The data therein indicates again the superiority of cement in enhancing the strength of Al-Qurayyah sabkha soil. Figure 4.25 reveals that the unconfined compressive strength value increased from 809 for 0\% cement (untreated sabkha soil) to 2667, 2766, 3939 and 5005 for 3, 5, 7 and 10\% cement by weight of dry soil, respectively. Such significant increases in the \( q_{u(max)} \) values correspond to an improvement ratio of 3.1, 3.3, 4.6 and 6.2 times that of the untreated sabkha soil.
Fig. 4.24: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (10% Cement)
Fig. 4.25: Effect of Moisture and Cement Contents on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil
It is worth mentioning that the optimum moisture content from the $q_u$ vs. $w$ data for stabilized sabkha soil mixtures with 3, 5, 7 and 10% cement was generally higher than the moisture content for the untreated soil (0% additive). This higher moisture could be attributed to the fact that the hydration kinetics of the cement-soil system needs an amount of water sufficient to fulfill two functions as previously stated for CBR results.

4.3.3.2 Lime-sabkha mixtures

Figure 4.26 presents the moisture-density-strength relationship for stabilized sabkha soil with 3% lime addition. The $q_u$(max) was 836 kPa at a moisture content of 15.2%. Comparison of the data in Figures 4.26 and 4.20 for untreated sabkha soil indicates that there was a little increase in the maximum strength over the untreated soil when 3% lime was added to Al-Qurayyah sabkha soil. This indicates that lime is not capable of significantly increasing the strength of this sabkha soil. The $w_{opt}$ from the $q_u$ curve was 15.2% compared with 17.5% when the $\gamma_d$-$w$ curve was considered. Therefore, $q_u$ requirement necessitates a reduction in the $w_{opt}$ obtained from the compaction curve. Furthermore, the $q_u$ at high moisture contents (at about 22%) was about 110 kPa which is more or less similar to that of the untreated sabkha soil (Figure 4.20).

The moisture-density-strength relationship for stabilized sabkha soil treated with 5% lime is depicted in Figure 4.27. The $q_u$(max) was 1103 kPa at a moisture content of
Fig. 4.26: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (3% Lime)
Fig. 4.27: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (5% Lime)
15.7%. Comparison of the data in Figure 4.27 with that in Figure 4.26 indicates that there was a little increase in the $q_{u(\text{max})}$ when 5% lime was added to the sabkha soil mixtures. At high moisture contents, however, the $q_u$ was about 150 kPa, which is comparable to that when 3% lime was used (Figure 4.26).

Figure 4.28 represents the moisture-density-strength for sabkha soil treated with 7% lime. The $q_{u(\text{max})}$ was 1142 kPa at a moisture content of 17.6%. Comparison of the data in Figures 4.28 and 4.27 indicates that there was just a little increase in the $q_{u(\text{max})}$ which can be considered as marginal when 7% lime was added to the sabkha-soil mixtures. Again, at a moisture content of 24%, the $q_u$ was about 175 kPa indicating the inability of the 7% lime to increase the strength of Al-Qurayyah sabkha soil at high moisture contents.

The moisture-density-strength for stabilized sabkha soil treated with 10% lime is depicted in Figure 4.29. The $q_{u(\text{max})}$ was 1201 kPa at a moisture content of 19.4%. Comparison of the data in Figures 4.29 and 4.28 reveals that there was again just a little increase in the $q_{u(\text{max})}$ which can be considered as marginal. Again, at a moisture content of 24%, the $q_u$ was about 424 kPa indicating that the 10% lime was much better than the 7% lime but not as efficient as cement to increase the strength of this sabkha at high moisture contents.
Fig. 4.28: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (7% Lime)
Fig. 4.29: Moisture-Density-Strength Relationship for Al-Qurayyah Sabkha Soil (10% Lime)
Figure 4.30 summarizes the results of unconfined compressive strength ($q_u$) for lime-sabkha mixtures. The data in this figure indicates that the improvement was only marginal; the $q_u(\text{max})$ for 0% lime-sabkha mixtures being increased from 809 to about 1200 kPa for 10% lime addition. The data in Figure 4.30 also indicates that while the 10% lime did not bring about any significant increase in $q_u$ as compared with the 7% lime addition, the 3% lime addition also did not improve the strength of sabkha at all. Although the increase in $q_u$ of about 30% was attained at 7% lime addition, such an improvement can be considered negligible for engineering applications. Furthermore, it should be mentioned that the moisture content for stabilized sabkha mixtures treated with 3, 5, 7 and 10% lime contents is greater than the moisture content for the untreated soil (0% additive). Such an increase in $w_{opt}$ of stabilized lime-sabkha mixtures has recently been reported for Ras Al-Ghar sabkha (Al-Amoudi et al., 1995b).

These preliminary results indicate that stabilization of Al-Qurayyah sabkha soil with lime is not efficient. Accordingly, only cement is recommended for stabilizing this sabkha soil.

Table 4.2 quantitatively compares the optimum values for the density, strength, CBR, and Clegg impact hammer test results. The data therein indicates that the density does not vary very much with the moisture content and the range of variations with the cement or lime content was very small. Accordingly, density cannot be considered a valid criterion for any sabkha stabilization program and this conclusion has already vividly been
Fig. 4.30: Effect of Moisture and Lime Contents on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil
<table>
<thead>
<tr>
<th>Agent (by weight of dry soil)</th>
<th>Density $\gamma_d$ (g/cm$^3$)</th>
<th>Unconfined Compressive Strength $w$ (%)</th>
<th>Unconfined Compressive Strength $q_u$ (kPa)</th>
<th>CBR $w$ (%)</th>
<th>CBR$_{max}$ (%)</th>
<th>Clegg Impact Value $w$ (%)</th>
<th>Clegg Impact Value $CIV_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (untreated)</td>
<td>18</td>
<td>1.79</td>
<td>13.9</td>
<td>809</td>
<td>14.9</td>
<td>111</td>
<td>14.9</td>
</tr>
<tr>
<td>3% Cement</td>
<td>17.5</td>
<td>1.81</td>
<td>15.4</td>
<td>2667</td>
<td>15.4</td>
<td>300</td>
<td>15.4</td>
</tr>
<tr>
<td>5% Cement</td>
<td>17.9</td>
<td>1.82</td>
<td>15.4</td>
<td>2766</td>
<td>15.4</td>
<td>395</td>
<td>15.4</td>
</tr>
<tr>
<td>7% Cement</td>
<td>17.2</td>
<td>1.82</td>
<td>17.2</td>
<td>3939</td>
<td>17.2</td>
<td>417</td>
<td>17.2</td>
</tr>
<tr>
<td>10% Cement</td>
<td>18.9</td>
<td>1.84</td>
<td>18.9</td>
<td>5005</td>
<td>18.9</td>
<td>533</td>
<td>18.9</td>
</tr>
<tr>
<td>3% Lime</td>
<td>17.5</td>
<td>1.79</td>
<td>15.2</td>
<td>836</td>
<td>15.2</td>
<td>123</td>
<td>15.2</td>
</tr>
<tr>
<td>5% Lime</td>
<td>20.1</td>
<td>1.77</td>
<td>15.7</td>
<td>1103</td>
<td>15.7</td>
<td>138</td>
<td>15.7</td>
</tr>
<tr>
<td>7% Lime</td>
<td>20.3</td>
<td>1.74</td>
<td>17.6</td>
<td>1142</td>
<td>17.6</td>
<td>150</td>
<td>17.6</td>
</tr>
<tr>
<td>10% Lime</td>
<td>19.4</td>
<td>1.70</td>
<td>19.4</td>
<td>1201</td>
<td>19.4</td>
<td>164</td>
<td>19.4</td>
</tr>
</tbody>
</table>
reported by Al-Amoudi et al. (1995b) when investigating Ras Al-Ghar sabkha.

The situation with regard to Clegg impact hammer is not the same as that of the CBR. The 0, 3 and 10% cement contents gave Clegg impact values of 60, 96 and 105; the increase being 60% for (0 and 3%) and 6% for (3 and 10% cement). In the case of lime, the 0, 3 and 10% lime gave Clegg impact values of 60, 61 and 75, the increase being 2% and 23%, respectively. Although the CIV results of lime-sabkha mixtures followed the same trends as for other tests (i.e. $q_u$ and CBR), the increase being very low, the cement-sabkha mixtures did not exhibit a significant increase in CIV results, particularly when the cement content was increased from 3% to 10%. It seems rational to conclude that the increase in Clegg impact values could not be attained above certain limit, probably beyond a CIV of 98, as shown in Fig. 4.17.

From the quantitative data presented in Table 4.2, the effect of the cement content on the unconfined compressive strength ($q_u$) is schematically presented in Figure 4.31. The data therein reveals that there is a linear relationship between $q_u$ and the cement content, indicating that as the cement content increases, the strength will increase almost linearly. This good correlation is further evidenced by the high $R^2$ value, and the linear relationship can be presented by the equation:

$$q_u \text{ (kPa)} = 405.672 \times \text{CC} + 1008.64$$
Fig. 4.31: Variation of the Unconfined Compressive Strength with Cement Content for Al-Qurayyah Sabkha Soil
where: $CC =$ cement content ($\%$)

In the same manner, the effect of the lime content on the unconfined compressive strength ($q_u$) is presented in Figure 4.32. Again, the data therein shows that there is a linear relationship between the strength and the lime content. This linear correlation can be expressed by the equation:

$$q_u \text{ (kPa)} = 44.431 \times LC + 795.845$$

where: $LC =$ lime content ($\%$)

The above $q_u$-lime content linear relationship is not very strong as for the case of $q_u$-cement content. This is clearly observed by the scatter of the data points about the best-fit line and by the relatively lower $R^2$ value, as shown in Fig. 4.32.

Similarly, the effect of cement content on the CBR is presented in Figure 4.33. The data therein indicates once again that there is a linear relationship between CBR and the cement content, indicating that as the cement content increases the CBR value will increase almost linearly and can be presented by the equation:

$$CBR = 40.4138 \times CC + 149.131$$

The same trend can also be observed for the effect of lime content on the CBR which is presented in Figure 4.34. The data therein reveals that there is a linear relationship between the CBR and the lime content, indicating that as the lime content increases the CBR value will increase almost linearly, however, the increase was
Lime
7 Day Curing
Exposed Specimens

\[ qu = 44.431 \times L.C + 795.845 \]

\[ R^2 = 0.858865 \]

Fig. 4.32: Variation of the Unconfined Compressive Strength with Lime Content for Al-Qurayyah Sabkha Soil
Fig. 4.33: Variation of the CBR with Cement Content for Al-Qurayyah Sabkha Soil
Fig. 4.34: Variation of the CBR with Lime Content for Al-Qurayyah Sabkha Soil
marginal. This good correlation is evidenced by the high $R^2$ value, and the linear relationship can be presented in the equation:

$$\text{CBR} = 5.5 \times \text{LC} + 109.7$$

Figure 4.35 summarizes the effect of cement content on the unconfined compressive strength of Al-Qurayyah sabkha. The results reported by Al-Amoudi (1994b) and Al-Amoudi et al. (1995b) for the Ras Al-Ghar sabkha soil has also been included in Figure 4.35 for the sake of relative comparison. It is interesting to note that all the data fits a linear relationship between the cement content and the unconfined compressive strength ($q_u$). These linear relationships can be presented in the following equations:

$$q_{G_{\text{max}}} = 152.16 \times \text{CC} + 56.5 \quad (R_1^2 = 0.975231)$$

$$q_{G_{16}} = 96.36 \times \text{CC} + 81 \quad (R_2^2 = 0.926927)$$

$$q_{G_{22}} = 79.32 \times \text{CC} + 134.5 \quad (R_3^2 = 0.969859)$$

$$q_{G_{\text{max}}} = 327.48 \times \text{CC} + 1547.5 \quad (R_4^2 = 0.916957)$$

where: $q_{G_{\text{max}}} = q_u$ for Ras Al-Ghar sabkha prepared at $w_{\text{opt}}$ (Al-Amoudi et al., 1995b)

$q_{G_{16}} = q_u$ for Ras Al-Ghar sabkha prepared at $w = 16\%$ (Al-Amoudi, 1994b)

$q_{G_{22}} = q_u$ for Ras Al-Ghar sabkha prepared at $w = 22\%$ (Al-Amoudi, 1994b)

$q_{G_{\text{max}}} = q_u$ for Al-Qurayyah sabkha prepared at $w_{\text{opt}}$

It should be observed that those specimens prepared at the optimum moisture content ($w_{\text{opt}}$) exhibited a higher slope as compared with those prepared at high moisture contents of $16\%$ and $22\%$ (see Fig. 4.35). The higher slope is a reflection of the significant positive
Fig. 4.35: Effect of Cement Content on the Unconfined Compressive Strength of Al-Qurayyah and Ras Al-Ghar Sabkha Soils
influence of the cement content on the $q_u$ strength thereby clarifying the optimum conditions for stabilization. In the case of Al-Qurayyah sabkha soil ($q_{Q\text{max}}$ above), the intercept is much higher, this may be due to the quality of the soil itself relative to the soil of the Ras Al-Ghar sabkha. The statistical analysis indicates that the $R^2$ values are very high for all the above linear correlations which indicates the excellent reliability of the test prediction.

Figure 4.36 depicts the effect of lime content on the unconfined compressive strength of Al-Qurayyah and Ras Al-Ghar soils. The data reveals that a linear relationship does exist between the lime content and $q_u$. These linear relationships can be presented in the following equations:

\[
q_{G_{\text{max}}} = 179.84 \times LC + 158 \quad (R_1^2 = 0.992604)
\]
\[
q_{G_{16}} = 10.28 \times LC + 16.5 \quad (R_2^2 = 0.998096)
\]
\[
q_{G_{22}} = 6.6 \times LC + 8.5 \quad (R_3^2 = 0.787419)
\]
\[
q_{Q_{\text{max}}} = 45.36 \times LC + 787 \quad (R_4^2 = 0.822338)
\]

where:  $q_{G_{\text{max}}}$ = $q_u$ for Ras Al-Ghar sabkha prepared at $w_{\text{opt}}$ (Al-Amoudi et al., 1995b)

$q_{G_{16}}$ = $q_u$ for Ras Al-Ghar sabkha prepared at $w = 16\%$ (Al-Amoudi, 1994b)

$q_{G_{22}}$ = $q_u$ for Ras Al-Ghar sabkha prepared at $w = 22\%$ (Al-Amoudi, 1994b)

$q_{Q_{\text{max}}}$ = $q_u$ for Al-Qurayyah sabkha prepared at $w_{\text{opt}}$
Fig. 4.36: Effect of Lime Content on the Unconfined Compressive Strength of Al-Qurayyah and Ras Al-Ghar Sabkha Soils
It should be observed, however, that the samples prepared at the optimum moisture content exhibited a high slope which means that the strength of these mixtures at high lime contents will be high. In the case of Al-Qurayyah sabkha soil, however, the strength at low lime contents was comparatively very high. This is due to the high intercept in the linear relationship (i.e. 787 kPa at lime dosage of 0%); this could be attributed to the quality of Al-Qurayyah sabkha soil relative to the Ras Al-Ghar one. Accordingly, the lime does not bring about significant improvements in strength. It worths mentioning that although Al-Qurayyah sabkha soil was compacted at the optimum moisture content, it did not bring about the same improvement in $q_u$ as that brought about by the Ras Al-Ghar soil. This means that Al-Qurayyah sabkha soil is not suitable for lime stabilization. The statistical analysis shows that the $R^2$ values are high for all the linear relationships and this indicates that the data is reliable.

4.4 Detailed Stabilization of Al-Qurayyah Sabkha Soil

The selected sabkha soil was to be stabilized using either portland cement or hydrated lime. The first step in the selection of chemical stabilizer was to investigate the relative improvement produced by the two candidates. Unsoaked CBR and the unconfined compressive strength values of the stabilized soil were taken as basis in the selection of the suitable stabilizer. Sulphate resisting (Type V) cement and hydrated lime were used as stabilizers. Comparison of CBR and strength values attained by adding
either cement or lime, lead to the conclusion that cement is the appropriate stabilizer which provides much higher strength than lime.

In addition to strength, economy should also be considered in this selection. Hydrated lime costs about 2.5 times that of Type V portland cement in the local Saudi market. Moreover, cement is effective in treating sandy soils, since the selected sabkha soil is coarse-grained in nature. On the other hand, it is well known that lime does not have inherent cementitious properties by itself, rather it produces cementitious material only after it reacts with certain constituents present in the soil. These constituents are called pozzolanas such as fly ash, and clay (Terrel et al, 1984). Owing to the lack of any pozzolanic material in this sabkha soil, lime did not produce a good results. Therefore, sulphate resistant (Type V) cement was selected as the chemical stabilizer to be used for the stabilization of Al-Qurayyah sabkha soil.

The above preliminary results vividly indicate that cement only succeeded in improving the strength of sabkha-stabilized mixtures. However, further investigation is needed in order to quantify the effects of exposure condition, durability and curing period on cement-sabkha mixtures. To study these effects, it would be feasible to select only one cement-sabkha mixture.

According to the ACI Committee 230 Report (ACI, 1990), the minimum 7-day $q_o$ specified for subbase and subgrade in rigid pavement construction by the USA Army Corps of Engineers (USACE) is 1380 kPa (200 psi) and for base course 3450 kPa (500 psi). For flexible pavement construction, however, these values are 1725 kPa (250 psi) and
5175 kPa (750 psi), respectively, as shown in Table 4.3. In the case of Al-Qurayyah sabkha-cement mixtures, the 7-day $q_c$ strength of 7 and 10% cement additions was 3940 and 5005 kPa (571 and 725 psi), respectively. Further, a factor of 1.10 is to be used in order to get the unconfined compressive strength corrected for a height to diameter (h/d) ratio higher than 1.15 (ACI committee, 1990). Therefore, the 10% cement-sabkha mixture doesn’t suit the base course criterion for base course requirements in flexible pavement and passes all the other requirements in Table 4.3. It is interesting to note that the 7% cement content passes the requirements in a way exactly similar to the 10% cement content. Therefore, the 7% cement content should be selected for the detailed investigation.

In particular, the effects of exposure temperature, period of curing, delay time in compaction on the unconfined compressive strength, resilient modulus and durability of the stabilized Al-Qurayyah sabkha soil were investigated in this research.

4.4.1 Effect of exposure temperature

The effect of exposure temperature during the curing period on cement stabilized-sabkha mixtures was investigated. The samples for the unconfined compressive strength of the sabkha soil were prepared and allowed to cure for 7 days under different temperatures, namely 23, 35, 50, and 70°C. Two curing regimes were investigated; i.e. exposed and sealed curing. The latter type was demanded to preserve the moisture content under the various temperatures. In addition, some samples were allowed to cure in
Table 4.3: USACE Minimum Unconfined Compressive Strength Criteria (ACI, 1990).

<table>
<thead>
<tr>
<th>Stabilized soil layer</th>
<th>Minimum Unconfined compressive strength at 7 days, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexible pavement</td>
</tr>
<tr>
<td>Base course</td>
<td>750</td>
</tr>
<tr>
<td>Subbase course, select material or subgrade</td>
<td>250</td>
</tr>
</tbody>
</table>
an exposed manner, but the samples were kept in a humid chamber (i.e. above a water tank). The test results on the effect of different exposure temperatures on the strength of Al-Qurayyah sabkha soil are shown in Figure 4.37 for exposed and sealed samples as well as for those samples which were preserved above the water tank. The general trend in Figure 4.37 is that the higher the exposure temperature, the higher is the unconfined compressive strength for both exposed and sealed samples. In addition, the exposed samples exhibited consistently higher strength than the sealed ones, and the increase in strength for the former samples was steady over the whole range of temperature. This is probably ascribable to the decrease in moisture content in these specimens thereby leading profuse cementation. This cementation is well-documented in the literature, whereby the sabkha can hold a significant load when dry. However, upon wetting, the sabkha soil becomes impassable (Akili, 1981). Moreover, cement setting and hardening rates tend to increase with an increase in exposure temperature, because the hydration kinetics of cement will be accelerated by heating, particularly at the early stages of exposure (Al-Amoudi et al., 1995a)

Moreover, the samples which were placed above the water tank displayed similar strength to those of the sealed samples. This is probably due to the accumulation of moisture on these samples from the water tank. The data in Figure 4.37 also indicates that the strength of the sealed samples increased only marginally within the temperature range of 23 to 50°C, however, there was a sharp increase in strength, thereafter. At 70°C, both the exposed and sealed samples had almost the same unconfined compressive
Fig. 4.37: Effect of Exposure Temperature on the Strength of Al-Qurayyah-Stabilized Sabkha (Treated with 7% Cement)
strength. This may suggest that the sealed samples could not preserve their moisture at such a high temperature.

4.4.2 Effect of curing period

The effect of curing period on strength of soil-cement mixtures was studied for Al-Qurayyah sabkha soil. Exposed samples were prepared and tested after curing periods of 1, 3, 7, 14, and 28 days at the various exposure temperatures (namely 23, 35, 50 and 70°C).

Figure 4.38 presents the results for the specimens containing 7% cement and prepared at a moisture content of 17.2% for the exposed samples at a temperature of 23°C (i.e. in the laboratory environment). The results shown in Figure 4.38 clearly indicate that the strength increased with the extended period of curing where the strength was about 7000 kPa, after 14 days of curing. However, beyond 14 days of curing the increase in strength was only marginal.

The same trend can be observed for the exposed specimens cured at a temperature of 35°C, as shown in Figure 4.39. There is an increase in strength up to 14 days where the strength was about 7500 kPa and the increase in strength thereafter was marginal. Again, similar behavior was observed for the case of exposed samples cured at a temperature of 50°C, as shown in Figure 4.40. There is an increase in strength up to 14 days where the strength was about 8000 kPa; the increase in strength was thereafter marginal.
Fig. 4.38: Effect of Curing Period on Strength of Al-Qurayyah Sabkha Soil (at Room Temperature 23°C)
Fig. 4.39: Effect of Curing Period on Strength of Al-Qurayyah Sabkha Soil (at 35°C)
Fig. 4.40: Effect of Curing Period on Strength of Al-Qurayyah Sabkha Soil (at 50°C)
In the case of exposed specimens cured at a temperature of 70°C, the effect is somewhat peculiar, as shown in Figure 4.41. There is a sharp increase in the unconfined compressive strength up to 14 days at which the strength was about 11500 kPa. However, there is a sharp decrease in q₀ after 14 days of curing whereby the strength decreased from 11500 to 6500 kPa, the reduction being more than 40%. Such a tremendous reduction in q₀ could be attributed to the development of micro-cracks that might have formed by the differential thermal expansion of the stabilized sabkha ingredients. Similar observations have recently been reported for mortar specimens exposed to 70°C environment (Al-Amoudi et al., 1995a). This observation should be double checked and advanced analysis with the help of (SEM) may be required.

Figure 4.42 summarizes the results of the effect of curing period on the strength at various exposure temperatures. The only peculiar result is observed at the temperature of 70°C. This indicates that the 70°C temperature is so extreme that a significant reduction in q₀ was manifested after long curing periods. Although the initial strength will be high, field engineers should expect some reduction in strength after some exposure period (i.e. 28 days), that is why the results of this investigation do not recommend to use high cement contents if the cement-stabilized sabkha mixture will be on the top layer where the ambient temperature is high because the temperature may be exacerbated by solar radiation. If, however, the stabilized sabkha is to be placed in the base, subbase or subgrade layers, the effect of exposure temperature will be less influential.
Fig. 4.41: Effect of Curing Period on Strength of Al-Qurayyah Sabkha Soil (at 70°C)
Fig. 4.42: Effect of Curing Period on the Strength of Al-Qurayyah-Stabilized Sabkha Cured at Different Temperatures
The data can also be represented in a different way, as shown in Figure 4.43, where the strength is plotted versus the exposure temperature at different curing periods. Apart from the $q_u$ results at $70^\circ$C which have already been discussed in Fig. 4.42, the strength increases with exposure period for all exposure temperatures. However, there is no fundamental difference in $q_u$ at 14 and 28 days of exposures; the reason could be the drying of the exposed samples. Therefore, these results confirm the fact that high moisture is needed for cement hydration.

4.4.3 Effect of delay in compaction

The effect of delay in compaction was investigated by allowing the cement-sabkha mixture to have some delay after mixing the samples (soil + cement + water) and before compaction. The dry density and unconfined compressive strength were the parameters used to study the effect of delay in compaction for Al-Qurayyah sabkha soil. Delays in compaction of 1/2, 1, 2 and 4 hours were used for practical purposes (Habib-ur-Rahman, 1995). Sabkha samples were allowed to cure under sealed and exposed conditions for 3, 7, 14 and 28 days at room temperature only (i.e. $23^\circ$C). The results of this phase of the program are presented in Figures 4.45 to 4.56.

One of the consequences of delay in compaction was the reduction in dry density as shown in Fig. 4.44. There was a continuous decrease in the dry density with the increase in the delay in compaction for the prepared samples. This reduction in dry
Fig. 4.43: Effect of Exposure Temperature on Strength of Al-Qurayyah Sabkha Soil at Different Curing Periods
Fig. 4.44: Effect of Delay Time on the Dry Density for Al-Qurayyah Sabkha Soil
density could be attributed to the fact that the cement started hydrating before the compaction process. This would result in the formation of soil-cement lumps in the loose soil. During compaction, these lumps would resist densification, thus resulting in lower densities. Moreover, it is well known that cement consumes some water for its hydration and this will reduce the availability of water for lubrication thereby reducing the dry density. Consequently, both factors tend to reduce the dry density of the cement-sabkha mixtures if there is any delay in compaction.

Figure 4.45 presents the data on the effect of delay in compaction on strength for the 7% cement-sabkha mixtures prepared at a moisture content of 17.2% after 3 days of curing and for both sealed and exposed samples. The results clearly indicate that the strength decreases as the delay time increases for both sealed and exposed samples. For the exposed samples, the strength continues to decrease even up to a delay period of 120 minutes. Beyond 120 minutes (2 hours), however, the decrease was very marginal. On the contrary, for the sealed samples, the strength continued on decreasing as the delay time is increased up to a delay of 240 minutes (4 hours).

The same trend could be seen for the samples prepared for 7 days of curing, as shown in Figure 4.46. The results clearly indicate that for the exposed samples, the strength was decreasing as the delay time in compaction increased up to a delay of 240 minutes. However, the strength of sealed specimens continued to decrease up to a delay
Fig. 4.45: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (3-Day Curing)
Fig. 4.46: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (7-Day Curing)
of 120 minutes, beyond 120 minutes the decrease was marginal. Again, the same behavior was observed for the samples prepared for 14 and 28 days of curing, as shown in Figure 4.47 and 4.48.

Figures 4.49 and 4.50 summarize the results of the effect of delay time in compaction on the unconfined compressive strength ($q_u$) at various curing periods of 3, 7, 14 and 28 days. These results indicate that $q_u$ of both sealed and exposed samples decreases gradually as the delay time increases for all curing periods of 3, 7, 14, and 28 days. The reason for this decrease in strength is ascribable to the fact that the cement has started hydration while the soil is loose, therefore, the strength will be reduced. Compaction will also result in destruction of cementation that has developed which is nonreproducible. The reduction in strength could also be attributed partly to the decrease in the dry density as was reported previously. Comparison of the exposed samples with the sealed ones indicates that the strength of the exposed samples were higher than that of the sealed ones and this is mainly due to the loss of moisture in the exposed samples. It worthwhile mentioning that similar findings were observed by Habib-ur-Rahman (1995) when stabilizing eastern Saudi marl soils.

The above data on the effect of delay in compaction can be replotted in terms of the curing period, as shown in Figures 4.51 to 4.54. As expected, and for all delays in compaction, the strength tends to increase with the extension in curing period. Again,
Fig. 4.47: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (14-Day Curing)
Fig. 4.48: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (28-Day Curing)
Fig. 4.49: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (Sealed Specimens)
Fig. 4.50: Effect of Delay Time in Compaction on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (Exposed Specimens)
Fig. 4.51: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (30 Min. Delay)
Fig. 4.52: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (60 Min. Delay)
Fig. 4.53: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (120 Min. Delay)
Fig. 4.54: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (240 Min. Delay)
exposed samples displayed consistently higher strength as compared with the sealed specimens.

Figures 4.55 and 4.56 summarize the results of the effect of curing period on the strength of Al-Qurayyah stabilized-sabkha samples at various delay times in compaction. The results indicate that the unconfined compressive strength of both the exposed and sealed samples increases gradually as the period of curing increases for all delay times. Comparison of the exposed samples with the sealed ones indicates that $q_u$ of the exposed samples were higher than the strength of sealed ones. This could be attributed to the loss of moisture in exposed samples. However, the peak strength of the exposed samples was observed after about 14 days; the increase in strength being marginal thereafter, except for the delay of 30 minutes whereby the strength increased with an extended period of curing, as shown in Fig. 4.55, even after 28 days.

The reason for the increase in strength for both exposed and sealed samples is attributed to the fact that cement usually needs some period to develop its strength and as the curing period increases, the cement hydration products will increase leading to an increase in strength.

It can be observed that the strength increases as the delay time decreases. The reason for this increase in strength could be attributed to the fact that the delay will make the cement hydrate before being compacted and, therefore, the soil particles will be
Fig. 4.55: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (Exposed Specimens)
Fig. 4.56: Effect of Delay Time in Compaction and Curing Period on the Unconfined Compressive Strength of Al-Qurayyah Sabkha Soil (Sealed Specimens)
cemented together before compaction thereby forming larger lumps. These lumps are very difficult to be compacted thereby reducing both strength and density (Habib-ur-Rahman, 1995). Compaction will also result in destruction of cementation that has developed which is non reproducible.

4.4.4 Resilient modulus

The diametral resilient modulus test was used to investigate the behavior of stabilized-sabkha soil under dynamic loadings whereby the samples were subjected to different curing conditions. The effect of exposure temperatures on the modulus of resilience is shown in Fig. 4.57. The resilient modulus values of the exposed and sealed samples for Al-Qurayyah sabkha soil premixed with different cement contents are shown in Fig. 4.58. The effect of delay in compaction on the resilient modulus was investigated for only two hour delay as shown in Figs. 4.59 up to 4.61. All resilient modulus samples were tested after a curing period of 28 days.

Figure 4.57 presents the data for the specimens containing 7% cement-sabkha mixtures for the exposed and sealed samples. The results clearly indicate that there is an increase in the modulus of resilience with the increase in the exposure temperature up to 50°C for the sealed samples. Beyond this temperature, however, the modulus of resilience seems to be constant, while no significant increase in resilient modulus was observed in the case of exposed ones. Furthermore, the sealed samples showed higher resilient modulus values compared to the exposed ones, and this could be attributed to the
Fig. 4.57: Effect of Exposure Temperature on Modulus of Resilience of Al-Qurayyah Sabkha Soil
formation of slow strong bond which resulted in lower resilient (recoverable strains) during testing in the case of sealed samples, while, the exposed samples do not have this strong bonding.

The results shown in Fig. 4.58 indicate that there is an increase in the modulus of resilience with the increase in cement content up to about 7% cement content. Thereafter, the increase is marginal, which means that 7% cement content could be considered as the optimum cement content. The increase in the modulus of resilience could be attributed to the fact that the stiffness of the mixture will increase with the increase in cement content.

Fig. 4.59 compares the effect of the delay on the sealed and exposed samples. The sealed specimens seem to be less affected by the two hour delay due to the presence of moisture. This means that the delay is more harmful for the exposed samples.

To compare the effect of the delay in compaction for the exposed samples, Fig. 4.60 indicates that there is a reduction in the modulus of resilience due to the delay. This difference increases as the cement content increases. The percent reduction is about 24% at 10% cement content. The reason for this reduction in the modulus of resilience due to the delay is ascribable to the fact that the cement has already hydrated while the soil is loose, therefore, the macropeds will be formed and when the soil is compacted after the delay in compaction there will be more voids and this will reduce the density, therefore, the modulus of resilience is also reduced (Habib-ur-Rahman, 1995).
Fig. 4.58: Effect of Cement Content on Modulus of Resilience of Al-Qurayyah Sabkha Soil (at Room Temperature)
Fig. 4.59: Effect of Compaction Delay on Modulus of Resilience of Al-Qurayyah Sabkha Soil (2 Hour Delay)
Fig. 4.60: Effect of Compaction Delay on Modulus of Resilience of Al-Qurayyah Sabkha Soil (Exposed Specimens)
The same trend can be observed for the sealed samples, as shown in Fig. 4.61. However, the difference between the samples without delay and those with delay is small, and the percent reduction is about 14% at 10% cement content. This could be attributed to the same reasons as for exposed specimens.

The above argument reveals that the resilient modulus results are not consistent with that of the unconfined compressive results, since the sealed samples had higher values than the exposed ones, and this behavior is due to the reason mentioned previously, where the sealed samples formed slow strong cement bond with the presence of moisture, which resulted in lower resilient (recoverable strains) during testing. While, the exposed samples lack this strong cement bonding. Further, sealed curing must be considered to have a material with a better resilient response. Sealing the cement-stabilized layer should be given more attention when the field temperature is high, as in the summer season (Habib-ur-Rahman, 1995).

4.4.5 Durability (wetting and drying)

The ASTM D 559 standard durability test and the modified slake durability test were performed on cement-sabkha mixtures. The results obtained from the durability tests are shown in Fig. 4.62. These tests measure the weight loss and volume change with the number of the cycles.

The above two durability tests were conducted on Al-Qurayyah sabkha soil stabilized with 0, 3, 5, 7 and 10% cement content. The 0% cement-sabkha specimens
Fig. 4.61: Effect of Compaction Delay on Modulus of Resilience of Al-Qurayyah Sabkha Soil (Sealed Specimens)
collapsed during the first cycle, and therefore, considered as “failed” the durability test. For the 3% cement-sabkha mixture, the specimens split apart from the top third of its height after 2 cycles. Also, this mixture failed the durability test. At the end of 12 cycles, the weight loss is about 3.5% for both tests. According to the ASTM D 559 and slake durability tests, the allowable weight loss is 14% and 12%, respectively, after 12 cycles. Therefore, the 5% cement-sabkha mixtures can be considered “passing” the durability tests.

The weight loss of the soil-cement mixtures at different cement contents for Al-Qurayyah sabkha soil is depicted in Figure 4.62. Furthermore, the weight loss was observed to decrease as the cement content increases. However, the data in Figure 4.62 indicates that there is no fundamental difference in the weight loss of the specimens stabilized with 7% and 10% cement.

In summary, the data in Figure 4.62 indicates the following:

1. There is strong consistency between the ASTM D 559 and slake durability tests. This means that using any one of them is sufficient to produce reliable results on the durability of stabilized soils. However, slake durability is proven to be a good alternative to the ASTM D 559 durability standard.

2. As the cement content increases the weight loss decreases indicating that cement is a suitable stabilizing agent, not only from strength perspective but also from durability point of view.
Fig. 4.62: Variation of the Weight Loss with Cement Content for Al-Qurayyah Sabkha Soil
3. Beyond 7% cement content, the decrease in weight loss is marginal. This means that the 7% cement content is considered as the best dosage for stabilizing Al-Qurayyah sabkha soil from economy point of view. The 7% cement content is further substantiated from the strength results (Figures 4.20 to 4.25), where the increase in strength beyond 7% was observed to be marginal. Therefore, the 7% cement content is recommended to be used to stabilize Al-Qurayyah sabkha soil.
Chapter 5

CONCLUSIONS AND RECOMMENDATIONS
FOR FUTURE RESEARCH

5.1 Summary

This investigation was undertaken to stabilize an eastern Saudi sabkha soil from Al-Qurayyah area. Lime and cement were initially used to improve and upgrade the quality of this soil. Several tests, including specific gravity, plasticity, grain-size distribution, chemical analysis of brines, compaction, CBR, Clegg hammer, unconfined compression, resilient modulus, and durability, were conducted to assess the mechanical properties of plain (with no stabilizing agent) and cement- or lime-treated sabkha mixtures. Owing to the inferior performance of this sabkha soil as a construction material, chemical stabilization was undertaken. Cement stabilization was found to be the most suitable and economical way of utilizing this "low quality" soil.

5.2 Conclusion

Based on the analysis and interpretation of the results presented in this investigation, the following main conclusions could be drawn:

- Density cannot be considered as a valid criterion for any sabkha stabilization program for Al-Qurayyah sabkha soil.
• Portland cement was proven to be a suitable chemical additive to stabilize Al-Qurayyah eastern Saudi sabkha soil. On the other hand, lime did not bring about a significant improvement to sabkha soil in terms of strength.

• The test results on the effect of different exposure temperatures on the strength indicate that the higher the exposure temperature, the higher is the unconfined compressive strength for both exposed and sealed samples. In addition, the exposed samples exhibited consistently higher strength than the sealed ones. However, the 70°C temperature is so extreme that a significant reduction in strength was manifested.

• There was a continuous decrease in the dry density with the increase in the delay in compaction for both the sealed and exposed samples for all curing periods.

• The results on the effect of delay in compaction on the unconfined compressive strength ($q_u$) at curing periods of 3, 7, 14 and 28 days indicated that $q_u$ of both sealed and exposed samples decreases gradually as the delay time increases for all curing periods.

• A cement content of 7% was found to be adequate for the effective stabilization of Al-Qurayyah sabkha soil. It meets the strength and durability requirements.

• Resilient modulus ($M_R$) values increased with the increase in the exposure temperature up to 50°C and with the increase in cement content up to about 7% cement content. However, there was a significant reduction in the modulus of resilience due to the delay in compaction.
• There was strong consistency between ASTM D 559 and slake durability tests. This means that using any one of them is sufficient to produce reliable data on the durability of stabilized soils. However, Slake durability is proven to be a good substitute to the existing ASTM D 559 durability standard test.

• As the cement content increases the weight loss will decrease indicating that cement is a suitable stabilizing agent, not only from strength perspective but also from durability point of view.

5.3 Recommendations for Future Research

• To study the effect of the sabkha brine on the mechanical properties of this sabkha soil.

• To investigate the microstructure of stabilized sabkha soil using scanning electron microscopy (SEM) techniques to clarify the mechanisms of chemical cementation.

• To stabilize this sabkha soil using emulsion and to study how effective is this stabilizer.

• To perform permeability and leaching tests on the plain (i.e. untreated) and stabilized soils.

• To investigate the compressibility of this sabkha soil.
REFERENCES


