An assessment of the possibility of stabilising Sabkha soils using oil lake residue - reuse of waste materials

Fahad A. Al-Otaibi

Geoenvironmental Research Centre

Cardiff School of Engineering

Cardiff University

Thesis submitted in candidature for the degree of Doctor of Philosophy at Cardiff University

August 2006

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed .... (Fahad A. N. Al-Otaibi)

Date ....14/10/2006........................

Statement One

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by the provision of references.

Signed .... (Fahad A. N. Al-Otaibi)

Date ....14/10/2006....

Statement Two

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .... (Fahad A. N. Al-Otaibi)

Date........14/10/2006

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed .... (Fahad A. N. Al-Otaibi)

Date ....

Statement One

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by the provision of references.

Signed .... (Fahad A. N. Al-Otaibi)

Date ....

Statement Two

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .... (Fahad A. N. Al-Otaibi)

Date..

Dedicated

To

My mother, my wife and children
Naser, Dana, Fay, Dala, Dhay, Hessah and Abooooood

And

My aunt who supported me during her life and even after her death

Acknowledgements

I would like to sincerely thank my supervisor Prof. Hywel Thomas for his continued support and invaluable academic guidance throughout the duration of the research.

For his consistent and valuable technical input I would also like to thank Dr. Mahdi. In particular, his support in interpretation of laboratory investigations and during the preparation of this thesis.

To all my colleagues at the Geoenvironmental Research Centre I owe my gratitude for their valuable interaction.

My immense gratitude goes to the Public Authority of Applied Education and Training (PAAET) for providing me with the PhD scholarship and also to the Ministry of Defence, Kuwait and Kuwait Institute for Scientific Research whose support was instrumental to the success of the field work.

I thank also my family for their continued moral support and for unceasingly bearing the brunt of my absence from Kuwait.

Abstract

This thesis describes the experimental work undertaken to investigate the possibility of using oil lake residue to stabilise Sabkha soils in Kuwait. Sabkha is a problematic salt-encrusted soil deposited under arid conditions which cannot be used for construction in its natural condition. The oil lake residue being considered is the waste hydrocarbons resulting from the destruction of oil wells in Kuwait during the Gulf War, 1990. The oil lake residue covers an overall area of 24 km^2, and represents an environmental hazard that needs to be eliminated.

The experimental programme included laboratory and field testing of physical properties and strength, consolidation and leaching aspects of the natural and oil mixed Sabkha soils. A soil survey of a large area was undertaken to select representative soil samples. Sabkha soils from four main locations were selected for the detailed experimental testing. Oil residue was added to the Sabkha soils at different percentages ranging from 0% to 10%. The focus of the experimental work was towards physical and mechanical behaviours due to low clay (less than 0.5%) and organic (less than 2%) contents of the soil and high content of non-polar compounds (85%) in the oil residue.

Results showed that the addition of oil residue reduced the friction between the soil particles in the range of 5% to 28% and the facilitated sliding over each other resulted in an increase in the density of the compacted Sabkha soils of between 2% to 8.5%. The *UCS* increased in the range of 34% to 504% of the natural values. The shear strength slightly increased with oil addition since the internal friction decreased and the cohesion intercept values increased in the range of 45% to 150%. The adsorbed oil residue on the cemented soil lumps acted as a waterproofing agent that reduced both salt dissolution by 56% of the natural soil and the long term coefficient of permeability in the range of 73% to 88%. Under soaked conditions, the improvement in strength properties were pronounced. The natural Sabkha soil disintegrated upon soaking while oil mixed Sabkha maintained its integrity. Yield stress increased in the range of 25% to 60% from the values of natural soils and compression index and collapsibility decreased in the stabilised Sabkha.

Field testing on 5% stabilised compacted test beds revealed an additional increase in *CBR* and *UCS* above that of the laboratory results. Density and shear strength of field samples showed similar results as those obtained by laboratory testing. Leachability of oil from the 5% oil stabilised Sabkha soil measured in the laboratory under a hydraulic gradient of 40 was less than 1 mg/l, which can be considered very low. Leachability of oil residue in the field was undetectable.

The main conclusion of the work is that the addition of 5% oil residue improved the performance of Sabkha soils especially under soaked conditions, which may result in its applications in the construction industry. These results are encouraging. However the acceptance of oil residue as a stabilising material necessitates further research and this future programme is briefly mentioned.

Contents

1. Introduction

2. Literature review

3. Experimental programme, sampling plan and materials characterisation

4. Physical properties of Sabkha soils mixed with oil residue

5. Strength aspects of natural and oil mixed Sabkha soils

6. Bearing capacity and consolidation characteristics of natural and oil mixed Sabkha soil

7. ***Leachability and waterproofing effect of oil residue***

8. Field testing

9. Summary, Discussion, Conclusions and Recommendations

Notations

J	Al-Jailaiaha
Z	Al-Zour
K	Al-Khiran
B	Benider
E	East geographical positioning
N	North geographical positioning
S_{J-4}	Soil Sample from Al-Jailaiaha
S_{Z-5}	Soil Sample from Al- Zour
S_{K-7}	Soil Sample from Al- Khiran
S_{B-8}	Soil Sample from Benider
NAPL	Non-aqueous phase liquid
Cu	Coefficient of uniformity
Cc	Coefficient of curvature
D_{10}	Particle-size diameter corresponding to 10 passing
D_{30}	Particle-size diameter corresponding to 30 passing
D_{60}	Particle-size diameter corresponding to 60 passing
SPu	Poorly graded sand - BSI classification system
SP	Poorly graded sand - USCS system
SPM	Poorly graded silty sand – BSI classification system
SP-SM	Poorly graded silty sand – USCS system
MDD	Maximum dry density

OMC	Optimum moisture content
i	Hydraulic gradient
k	Coefficient of permeability of soil
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
CEC	Cation Exchange Capacity
G_s	Specific gravity
NM	Not measured
UCS_n	Unconfined compressive strengths of natural soil
UCS_{st}	Unconfined compressive strengths of oil mixed soil
UCS_D	Unconfined compressive strength (Dry condition)
UCS_S	Unconfined compressive strength(Soaked condition)
φ_f	Angle of shearing resistance
C	Cohesion intercept
τ_f,	Maximum shear stress
σ_n	Normal stress
H_o	Initial height of the soil sample
ΔH	Change in the height
e_o	Initial void ratio
Δe	Change in the void ratio
C_c	Compression Index
C_s	Swelling Index
C_P	Collapse potential

Δe_c	Change in the void ratio upon wetting
ΔH_c	Change in height upon wetting
F	Field
L	Laboratory
D	Dry testing: soil tested at their optimum moisture content
S	Soaked testing: soil tested under soaked conditions
PV	Pore volume

Chapter 1

Introduction

1.1 Introduction

Sustainable development involves "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UNCED, 1992). It is the key goal of every government today since as the world population increases, so pressure on the environment also increases and life style quality may be compromised. At the same time, wellbeing depends on strong economic development. Thus governments must strive continuously to achieve a balance between economic targets and environmental preservation (UNCED, 1992 and WSSD, 2002).

However, sustainable development, as a whole, cannot be achieved without a sustainable geoenvironment, whose importance is now recognised at national and international levels. Land regeneration and reclamation are essential aspects of achieving a sustainable geoenvironment and must be taken into account in any site development. Since sustainable development requires the wise use of limited natural soil resources, one aspect of land regeneration is soil stabilisation. In arid and semi-arid environments, stabilised soil becomes very important as a foundation soil for various construction purposes. Soil stabilisation is the process of modifying the properties of problematic soils utilising different mechanical and chemical methods. In arid or semi-arid environments soil stabilisation becomes very important due to the lack of suitable soils for construction usage. Stabilisation is also recommended to protect limited natural resources, which may become depleted due to the extensive development, as taken place in the Gulf region in the recent years. The increase in population has led to a huge demand for construction materials, including sand and other fill materials.

This thesis seeks to address the problematic nature of Sabkha soils within the context of Kuwait, a small oil rich country located in the Arabian Gulf in the Middle East, with a population of about 3 million. Kuwait has been selected for this study since it is this author's home country and the research work is of relevance to his government. Kuwait is, in general, a flat or gently undulating desert plain sloping toward the east, which has several types of surface soil deposits. On the north and south coasts, the terrain is salt-encrusted, consisting mainly of Sabkha deposits (Figure 1.1).

Sabkha soils are not considered suitable for construction purposes in their natural condition due to their problematic geotechnical properties. Their complex behaviour makes them unsuitable for many types of construction and necessitates improvement or replacement before construction takes place (Al-Amoudi, 1994; Al-Amoudi and Abduljauwad, 1995b).

On account of the arid conditions in the country, most development activities take place in the coastal zone, which is mostly covered by Sabkha soil flats. Usual construction practice is excavation of the Sabkha soil, up to a certain depth, depending on the structure to be built, and then discarding and replacing it with clean sand. However, due to the high cost and limited availability of bulk fill construction materials, upgrading of marginal abundant material, such as Sabkha soil, becomes imperative.

Kuwait's environment was severely affected during the 1990-1991 invasion and second Gulf war. During the war, hundreds of active oil wells were blown up, resulting in the burning and release of large amounts of crude oil into the air, Gulf and Kuwaiti desert. This environmental disaster led to the formation of large oil lakes in northern and southern parts of Kuwait around oil fields area. These large lakes of oil residue present a major hazard to the ecological system and human health since they have been left untreated and therefore pose a serious threat to the environment (GCI, 1998) and the safety of both humans and animals. Treatment of such huge amounts of contaminants to reduce their negative impact on different aspects of the environment is required. However, there is a potential for further oil lakes residue formation in the future due to accidental oil leakages or spillages in the Gulf region. Research in this area has been primarily oriented towards investigating the migration of oil contaminants, identifying effective treatment techniques and assessing environmental impact.

This study's primary aim is to investigate the possibility of stabilising Sabkha soil by mixing it with oil lake residue for utilisation in construction and beneficial applications, including road subgrade, backfilling and other bulk engineering usages. This will reduce the pressure on limited sand resources and help to reduce oil lakes residue and their potential hazards. Research in this area will be primarily oriented towards achieving a fundamental understanding of the geotechnical and engineering properties of Sabkha soil. If mixing with oil residue proves viable for construction purposes, stabilised Sabkha soil could be used in huge quantities in the construction industry in the future.

To encourage research in this field, the Kuwaiti Ministry of Defence has put its facilities (laboratories and field testing equipment) at the author's disposal. Moreover, if the suggested approach proves successful, it will contribute significantly to large infrastructure projects which are expected to commence in the study area in the near future. These will require large amounts of fill and road construction materials.

This chapter's main objective is to provide detailed background information on Kuwait's Sabkha soil and oil lake residue, to define the research problem, and to outline the solution adopted. Section 1.2 provides details of Kuwait's location and the climatic conditions that have led to the formation of Sabkha soil. A brief description of Sabkha and its problematic properties is also presented. Problems associated with construction on Sabkha soil are also described in this section. Section 1.3 focuses on oil lake residue, their causes, and potential threats. The main problems, proposed solution and expected potential benefits are stated in section 1.4. The research programme's objectives are presented in section 1.5. The organisation of the thesis is outlined in section 1.6. References related to the work presented and discussed in this chapter are provided in section 1.7.

1.2 Sabkha deposits in Kuwait

Kuwait is located on the North West shore of the Arabian Gulf, and is bordered by Iraq in the north and west, by Saudi Arabia in the south, and by the Arabian Gulf in the east

(Figure 1.1). It lies between 28° 30′ N and 30° 05′ N latitudes and 46° 33′ E and 48° 30′ E longitudes. Its area is approximately (17600 km^2), including the mainland and several islands, i.e. Bubiyan, Warba, Failaka and Qubbar.

Kuwait is characterised by flat, gently undulating desert plains (Al-Saleh and Khalaf, 1982). Surface deposits consist of the following major groups: Aeolian, residual, playa, desert plain, slope deposits, alluvial fine sand and coastal deposits (Khalaf et al., 1984). North and south coast deposits consist mainly of Sabkha flats. Sabkha is an Arabic term used to describe the large, flat, salt-encrusted terrain, deposited under arid conditions, which is composed of clays, silts, sands and salty mixtures. Sabkha deposits are generally associated with high moisture content and a high groundwater table (Al-Amoudi et al., 1992; Al-Shamrani and Dhowian, 1997; Banat et al., 2005 and Dhowian, 1991). Their development is due to low wave energy allowing the settlement of silt and clay particles to take place and then be loosely cemented by soluble material (Akili, 1981 and James and Little, 1994).

The surface soil layer consists of fine to medium size particles, non-plastic, medium dense to dense, calcareous, wind blown silty sand extending to a depth of 7 m (Al-Sanad and Shaqour, 1991; Ismael and Jeragh, 1986; Ismael et al., 1986-a). At depths below this, the soil consists of more competent calcareous, silty, fine to medium sand with varying degrees of cementation called locally *Gatch* (Al-Sulaimi et al., 1990; Ismael and Jeragh, 1986; Ismael et al., 1986-a and 1986-b). The soil in Kuwait may be classified as poor to well graded silty sand according to the Unified Soil Classification System (Ismael, 1980; and Khalaf et al., 1985).

Because of its location in the northern part of the hot arid desert zone of the Arabian Peninsula, climatically Kuwait is arid and dry. The temperature varies between 3°C to 15°C in winter and 25°C to 45°C in summer (Figure 1.2). Extreme temperatures of 53°C in summer and -3°C in winter have been recorded (Al-Kulaib, 1984). The mean annual rainfall is about 105 mm, with most rain falling between November and May (Al-Ruwaih, 1995). Winds, which are predominantly from the northwest are sometimes loaded with dust and followed by thunderstorms and rains in March and April (Figure 1.3) (Al-Kulaib, 1984).

Due to the effect of high temperatures and low rainfall, evaporation potential in Kuwait is extremely high and exceeds precipitation by a ratio of 30:1 (Al-Kulaib, 1984). This leads to upward movement of saline ground water (Yechieli and Wood, 2002) and an increase in the concentration of soluble material at or near the ground surface, resulting in the development of a cemented crust on the latter (Ismael, 1993-b). The main precipitated salts, which act as cementing agents, are gypsum, carbonates and chlorides (Al-Amoudi, 1994; Ismael and Mollah, 1998; and Ismael et al., 1986-b).

1.2.1 Engineering problems associated with Sabkha soil

Sabkhas are commonly divided into "coastal Sabkhas" and inland or "continental Sabkhas" (Akili and Torrance, 1981; Al-Amoudi et al., 1992; and Dhowian, 1991). Coastal Sabkhas predominate in Kuwait along the coastal flats just above the high tide level (Al-Hurban and Gharib, 2004; and Khalaf et al., 1984) and extend a few kilometres landward in some locations. Khalaf et al. (1984) classified Sabkha flats in Kuwait as northern Sabkhas and southern Sabkhas. Northern and southern Sabkha flats are 125 km apart from each other and differ in physiographic, hydrological, sedimental and compositional characteristics (Saleh et al., 1999). Southern coastal Sabkha flats are mainly along the elongated depression in the Al-Jailaiaha and Al-Khiran areas, and extend landward for about 20 km (Al-Hurban and Gharib, 2004). In closed lowland areas, these Sabkhas flats are scattered, irregular, differently sized, unconsolidated to slightly consolidated heterogeneous deposits, mainly composed of sand, silt and gypsum (Al-Hurban and Gharib 2004; and Al-Sanad, 1986).

Sabkha soils are known for their low-bearing strength in their natural condition and therefore improvement of this unfavourable property is deemed desirable (Al-Amoudi, 2002; and Al-Shamrani and Dhowian, 1997). Structures built on Sabkha soil must be carefully designed in order to avoid future problems that can arise after construction (Shehata and Amin, 1997). Due to rapid development and rushed construction in the Gulf Region, construction projects have been built on Sabkha formations without careful consideration (Aiban et al., 2006). As a result of the high deformation of these problematic soils, structural problems have occurred, ranging from severe, that is, beyond repair, to moderate, which, with appropriate repair measures, can be rectified (Juillie and

Sherwood, 1983; and Ghazali et al., 1985). Several buildings and other construction facilities constructed on Sabkha flats show extensive damage, such as tilting and cracks (Erol, 1989; Dhowian, 1991; and Khan and Hasnain, 1981).

Despite traditional precautions taken during the design and construction of roads built on Sabkha flats, they have exhibited various types of deterioration in the form of ravelling, cracking, rutting and formation of potholes and depressions (Farwana and Majidzadeh, 1988), mainly attributed to the low bearing capacity of Sabkha soils and their huge loss of strength upon wetting (Ismael, 1993-b; Ghazali et al., 1985). Physical and chemical weathering of building materials and structures built on Sabkha soils is common in Kuwait (Goudie, 1994). The corrosive damage to both concrete and steel structures is caused by high sulphates and chlorides concentrations in Sabkha (Naifeng, 1994).

Due to their problematic geotechnical properties, Sabkha soils can not be used for construction purposes in their natural conditions and have to be excavated to a considerable depth, discarded and replaced by clean sand.

1.3 Oil Lakes

In 1991, Kuwait's desert plain was inundated with massive oil-spills resulting from the destruction and burning of oil wells during the Gulf War. Five hundred and sixty-five oil wells were set ablaze (Plate 1.1), and 74 others gushed uncontrollably from the damaged well heads (Plate 1.2) (Besharah, 1991). This disaster has had a serious impact on the environment. Within nine months of the disaster, more than 60 million barrels of oil had been spilled in the northern and southern oil fields of Kuwait (Al-Saad, 1993) and 4.4 % of the country's total area had been affected (Koch and El-Baz, 1998). Moreover, approximately 300 oil lakes comprising an overall area of more than 49 km^2, had been formed in the oil fields area north and south Kuwait (Al-Awadhi et al., 1996). These oil lakes differed in size, were of irregular shape, and varied in depth, ranging from few centimetres to 1.5 meters (Plate 1.3) (Al-Besharah and Salman, 1991).

An examination of pollution in the Burgan oil field area indicated that oil had penetrated into soil to a one-meter depth on average, of which the top 30 cm was oily-sludge, containing oil concentrations greater than 40% (PEC,1999). A study of soil profiles in the affected area revealed that soil horizons in some locations in Kuwait contained very high concentrations of hydrocarbons down to a depth of 80-95cm, and in other locations in the upper 50cm (Massoud et al., 2000). It was also concluded that the *Gatch* layer present below these depths, acted as a moisture barrier, impeding any further downward movement of oil or water. This calcareous sand soil layer could be considered linear due to its low permeability (Al-Yaqout and Townsend, 2004).

Huge amounts of the oil were recovered by the Kuwait Oil Company after fires were extinguished (Hussain, 1995). However, the remaining quantity of oil is deemed irrecoverable from the bottom of the oil lakes (Saeed et al., 1995). Different treatment plans and strategies for the cleaning and rehabilitation of the oil lakes, such as bio-treatment, heat treatment, physical/chemical treatment, and physical methods have been proposed. These plans however, have not been implemented for economic, technical, environmental and safety reasons (Elgibaly, 1999). The biodegradation effect has not been a major factor in the compositional change of the oil lakes (Bufarsan et al., 2002). With regard to treatment processes, bioremediation methods have been effective for soils containing less than 4% oil. For heavily contaminated soil (20% oil concentration), physical/chemical remediation has been required to reduce contaminants to less than 4%, at which bioremediation becomes possible (PEC, 1999).

The total volume of oil contaminated soil reached 22652500 m^3 as shown in Table (1.1) (Al-Saad, 1993). The severest oil contaminated material is to be found on the top layer of the bed of oil lake and varies from hard crusty soil to viscous tarry sludge, containing 133 g/kg and 694 g/kg total petroleum hydrocarbons, respectively (Balba et al., 1998). Different procedures and plans to reclaim these huge amounts of contaminated soil after the removal of oil lakes residue are expensive as well as time consuming and it may take many years, if not decades, for Kuwait's environment to return to its pre-war state (Nicolson, 1998).

In 1998, the remaining area of oil lakes was reported to be 24.13 km^2 (Kwarteng, 1999). In 2001, it was reported that no change had occurred in the size of the oil lakes (Kwarteng, 2001). As a result of climatic conditions, huge parts of these oil lakes have been partially covered by sand and dust, while the smaller oil lakes have been completely covered and their original location is not easily detected (Kwarteng, 1998).

Due to weathering effects in the hot climate of Kuwait (ambient summer temperature is 50C°), the oil remaining has thickened to a semi- solid mass in most lakes and is not easy to remove. The total amount of oil to be lifted from the lake is estimated to be 1.55 million tons (Saeed et al., 1995). Ongoing chemical testing results indicate that asphaltene, aromatic and resins content of oil samples from most lakes has increased due to the decrease in volatile hydrocarbons and saturates (aliphatic compounds) as weathering has progressed (Saeed et al., 1998).

The continuous loss of volatile hydrocarbons from the surface has led to the formation of a devolatilised viscous surface layer "skin". This layer protects the underlying oil and causes a decrease in the overall rate of evaporation (Bufarsan et al., 2002, and Barker and Bufarsan, 2001). The clean, water-free oil residue located underneath the surface layer skin possesses properties similar to those of a typical medium crude residue with a boiling point of more than 300°C. This suggests that the oil has lost most of its light hydrocarbons (Khan et al., 1995).

Another source of oil residue contamination is accidental oil leakages and spills that have been recorded in different locations in Kuwait. Different sizes of oil spills occurring as a result of these accidents have been recorded and left without treatment.

1.4 Statement of the problems and proposed solution

Environmental pollutants from oil lakes as well as pollution from continuous accidental oil spills have been shown to have an adverse effect on the Kuwaiti environment (Kostreba, 1999). In addition, contaminated soils represent a serious threat to sustainable economic development. Immediate substantial actions in the form of national contingency plans are needed to control these pollutants, although it is recognised that the treatment of oil residue and associated contaminated soils is expensive due to the nature and scale of the problem.

Moreover, discarded Sabkha soils which are considered waste materials, contribute greatly to dust storms in Kuwait, since upon drying under arid conditions their fine contents are carried away by the prevailing winds. Thus, although Sabkha soil utilisation and stabilisation present a challenge, they are necessary, particularly in countries such as Kuwait with limited construction material resources.

The proposed solution to the stated problems is utilisation of locally available Sabkha soils, after modification, in different construction projects, including road construction. The large amounts of oil lakes residue could be beneficially used by mixing them with Sabkha soils in order to modify the latter's geotechnical properties. An investigation of this approach may provide valuable information about Sabkha soil-oil residue mixtures and ultimately lead to beneficial application of the vast amounts of oil contaminated Sabkha soils.

Utilisation of oil residue in the stabilisation of Sabkha soils may result in multiple economic and environmental benefits, which include:

- Reduction in oil lakes residue quantities and accompanying pollution.
- An economically feasible solution to the oil residue problem.
- Reduced demand for available natural resources, i.e. clean sand and other backfill materials.
- Reduction in primary quarrying activities.
- Reduced negative impact on the environment as a result of decreased need to transport clean sand and/or other filling materials to the development site and transporting Sabkha soil away from the site.
- Reduced cost of transporting new and discarded material.
- Substantial reduction in the cost of some projects in terms of time and resources, due to the use of locally available materials.

1.5 Study objectives and tasks

The main objectives of this study are to contribute to and promote sustainability by conserving soil resources in Kuwait through investigating the possibility of using two main waste streams materials, namely, Sabkha soil and oil lake residue.

In order to investigate the possibility of stabilising the Sabkha soil using oil lake residue, the following tasks were performed:

- Investigation of the physical properties of Sabkha soil mixed with different oil residue percentages.

- Investigation of the geotechnical properties of Sabkha soil mixed with different oil residue percentages. The geotechnical properties that are of particular interest in this work are :
    - Strength.
    - Consolidation.
- Investigation of the leachability of stabilised Sabkha soils.

- Investigation of the effect of field conditions on stabilised Sabkha soils.

1.6 Scope of this work

The experimental work in this study concentrated on the physical and mechanical behaviour of Sabkha soils mixed with different oil residue contents. Due to the chemical composition of oil and Sabkha soils, which will be detailed in chapter 3, the major type of bonding mechanisms between oil residue and salty sand soil surfaces is expected to be limited to weak physical adsorption.

1.7 Organisation of the thesis

This thesis consists of nine chapters detailing the work undertaken during the duration of the project.

In this chapter the reasons for the research and background details have been presented. The problem has been identified and the proposed solution outlined. Study objectives and tasks have also been delineated as well as the forthcoming contents of this thesis.

Chapter two reviews previous studies on Sabkha soil and oil lake residue. Sabkha soil stabilisation methods carried out in Kuwait and the Gulf region are discussed. These include mechanical and chemical stabilisation methods. Studies on oil contaminated soils related to the present work and others hydrocarbons are also presented.

Chapter three describes the first phases in the research programme, namely, the soil survey, the sampling strategy, and materials' characterisation. Detailed analyses to characterise both the Sabkha soil and oil residue are explained in this chapter.

Chapter four concentrates on the physical properties of the oil mixed Sabkha soils. The results derived from the experimental programme are presented and discussed.

Chapter five describes a series of unconfined compression and direct shear tests conducted on natural and oil mixed Sabkha soils. Results of the work are presented.

The bearing capacity and consolidation characteristics of natural and oil mixed Sabkha soils are assessed in chapter six. California bearing ratio and consolidation tests are described in detail.

The leachability characteristics of natural and oil mixed Sabkha soils are investigated in chapter seven. Leaching column tests are conducted to ascertain the leaching of oil constituents from the stabilised soil layers. The water proofing effect of oil residue and long-term permeability results are presented and discussed in this chapter.

Chapter eight describes field testing carried out on compacted patches of stabilised Sabkha soil samples. These patches had been left exposed to climatic conditions for more than one year. Geotechnical tests and leachability analyses are carried out on these samples to understand the long-term effect of stabilising Sabkha soils.

Conclusions drawn from the study findings and recommendations for further studies are presented in chapter nine.

1.8 References

Aiban, S.A., Al-Ahmadi, H.M., Asi, I.M., Siddique, Z.U. and Al-Amoudi, O.S.B., 2006. Effect of Geotextile and Cement on the Performance of Sabkha Subgrade. *Building and Environment*, 41(6): 807-820.

Akili, W., 1981. On Sabkha Sands of Eastern Saudi Arabia. In Proceedings of the Symposium on Geotechnical Problems in Saudi Arabia. King Saud University, Riyadh, Saudi Arabia, 2: 775-779.

Akili, W. and Torrance, J.K., 1981. Development and Geotechnical Problems of Sabkha, with Preliminary Experiments on the Static Penetration Resistance of Cemented Sands. *Quarterly Journal of Engineering Geology*, 14(1): 59-73.

Al-Amoudi, O.S.B., 1994. Chemical Stabilisation of Sabkha Soils at High-Moisture Contents. *Engineering Geology*, 36(3-4): 279-291.

Al-Amoudi, O.S.B., 2002. Characterisation and Chemical Stabilisation of Al-Qurayyah Sabkha Soil. Journal of Materials in Civil Engineering, 14(6): 478-484.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-b. Strength Characteristics of Sabkha Soils. *Geotechnical Engineering*, 26(1): 73-92.

Al-Amoudi, O.S.B., Abduljauwad, S.N., El-Naggar, Z.R. and Rasheeduzzafar, 1992. Response of Sabkha to Laboratory Tests - A Case Study. *Engineering Geology*, 33(2): 111-125.

Al-Awadhi, N., Al-Daher, R., El-Nawawy, A. and Balba, M.T., 1996. Bioremediation of Oil-Contaminated Soil in Kuwait, Land Farming to Remediate Oil - Contaminated Soil. *Soil and Sediment Contamination*, 5(3): 243-260.

Al-Besharah, J. and Salman, M., 1991. Assessment of the Oil lakes in Kuwait's Oil Fields. Rep.4005, Kuwait Institute for Scientific Research (KISR), Kuwait.

Al-Hurban, A. and Gharib, I., 2004. Geomorphological and Sedimentological Characteristics of Coastal and Inland Sabkhas, Southern Kuwait. *Journal of Arid Environments*, 58(1): 59-85.

Al-Kulaib, A.A., 1984. The Climate of Kuwait. Directorate General of Civil Aviation (DGA), Meteorological Department, p. 178.

Al-Ruwaih, F.M., 1995. Hydrogeochemical Variation of Carbonate Aquifer Al-Sulaibiya (South) Kuwait. *Journal of Water, Air and Soil Pollution*, 90: 489-505.

Al-Saad, A., 1993. Oil lakes. Lecture Presented at Kuwait Engineering Society, Kuwait, p. 32.

Al-Saleh, S. and Khalaf, F.I., 1982. Surface Texture of Quartz Grains from Various Recent Sedimentary Environments in Kuwait. *Journal of Sedimentary Petrology*, 52(1): 215-225.

Al-Sanad, H.A., 1986. Characterisation of Salt-Bearing Soils (Sabkha) for Pavement Design Purposes in the State of Kuwait. *Journal of the University of Kuwait-Science*, 13(1): 29-41.

Al-Sanad, H.A. and Shaqour, F.M., 1991. Geotechnical Implications of Subsurface Water Rise in Kuwait. *Engineering Geology*, 31(1): 59-69.

Al-Shamrani, M.A. and Dhowian, A.W., 1997. Preloading for Reduction of Compressibility Characteristics of Sabkha Soil Profiles. *Engineering Geology*, 48(1-2): 19-41.

Al-Sulaimi, J., Mohammad, A., Mollah, M.A. and Matti, A., 1990. Geotechnical Properties of Calcrete Soil (Gatch). *Engineering Geology*, 28: 191-204.

Al-Yaqout, A. and Townsend, F., 2004. Applicability of Calcite (Gatch) as Linear/Cover in Arid Climate Landfills: Laboratory and Field Permeability. *Practice Periodical of Hazardous, Toxic and Radioactive Waste Management*, 8(4): 238.

Balba, M.T., Al-Daher, R. and Al-Awadhi, N., 1998. Bioremediation of Oil-Contaminated Desert Soil: The Kuwait Experience. *Environment International*, 24(1/2): 163-173.

Banat, K.M., Howari, F.M. and Kadi, K.A., 2005. Water Chemical Characteristics of the Red Sea Coastal Sabkhas and Associate Evaporite and Carbonate Minerals. *Journal of Coastal Research*, 21(5): 1068-1081.

Barker, C. and Bufarsan, A., 2001. Evaporative Losses from the Surfaces Oil lakes of Southern Kuwait. *Environmental Geosciences,* 8: 123-129.

Besharah, J., 1991. The Kuwait Oil Fields - Facts and Numbers. In: Al-Shatti, A.K.S. and Harrington, J.M. (Editors), Proceedings of an International Symposium, The Environmental and Health Impact of the Kuwaiti Oil Fires, The University of Birmingham, pp. 12-15.

Bufarsan, A., Barker, C., Wavrek, D.A. and Al-Sarawi, M., 2002. Compositional Changes Induced by Evaporation of Burgan Crude Oil Spilled into the Desert of Southern Kuwait. *Environmental Geosciences*, 9(1): 8-16.

Dhowian, A.W., 1991. Secondary Compression of Sabkha Saline Soils. *Engineering Geology*, 30(2): 155-169.

Elgibaly, A.M., 1999. Clean up of Oil-Contaminated Soils of Kuwaiti Oil lakes by Retorting. *Energy Source*, 21(6): 547-565.

Erol, A.O., 1989. Engineering Geological Considerations in a Salt-Dome Region Surrounded by Sabkha Sediments, Saudi Arabia. *Engineering Geology*, 26(3): 215-232.

Farwana, T.A. and Majidzadeh, K., 1988. An Investigation in the Use of Emulsified Asphalt in the Stabilisation of Sandy Sabkha, Proceedings of the 3rd International Road Federation Middle East Regional Meeting, Riyadh, Saudi Arabia, pp. 203-213.

GCI, Green Cross International, 1998. Legal, Economic and Scientific Perspectives, Background Paper for the 1st International Conference on Addressing Environmental Consequences of War. Environmental Law Institute, Washington, D.C.

Ghazali, F., Fatani, M.N.Y. and Khan, A.M., 1985. Geotechnical Properties of Sabkha Soils of Jeddah and Jaizan, Saudi Arabia, Proceedings of the 2nd Saudi Engineers, Dhahran, pp. 286-307.

Goudie, A.S., 1994. Keynote Lecture; Salt Attack on Buildings and Other Structures in Arid Land. In: P.G. Fookes and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Areas, Balkema, Rotterdam, London, pp. 15-28.

Husain, T., 1995. Kuwait Oil Fires, Regional Environmental Perspective. Pergamon Press Ltd., Oxford, UK.

Ismael, N.F., 1980. Compressive Strength of Soil Cement Mixes. Research Report, Project 790804, Civil Engineering Department, Kuwait University, Kuwait.

Ismael, N.F., 1993. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035, Washington, D. C.

Ismael, N.F. and Jeragh, A.M., 1986. Static Cone Tests and Settlement of Calcareous Desert Sands. *Canadian Geotechnical Journal*, 23: 297-303.

Ismael, N.F., Jeragh, A.M., Mollah, M.A. and Al-Khaldi, O., 1986-a. A Study of the Properties of Surface Soils in Kuwait. *Geotechnical Engineering*, 17: 67-87.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Ismael, N.F., Mollah, M.A. and Al-Khaldi, O., 1986. Geotechnical Properties of Cemented Soils in Kuwait. Australian Road Research, 16(2): 94-104.

James, A.N. and Little, A.L., 1994. Geotechnical Aspects of Sabkha at Jubail, Saudi Arabia. *Quarterly Journal of Engineering Geology*, 27(2): 83-121.

Juillie, Y. and Sherwood, D.E., 1983. Improvement of Sabkha Soils of the Arabian Gulf Coast, Improvement of Ground. Proceedings of the 8th European Conference on Soil Mechanic and Foundation Engineering, Helsinki, pp. 781-788.

Khalaf, F.I., Al-Kadi, A. and Al-Saleh, S., 1985. Mineralogical Composition and Potential Sources of Dust Fallout Deposits in Kuwait Northern Arabian Gulf. *Sedimentary Geology*, 42(3-4): 255-278.

Khalaf, F.I., Gharib, I.M. and Al-Hashash, M.Z., 1984. Types and Characteristics of Recent Surface Deposits of Kuwait Arabian Gulf. *Journal of Arid Environments*, 7(1): 9-33.

Khan, I.H. and Hasnain, S.I., 1981. Engineering Properties of Sabkha Soils in the Benghazi Plain and Construction Problems. *Engineering Geology*, 17(3): 173-183.

Khan, Z.H., AbuSeedo, F., Al-Besharah, J. and Salman, M., 1995. Improve of the Quality of Heavily Weathered Crude Oils. *Fuel*, 74(9): 1375-1995.

Koch, M. and El-Baz, F., 1998. Identifying the Effects of the Gulf War on the Geomorphic Features of Kuwait by Remote Sensing and GIS. *Photogrammetric Engineering and Remote Sensing*, 64(7): 739-747.

Kostreba, L., 1999. Oil Spill Remediation Efforts in the Middle East. International Restoration and Reclamation Review, University of Minnesota, Restoration Efforts, Asia and Africa, 4 (4.3), http://horticulture.coafes.umn.edu/vd/h5015/rrrmain.htm, 4.

Kwarteng, A.Y., 1998. Multi-Temporal Remote Sensing Data Analysis of Kuwait's Oil lakes. *Environment International*, 24: 121-137.

Kwarteng, A.Y., 1999. Remote Sensing Assessment of Oil lakes and Oil-Polluted Surfaces at the Greater Burgan Oil Field, Kuwait. *International Journal for Applied Earth Observation and Geoinformation*, 1(1): 36-47.

Kwarteng, A.Y., 2001. LandSat Thematic Mapper Assessment of Oil lakes and Oil-Contaminated Soils in Burgan Oil Field, Kuwait. *Contaminated Soil, Sediment, Water*: 52-56.

Massoud, M.S., Al-Sarawi, M. and Wahba, S.A., 2000. Variations in the Chemical Properties of Soils Contaminated with Oil lakes in the Greater Burgan Oil Fields, Kuwait. *Water, Air and Soil Pollution*, 118(3-4): 281-297.

Naifeng, H., 1994. Corrosiveness of the Arid Saline Soils. In: P.G. Fookes and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Areas, Balkema, Rotterdam, London, pp. 29-34.

Nicolson, G.L., 1998. Report from Kuwait: Gulf War Illness Strike Civilians and Veterans of the 1991 Gulf War, Health Freedom News.

PEC, Petroleum Energy Centre, 1999. Survey of Technology for Remediation of Oil-Contaminated Soil in Kuwait, http://www.pecj.or.jp/japanese/report/report02/report-pdf/99surv8-e.pdf.

Saeed, T., Al-Bloushi, A. and Al-Matrouk, A., 1995. Assessment of levels of Polycyclic Aromatic Hydrocarbons in the Oil from Kuwait Oil lakes. *Archives of Environmental Contamination and Toxicology*, 29: 45-51.

Saeed, T., Al-Hashash, H. and Al-Mutairi, N.M., 1998. Assessment of the Changes in the Chemical Composition of the Crude Oil Spilled in the Kuwait Desert After Weathering for Five Years. *Environment International*, 24(141-152).

Safar, M.I., 1980. Frequency of Dust in Day Time Summer in Kuwait. Meteorological Department, Directorate General of Civil Aviation, Climatological Section, State of Kuwait: 107.

Saleh, A., Al-Ruwaih, F., Al-Reda, A. and Gunatilaka, A., 1999. A Reconnaissance Study of a Clastic Coastal Sabkha in Northern Kuwait, Arabian Gulf. *Journal of Arid Environments*, 43(1): 1-19.

Shehata, W.M. and Amin, A.A., 1997. Geotechnical Hazards Associated with Desert Environment. *Natural Hazards*, 16(1): 81-95.

UNCED, 1992. Agenda 21, The Rio Declaration on Environment and Development, United Nations Conference on Environment and Development, Rio de Janeiro, Brazil.

WSSD, 2002. The Arab Declaration to the World Summit on Sustainable Development, World Summit on Sustainable Development, Johannesburg, South Africa.

Yechieli, Y. and Wood, W.W., 2002. Hydrogeologic Processes in Saline Systems: Playas, Sabkhas, and Saline Lake. *Earth-Science Reviews*, 58(3-4): 343-365.

Table 1.1. Estimate of oil-polluted land areas and soil volumes in Kuwait(Source: PEC,1999)

Oil field region	Oil polluted area (km^2)	Oil polluted soil volume (m^3)
Wafra	3.26	1,956,000
Burgan	25.6	14,520,000
Minagish	0.19	95,000
Umm Gudair	0.27	135,000
Raudhatain	12.28	2,456,000
Sabriya	6.85	3,082,5000
Bahra	0.68	408,000
Total	49.13	22,652,500

Figure 1.1. Map of the state of Kuwait (Source: http://wwp.greenwichmeantime.com/time-zone/asia/kuwait/map.htm)

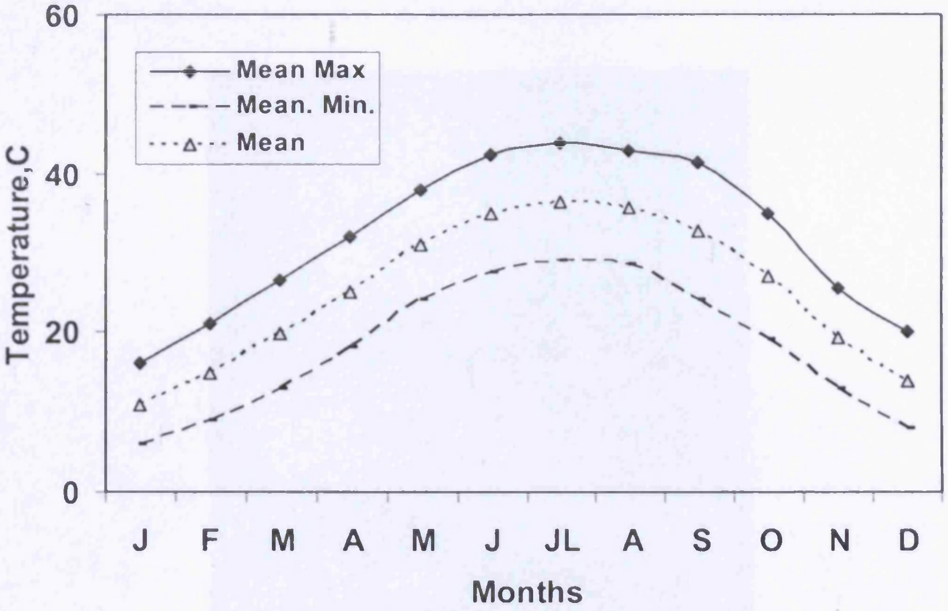

Figure 1.2. Temperature variations in Kuwait (Source: Safar, 1983)

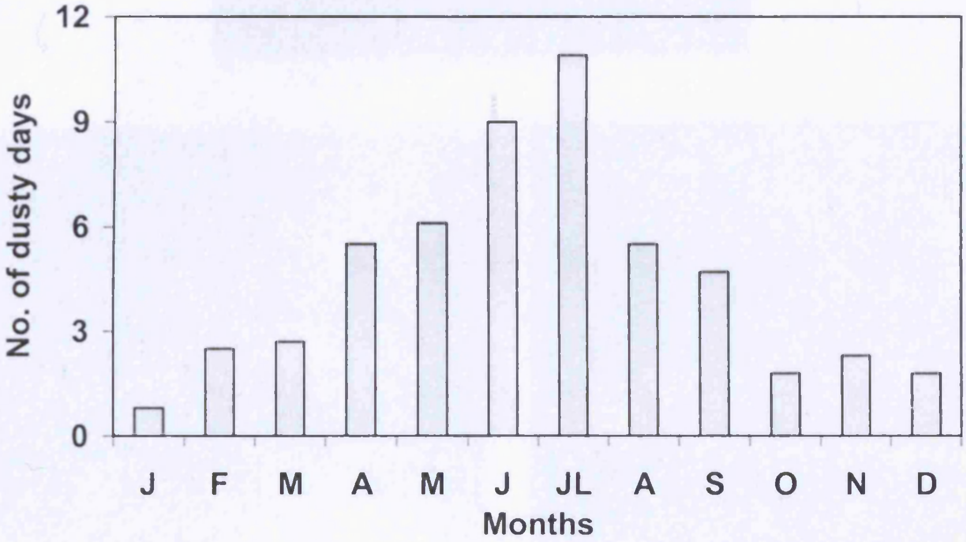

Figure 1.3. Sandstorm frequency in Kuwait (Source: Safar, 1983)

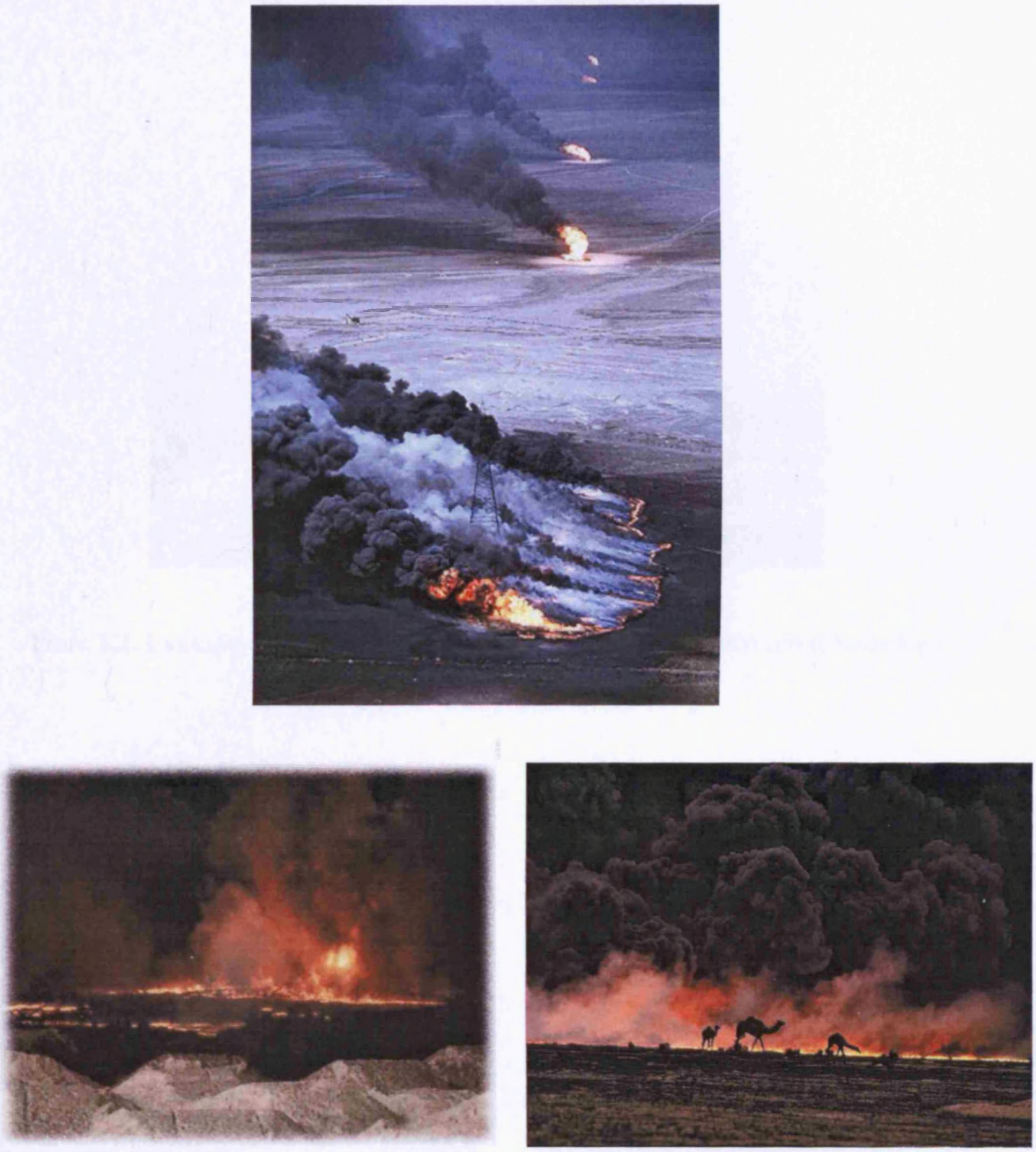

Plate 1.1. Oil well fires during the Gulf War (Sources http://www.sohoblues.com/GulfWarWeb/index.htm, http://www.nationalgeographic.com/ngm/100best/storyD_story.html)

Plate 1.2. Leaking oil well (Source: http://www.sohoblues.com/GulfWarWeb/index.htm)

Plate 1.3. Oil lakes in Kuwait (Sources: http://photos.orr.noaa.gov/gallery_4/incidents-24.htm and http://www.kritzberg.com/kuwait.htm)

Chapter 2

Literature Review

2.1 Introduction

This chapter presents information on the geotechnical properties of Sabkha soils and factors affecting these properties. It reviews methods used to modify the physical and geotechnical properties of Sabkha soils cited in previous studies and identifies their limitations. Due to sparse information on the properties of oil contaminated Sabkha soils, studies on other oil contaminated soil types will be reviewed.

Section 2.2 describes the geotechnical properties of Sabkha soils and factors affecting these properties, while Section 2.3 reviews different methods of Sabkha soil stabilisation and their limitations. Previous studies on oil-contaminated soils and their potential use in construction are discussed in section 2.4. This section also reviews uses of oil contaminated soil in Kuwait. Limitations of previous studies are presented in section 2.5. Section 2.6 summarises the foregoing review of the literature. Section 2.7 presents the approach adopted in this study to address some of the gaps identified in previous studies. A list of references is provided in Section 2.8.

2.2 Sabkha soils

Arid soils are those which have been conditioned by an arid environments in which there is an annual net moisture deficit (Atkinson, 1994). In such environment, there is continuous evaporation and the upward flux of groundwater results in the concentration and precipitation of some minerals in the uppermost part of Sabkha flats (Yechieli and Wood, 2002). Several site investigations have indicated that Sabkhas vary in horizontal (lateral) and vertical directions in terms of textural characteristics, chemical and mineralogical compositions, and the chemistry of the interstitial brine (Al-Hurban and

Gharib, 2004; Al-Sanad, 1986; Livneh et al., 1998; Sabtan and Shehata, 2002; 2003; and Saleh et al., 1999). Horizontal variations are related to the proximity to the shoreline (Akili and Torrance, 1981), while vertical variations are due to the repeated drying of inundation waters rich in dissolved salts (Livneh et al., 1998; Yechieli and Wood, 2002). Horizontal and vertical variations, in addition to the presence of highly concentrated brines, are distinguishing features of Sabkha soils that can lead to highly variable geotechnical properties (Al-Amoudi et al., 1991, and Shehata et al., 1990) and excessive settlement (Akili and Torrance, 1981). The occurrence of surface crusts of salts, carbonates and other minerals is an indication of a potentially unstable and collapsible soil structure (Rogers et al., 1994).

Sabkha flats in most Arabian Gulf countries have been left undeveloped due to their problematic characteristics. The dissolution of cementing materials (gypsum, carbonates, and halite) due to inundation of Sabkha flats with water can significantly affect the geotechnical properties of these flats and create serious problems for the structures built on them (Al-Amoudi et al., 1992-a).

Geotechnical properties that are considered when analysing Sabkha soil behaviours are strength, compressibility characteristics, hydraulic conductivity and collapse potential (Al-Amoudi & Abduljauwad, 1994-a; 1995-b; and Al-Amoudi et al., 1992-b). These geotechnical properties can be influenced by several parameters, such as moisture content, soil type, fines content, salt type and content.

2.2.1 Moisture content

Variation in soil moisture in Sabkha flats may result from changes in climatic conditions, such as rainfall, and from fluctuation in the groundwater table due to tidal wave activity of the sea. In general, Sabkha flats are susceptible to flooding because of their flat topography, low elevation, gentle gradient and relatively low permeability (Sabtan and Shehata, 2002).

The presence of water in Sabkha soil is reported to cause the following: (1) swelling due to the transition of anhydrite to gypsum; (2) collapse due to dissolution of sodium chloride (Al-Amoudi and Abduljauwad, 1994-a; 1995-a; Al-Amoudi, 2002 and Al-Sanad, 1986), and (3) decrease in strength of the surface crust as a result of inundation and absorption of moisture by hygroscopic salts (Akili and Torrance, 1981). Experimental studies on Sabkha soil in Saudi Arabia undertaken by Al-Eesa and Hasan (1979) revealed that dry Sabkha soil has high strength, but, when wet, loses its shear strength and becomes impassable. Akili (1981) studied the influence of moisture content on the strength of some soil samples in the eastern part of Saudi Arabia. He concluded that the maximum California Bearing Ratio (CBR) value of the soil occurs just to the drier side of the optimum moisture content. Al-Amoudi et al. (1991) revealed a reduction in CBR values upon saturation, by as much as 50%. High reduction in CBR values in submerged samples was attributed to the dissolution effect of the cementing agents in the Sabkha matrix (Al-Amoudi and Abduljauwad, 1994b; and 1995-b). Moreover, long-term saturation results in the loss of all or most of the cementation component of strength (Ismael et al., 1986b).

Field soil testing, including unconfined compressive strength and CBR, was conducted by Livneh et al. (1998) on samples at natural moisture conditions and after saturation. Results of these tests revealed that strength values were found to depend on samples' density and the wetting condition.

Similar conclusions were reached by Al-Sanad and Shaqour (1987); Ismael (1993-b); Ismael et al. (1986a and 1986b) in their investigations of the effect of saturation on the geotechnical properties of cemented sands in Kuwait. Their results indicated that saturation or soaking causes a loss of the cementation component of strength and leads to some loss of shear strength and reduction in bearing capacity. These results were confirmed by another study conducted by Al-Sanad et al. (1990). Their study investigated the effect of changing groundwater level and infiltration on the strength of cemented soils in Kuwait. Results indicated a reduction in the CBR values and shear strength of the submerged soil samples.

Salt leaching potential depends on the amount of water passing through the soil and the rate of movement of that water (Huddleston, 1996). Continuous flow of water, either as a result of pumping during construction or as a result of pumping from sumps in basements infiltrated by water, may result in the washing out of fines or salts cementing the soil particles (Al-Bader, 1989). The effect of water leaching force on some geotechnical properties of collapsible soils from Kuwait was investigated by Ismael (1993a). Results indicated a reduction in soil shear strength and preconsolidation pressure and an increase in soil permeability and void ratio as a result of leaching. Leaching also increased the compressibility by 20% to 50% and was largely noticed in weak cemented specimens. These effects were mainly attributed to the salts' dissolution and softening of bonds.

The effect of the type of leaching water (distilled water and Sabkha brine) on the coefficient of permeability values of Sabkha soils was investigated by Al-Amoudi et al. (1992-a) using undisturbed Sabkha soil samples obtained from the Ras Al-Ghar area in Saudi Arabia. Results showed that the coefficient of permeability measured using distilled water was higher than that measured using Sabkha brine by as much as a factor of ten. The same trend was observed for both constant and variable head tests. The higher values of the coefficient of permeability with distilled water was attributed to salt dissolution which causes more channels to form, thus tending to increase the coefficient of permeability. Salt leaching due to test repetition has been observed by Al-Sanad and Al-Bader (1990), although they reported negligible changes in the permeability coefficient.

Conventional consolidation testing undertaken on surficial Sabkha soils found an insignificant effect when Sabkha specimens were flooded with either distilled water or Sabkha brine (Al-Amoudi et al., 1992-a). They attributed this to the profuse cementation and desiccation of surficial Sabkhas that could not be destroyed or disrupted (Hossain and Ali, 1988). Another very important point is that the water, whether distilled or Sabkha brine was not allowed to seep continuously through the specimens and therefore the collapse potential could not accurately be detected.

Al-Amoudi et al. (1992-a) results indicated no clear difference in the moisture-density curves when using either distilled water or Sabkha brine, although minute reduction in optimum moisture content was associated with Sabkha brine. In addition, results also showed an increase in the compacted soil strength to 370 % and 550% using distilled water and sabkha brine, respectively. The difference was attributed to the excessively high salt content in the brine.

2.2.2 Soil type and fines content

Sabkha soils have generally been viewed as having an unconsolidated, heterogeneous, layered or un-layered sedimentological framework, bathed in highly concentrated subsurface brines (Al-Amoudi and Abduljauwad, 1995-b). In general, the loose, low density, low strength, bulky structural arrangement and metastable fabric of Sabkha particles characterise these soils (Al-Amoudi, 1994). Individual sand particles are often coated by clay particles, carbonates, gypsum or soluble salts (Rogers et al., 1994). Permeability of Sabkha soil is largely controlled by the grain size and the presence of fissures and fine contents, where higher fines and clay contents reduce permeability (Atkinson, 1994 and Rogers et al., 1994).

Particle size analysis of Sabkha sediments from the Al-Khiran area (south Kuwait) revealed that gravel size grains were more pronounced in inland Sabkhas due to their location in desert areas, while clay size grains were found more in coastal Sabkhas (Al-Hurban and Gharib, 2004).

The ffect of soil type and fines content on the geotechnical properties of Sabkha was studied by Doshi and Gurguis (1983). Results of the comparison of the CBR values for Kuwait soils and other soils with the same AASHTO classification showed an appreciable variation. The authors attributed this variation to the soil type, since Kuwait's soils are generally calcareous in nature and contain gypsum and salts of magnesium and sodium in varying proportions (Bissada 1974). Qahwash (1989) reported a significant increase in soil strength, CBR values and a dramatic reduction in swelling and plasticity potential as the sand content in Sabkha soil increases.

Basma and Tuncer (1992) investigated the effect of soil type, compaction, water content, initial dry density and applied pressure on the collapse potential of Jordanian soil upon wetting. Their study also concluded that the collapse potential decreased with an increase in (1) the difference between the sand and clay percentage; (2) compaction moisture content; and (3) initial dry unit weight.

Highly compressible Sabkha soils consist mainly of soft, loose materials composed of soils varying from non-plastic silty, clayey fine sand to highly plastic organic clays and silts (Al-Shamrani and Dhowian, 1997). Further, these flats are characterised by long-term settlement problems due to high organic content which varies over a range from 3% to 8%. Al-Shamrani and Dhowian (1997) investigations indicated that the organic contents of sandy Sabkha were less than that of silty clay Sabkha and generally tended to decrease with depth.

2.2.3 Salts type and content

The occurrence of surface crusts consisting of gypsum, carbonates, chlorides and other minerals, indicates that the soil structure could be leached and therefore a potentially unstable, collapsible deposit may be encountered (Ismael and Mollah, 1998; Rogers et al., 1994). The observed behaviour of Sabkhas might be attributed to the interplay of salts dissolution; mainly NaCl, Ca^{2+} leaching and soil grain adjustment. In addition, these salts can lead to highly variable geotechnical properties of Sabkha soils (Al-Amoudi et al., 1992-a; Al-Amoudi and Abduljauwad, 1995-b).

A field study on Sabkha soil carried out by Livench et al. (1998) revealed that the dissolved salts in the tested area were NaCl, $MgCl_2$, and $MgSO_4$. The water enriched with such dissolved salts rose up from groundwater level to the upper soil layer. These salts were deposited due to the arid local climate.

Al-Nouri and Saleam (1994) concluded that the compressibility index of Sabkha soil decreased with an increase in the gypsum content due to increase in the cementation action of gypsum. The authors noted that leaching of such soil increased its compressibility index due to reduction in the cementation action of gypsum. However, gypsum, which represents a high percentage of Sabkha composition, is unstable and at high temperature dehydrates to form anhydrite (Al-Amoudi & Abduljauwad, 1995-a and Ismael, 1993-b). When soil gets waterlogged in these regions, the generally dense structure of the salty soils and clays prohibits drainage, making it difficult to treat these soils effectively (Rogers et al., 1994).

Al-Sanad et al. (1989) investigated the influence of cementation on the engineering properties of clean uniform sand. They showed that the cone penetration resistance, soil cohesion, and friction angle increase with the increase in salt content. In a following study, the effect of salt types was investigated by Al-Sanad et al. (1990). In this study samples were prepared with different percentages of chlorides, calcium carbonate and calcium sulphate. Results revealed that cementation by various salts provided an increase in shear strength parameters (cohesion and angle of friction). Tests on dry cemented sand, with 2% by weight of calcium sulphate (gypsum) showed an even higher increase in strength to a factor of 4.4 over uncemented sand and almost double that for halite cemented samples.

The relationship between salt dissolution and soil permeability was investigated by Al-Amoudi and Abduljauwad (1995-a). This study revealed that the amount of flow, and consequently the permeability of Sabkha, correlated very well with the concentration of sodium and chloride ions; and as these ions reduced after the initial two days to very small amounts, the rate of flow reduction was also significantly reduced. This phenomenon of chloride dissolution was also investigated by Ismael (1993-b) using leaching tests on similar salt-bearing soils in Kuwait. Ismael also concluded that the influence of leaching is proportional to the amount of soluble salts removed due to leaching.

2.2.4 Corrosive effect of Sabkha soil

Corrosive action caused by the salinity of Sabkha soil and groundwater is one of the main hazards associated with construction on Sabkha soils (Sabtan and Shehata. 2002). Sabkha flats contain different types of salts, such as sulphate and chlorides, which make these flats aggressive to concrete and steel structures and cause physical and chemical corrosion failure (Ismael, 1993-b and Jeragh and Ismael, 1984). The corrosiveness of saline soils containing chlorides is manifested by corrosions occurring to metal structures, pipe lines and reinforcing bars. In addition, change in volume of chloride can be produced by the crystallisation and crystal changes of the chloride, leading to expansive failures of mortar, concrete and clay bricks (Naifeng, 1994). Sulphate attack on cement stabiliser, due to high gypsum content in the soil (Al-Sanad and Bindra, 1984), is manifested by the reaction of sulphate with the hydration products of the cement that results in the production of continuous chemical expansion and corrosion. This chemical expansion could cause serious damages to structures built with cement-based materials (Naifeng, 1994). In Kuwait, the hot climate and high humidity could accelerate deterioration and corrosion of reinforced concrete foundations built on Sabkha soils (Jeragh and Ismael, 1984). In general, the high sulphate and chloride contents of both soils and the shallow groundwater pose severe corrosion hazards for the foundations of any engineering structures and the subsurface utilities built on Sabkha (Sabtan and Shehata, 2002).

Due to the high concentrations of chloride-sulphate salts existing in Sabkha soils and groundwater, the use of conventional concrete has resulted in many deterioration problems in substructures placed in Sabkha environments (Al-Amoudi et al., 1992-b).

2.3 Sabkha soil stabilisation

Previous studies presented in Section (2.8) pointed out that Sabkha soils, in their natural conditions, can be considered non-suitable materials for construction. These Sabkhas are known for their low-bearing strength (Al-Amoudi, 2002; Al-Shamrani and Dhowian, 1997), high susceptibility to collapse (Al-Amoudi and Abduljauwad, 1994-a and 1995-b), high corrosiveness to concrete and reinforcement (Ismael, 1993-b; Jeragh and Ismael, 1984), high permeability under leaching (Al-Amoudi et al., 1992-a) and high volume changes (Ismael, 1993-b). Common practice during construction on Sabkha soil flats is to excavate Sabkha soils and replace them with superior materials. Another possible way to use Sabkha soils for construction purposes is to stabilise them. Different stabilisation methods have been implemented to improve their physical and geotechnical properties, with varying degrees of success (Akili, 1981 and Juillie and Sherwood, 1983)

Soil stabilisation is a process designed to modify the physical and/or geotechnical properties of soils to meet specific engineering requirements and to maintain the soils' stability (Arora, 1997). The major physical and geotechnical properties to be treated include density, permeability, volume stability, strength and durability (Stavridakis, 2005). Soil stabilisation may be used to increase the bearing capacity and the shear strength and to reduce the permeability and the compressibility of the soil mass (Arora, 1997). Stabilisation can be viewed as a modification treatment and a preventive step against adverse conditions (Ingles and Metcalf, 1972), and by stabilising Sabkha soil to a reasonable standard, it can be used as a construction material.

Choice of a suitable stabilisation method depends on many factors, including: type of soil to be stabilised, type and purpose for which the stabilised layer is to be used, degree of modification, economic and environmental considerations, construction and design period, and availability of materials (DANA, 1994).

Soil stabilisation can be divided into two main categories: mechanical/physical and chemical. Mechanical stabilisation is the process of changing mechanical properties such as density, strength, compressibility characteristics and permeability. Physical stabilisation is the process of modifying a soil's properties by changing its gradation or texture. On the other hand, chemical stabilisation is the process of adding different material which results in a physico-chemical reaction or formation of a physical bonding between soil particles to modify the unfavourable geotechnical properties.

2.3.1 Mechanical and physical stabilisation

Mechanical and physical stabilisation include compaction, mixing soils of two or more gradations and using fibrous and other non-biodegradable reinforcing of geo-materials to improve strength (Das, 2003). Stabilisation techniques implemented to improve the Sabkha in the Gulf region include soil replacement, vibratory compaction, deep soil densification, stone columns and dynamic compaction (Al-Amoudi, 1995-a).

2.3.1.1 Compaction

Compaction is the most commonly used method of ground modification to reduce compressibility, reduce permeability, increase shear strength and control volume change (Hausmaun, 1990). Vibratory and impact compactors, which are used to densify the soil layer, are not effective with soils that contain high percentage of fines.

Mechanical improvement of soft ground soils has been successfully performed by techniques such as vertical strip drains with surcharging (USEPA, 1996). Vertical strip drains are used to consolidate degraded fill and soft foundation soils. This method has been used to modify bearing capacity, shear strength and consolidation characteristics to produce sufficient preconsolidation with respect to the final permanent structure load. Experience with construction on Sabkha soils has shown the ability of mechanical stabilisation to densify soil with low shell contents (Juillie and Sherwood, 1983), and the precompression method is an effective technique for eliminating primary consolidation settlements and reducing secondary compression of Sabkha sediments (Al-Shamrani and Dhowian, 1997). Improvement of Sabkha soil at a site in Saudi Arabia was performed by preloading and dynamic compaction (Swan, 2003). Vibroflotation has been used in Saudi Arabia to densify some Sabkha soils to increase the bearing capacity of highway bridges' foundations (Al-Sanad and Bindra, 1984). However, cemented Sabkha layers with varying thickness, due to cementing agents such as calcium carbonates and gypsum, have shown a marked increase in static penetration resistance (Akili and Torrance, 1981), which may create difficulties in compacting deep soils.

The different compaction methods of mechanical stabilisation may have a few limitations in their application to Sabkha soil stabilisation. These limitations may be attributed to the climatic conditions and to the problematic nature of the Sabkha soil. A major problem encountered in road construction in arid areas is the provision of water for soil compaction and to achieve the maximum dry density by compacting the soil at its optimum moisture content. In addition to that and due to the high evaporation rate during and after compaction it is difficult to maintain the required moisture content and achieve the required compaction (Newill and Connell, 1994).

Different mechanical methods for Sabkha soil stabilisation, which densify the soil by packing the particles closer together, may result in an increase in the bearing capacity of the Sabkha soil at the time of finishing the job. Since Sabkha soils contain appreciable amounts of different types of salts, compacted Sabkha layers are very sensitive to moisture so that complete collapse and a considerable reduction in the bearing capacity are anticipated when these soils come into contact with water (Al-Amoudi et al., 1992-a; Ismael, 1993-b; Abduljauwad and Al-Amoudi, 1995). High concentrations of salts in the Sabkha soil and the presence of clay prohibit drainage, making it difficult to treat these soils effectively (Rogers, 1994). The other important parameter in deep densification stabilisation is that it requires special technical expertise and large-scale sophisticated equipment (Al-Amoudi, 1994).

2.3.1.2 Geotextiles

The other mechanical stabilisation method that may have potential application in improving the engineering performance of Sabkha soils is the use of geotextiles (Aiban and Ali, 2001; Fatani et al., 1991; and Aiban et al., 2006). The main usage of different geosynthetic materials in different positions within the road layers is to create impermeable membranes, drainage layer or subgrade support (Newill and Connel, 1994).

An investigation carried out by Aiban et al. (2006) to assess the effect of geotextiles on the performance of Sabkha soil found that Sabkha soils displayed a significant improvement in load-carrying capacity when stabilised with geotextiles. The improvement was much higher in soaked conditions. They also reported that that the effectiveness of the geotextiles in reducing permanent deformation diminished as the thickness of the base layer increased. In north Kuwait, geosynthetic materials were used in constructing a project within a tidal area on very soft marine silts and clay. Usage of the geotextiles increased the bearing capacity of the subgrade and decreased the required thickness of the improved fill materials without compromising the long term performance (Tenax, 2004). Geotextile fabric, as an earth reinforcing material, is considered to have potential in solving problems in road constructions projects over Sabkha soils in Saudi Arabia (Al-Eesa and Hasan, 1979). The advantage of using geotextile fabric is in reducing the stresses and strains reaching the underlying soft Sabkha. The fabric acts as a separator thus eliminating the problem of fill penetration into Sabkha.

This author has observed during the construction of some roads in Kuwait many difficulties in laying geotextiles on highly unstable Sabkha. In addition, geotextile fabric is used as an earth reinforcing and insulating material between Sabkha soils and the new fill material above it and not as a material to stabilise the Sabkha soil.

Previous research and experiments performed on Sabkha soils have demonstrated the use of geotextile as an efficient and cost effective solution for some types of construction on Sabkha soils, however, no long-term records are available for Sabkha soil stabilisation by this method (Al-Amoudi, 1994). Aiban et al. (2006) have reported an improvement in the load carrying capacity of Sabkha soils due to the inclusion of geotextiles almost similar to that achieved by adding 6.5% of Portland cement.

2.3.1.3 Soil blending

Soil stabilisation can also be accomplished by mixing or blending soils of two or more gradations suitably to obtain a material that meets the required specification (DANA, 1994). Fine-grained base and subbase materials with excessive plasticity may be improved by the addition of non-plastic coarse fractions (Hausman, 1990).

Kuwait's soil profile consists of surface layers of windblown deposits that comprise fine calcareous sands and become denser with depth (Ismael and Jeragh, 1986). Several studies on the properties of these soils have revealed that the strength is so low that the use of raft foundations is preferred to strip foundations, even for light load structures (Ismael et al., 1986a). Several construction projects carried out at different locations in Kuwait by the Ministry of Defence have been preceded by stabilising the soil by mixing it with coarser soil (MOD, 1996 and 1997). Different mix trials were carried out in the laboratory before the commencement of construction to select the mix proportion that would improve the particle size distribution, increase the density and other geotechnical properties of the mixture so that the final approved mix design met the requirements of the relevant standard. In these projects, the bearing capacity of the soil was modified by soil blending which also reduced the cost of the project by a considerable amount.

Soil blending is not suitable for stabilising Sabkha soils, due to their high salts content. Sabkha soils, as stated earlier, loses its strength upon wetting.

2.3.2 Chemical stabilisation

Chemical stabilisation, which is the alternative to mechanical stabilisation due to economical and technical reasons, has many applications in road construction, backfilling, paving slopes, embankment protection, pipe bedding, etc. (Al-Amoudi and Asi, 1991; and Ismael, 1984). Stabilisation admixtures that are used in chemical stabilisation include: lime, cement and bitumen (Al-Abdul Wahhab and Asi, 1997; Al-Amoudi 1994; 2002; Asi et al., 2002 and Terrel et al., 1984). Chemical stabilisation has been used to modify the strength and consolidation characteristics of Sabkha soils in many construction projects in the Gulf area.

2.3.2.1 Lime stabilisation

Lime is used in the form of quicklime, or hydrated lime and primarily used in the modification of clayey soils to improve workability and increase strength and volume stability (Hausmaun, 1990). Treatment of soils with lime has brought many beneficial effects, such as improvements in the plasticity characteristics and strength behaviour with time (Kamon, 1992; Narasimha Rao and Rajasekaran, 1996). Bell (1996) found that many important engineering properties of clay soils were enhanced by the addition of lime. He stated that the properties of such soil-lime mixtures vary and depend upon the characteristics of the soil, the type and length of curing, and the method and quality of construction. He also noticed that the plastic limit of clay soils increases considerably with lime addition while that of fine quartz does not change significantly with lime addition. It is also well established that the use of lime in fine grained soils makes the system less sensitive to change in stress (Kamon and Nontananandh, 1991).

Sharif (1991) studied the effect of organic materials in Jordanian clay on lime stabilisation. He concluded that the addition of 3% to 6 % of lime, by weight of dry soil, reduces plasticity of the soil and increases the unconfined compressive strength and California Bearing Ratio (CBR) considerably, even when the soil contains organic materials.

In Kuwait, the presence of fines in crushed cemented sand can be treated by the addition of 5% of hydrated lime. Ismael et al. (1990) concluded that this approach is effective in limiting volume changes to a negligible amount.

High sulphate concentration in Kuwait soil (Jeragh and Ismael, 1984) may affect the engineering properties of lime stabilised soil. The extent to which it is affected depends on sulphate concentration, amount and type of lime added, particle size of the soil, temperature and humidity, and the reaction between sulphates and stabilised lime. This reaction results in a large volume change which can lead to pavement failure (Hunter, 1988 and Mitchell, 1986).

Experimental investigation revealed the effect of cyclic wetting and drying on the swelling behaviour of lime treated soils. Results with lime-treated specimens indicated that the beneficiary effect of lime stabilisation is partially lost after four cycles of wetting and drying. These four cycles lead to a partial breakdown of the cemented aggregates which, in turn, increases the clay content causing changes in engineering properties (Rao et al., 2001). To the best of the author's knowledge, this method of stabilisation is not commonly used in Kuwait.

2.3.2.2 Cement stabilisation

Stabilisation of soil with cement has been extensively used for coarse-grained soil, (Ismael, 1984). Most types of soils, with the exception of soil with high organic content, may be treated with cement and will exhibit an improvement in properties (Ingles and Metcalf 1972). The quantity of cement required for stabilising fine grained soil is more than that required for coarse grained, due to its high specific surface area. Heavy clays are usually stabilised after pre-treatment with 2-3% cement or hydrated lime for a few days in order to reduce the plasticity and render the soil more workable (Ingles and Metcalf 1972).

Experimental investigations have indicated that cement improves the performance of stabilised Sabkha much more than lime at high moisture contents (Al-Amoudi, 2002). Several investigators (Ismael, 1984; and Al-Amoudi, 2002) have found that the amount of cement needed to satisfy strength requirements, so that Sabkha soil can be used as a base course in rigid pavement, ranges between 5% and 10%.

The presence of sulphates in large concentrations in Kuwait's soils, especially in areas close to the shoreline (Jeragh and Ismael, 1984), have significant effects on cement stabilised soil, where the use of cement for fine-grade soils containing more than about one per cent of sulphate should be avoided (DANA, 1994). Juillie and Sherwood (1993) concluded that the adverse effect of sulphates is due to the reaction with the clay content of the soil. He also added that use of sulphate resisting cement is of little value. Moreover, sulphate attack on cement-stabilised soils is highly destructive and that cement stabilised techniques for soils should be carefully approached in a sulphate enriched environment (Rajasekaran, 2005).

The possible delay of compaction during field construction of cement stabilised soil layers coupled with high temperature in arid areas are major causes of loss in strength (West,

1959) of these soils. Cement stabilisation is expensive for desert soils due to high cement requirements and shortage of water (Al-Sanad and Bindra, 1984).

2.3.2.3 Bituminous stabilisation

Bitumen is a product obtained from processing the residues that remain after the distillation or evaporation of crude petroleum (Hausman, 1990). The bituminous stabilisation technique is widely used for sub-base and base road layer construction. Bituminous stabilisation can be used in some cases where lime or cement is not applicable (Al-Homoud et al., 1996).

Bituminous stabilisation is generally accomplished using asphalt cement, cutback asphalt, or asphalt emulsions. The type of bitumen to be used depends upon the type of soil to be stabilised, methods of construction, and weather conditions (DANA, 1994). Soils most suitable for bituminous stabilisations are sandy gravels and fine crushed rock; but even highly plastic clays can be treated successfully using this method. However, higher quantities of bitumen may be required for plastic clays (Hausmaun, 1990).

Bituminous stabilisation studies on clayey sand undertaken by Kedzi (1974) and Ingles and Metcalf (1972) concluded that: (1) the maximum dry density, achieved with a constant compaction effort, falls as the bitumen content increases; (2) the optimum amount of water necessary to reach maximum density decreases with the increase in bitumen content; (3) the unconfined compressive strength initially increases with the increase in bitumen content until the maximum mechanical stability is reached, beyond which a reduction in the strength is recorded; (4) the adsorption of water, due to soaking, leads to a reduction in soil strength. The reduction in the dry density of stabilised soil with bitumen content was attributed to the fact that bitumen films surrounding the soil particles have high viscosity, resulting in an increased resistance by the mixture to the compaction (Basma et al., 1994). The degree of water absorption and corresponding loss of strength as a function of the soaking period was also reported by Giffen et al. (1978). They reported reduction in water absorption with the amount of stabiliser. However, the amount of water absorbed is reported to increase with the period of soaking.

A study on bituminous stabilisation of silty sand (Ola, 1978) reported an increase in the mixing dry density, bearing capacity (CBR) and unconfined compressive strength of the sand-bitumen mixture up to a bitumen content of 3%. Ola also reported that any further increase in bitumen might result in lower strength. Ingles and Metcalf (1972) attributed the reduction in strength to two opposing mechanisms: (1) the thinner the bitumen film the stronger the stabilised soil and (2) the thick films that fill the pores and prevent the ingress of water. Basma et al. (1994) concluded that the loss of strength at high level of bitumen content may be due to lubrication of the particles preventing interlocking. This may also be attributed to the decrease in unit weight due to the resistance of the mixture to compaction that in-turn offsets the increase in strength.

The basic mechanisms involved in bituminous stabilisation of fine-grained soils are the waterproofing phenomenon and adhesion effect (DANA, 1994; and Ingles and Metcalf, 1972). Sections of bitumen-treated heavy clays have shown that the bitumen is far from being uniformly distributed but exists as distinct patches with areas of apparently unmixed clay in between; even where quite marked improvements in strength and water absorption have been measured (Ingles and Metcalf 1972). Waterproofing may occur by coating the surface of particles or aggregated lumps of particles, or by blocking the pores of the soil mass. This reduces water absorption (Hausmann, 1990) and prevents or slows the penetration of water which normally results in a decrease in soil strength (DANA, 1994). The presence of salts in the Sabkha matrix makes the wetting process of these materials a critical factor (Livneh et al., 1998). Due to the viscosity of the bituminous materials, the coating layer around soil particles acts as a binder or cement, which increases shear strength by increasing cohesion (DANA, 1994; and Asi et al., 2002).

Foamed asphalt technology has increasingly gained acceptance as an effective and economical soil improvement and stabilising technique, mainly because of its improved aggregate penetration, coating capabilities and handling and compaction characteristics (Asi et al., 2002). A properly designed foamed asphalt-Sabkha soils mixture displayed significant improvement in strength properties (Asi, 2001). However, the strength properties of the foamed asphalt stabilised soil followed the same pattern as that of bitumen stabilisation; the strength increased with the asphalt content up to an optimum level, and upon further addition, it started to decrease.

Application methods and types of additives in bituminous stabilisation have an effect on the properties of stabilised Sabkha soils (Asi, 2001; Asi et al., 2002; Al-Abdul Wahhab and Asi, 1997; and Al-Amoudi et al., 1995). An investigation was carried out to stabilise weak soils in Saudi Arabia using emulsified and cutback asphalt with cement and lime as admixtures (Al-Abdul Wahhab and Asi, 1997). The investigation revealed that both additives tend to modify the gradation of the treated soil and improve the shear strength and resistance to water damage. Cut back asphalt (MC-70) causes higher reduction in swell potential than cement and lower reduction than lime (Al-Homoud, 1996). A study by Ali & Youssef (1981) to determine the type and quantity of stabilisers suitable for silty soils, which dominate the surface geology of Saudi Arabia, showed that the addition of bitumen with economic quantities of 3% to 5 % did not improve the density of the mixture. However, about 8% of bitumen was reported to increase density.

The mechanisms of stabilisation with bituminous materials consist of adding cohesive strength and reducing water penetration by the physical presence of bitumen (Ingles and Metcalf, 1972). These properties are expected to make bituminous stabilisation effective for the Sabkha treatment, since the presence of salts in Sabkha matrix makes the wetting process of these materials a critical factor (Livneh et al., 1998). Waterproofing reduces the water absorption and hence reduces the dissolution of different types of salts and increases the stability of the soil structure. The cohesion property of the stabilised Sabkha is expected to increase the binding between soil particles due to the viscous coating bitumen layer. However, the effectiveness of bitumen in imparting cohesion and waterproofing depends on the nature of soil and the salts contents. On the other hand, bitumen is not as common as other major stabilisers, mainly because of its relatively high cost, conventional heavy and costly hot-mix equipment, and the considerable expertise required in its application (Hausmann, 1990; Ingles & Metcalf, 1972; and Al-Homoud et al., 1996).

2.4 Oil-contaminated soils

Oil contaminated soil is an earthen material or artificial fill that has human or natural alteration of its physical, chemical, biological or radiological integrity resulting from the introduction of crude oil, fraction or derivative thereof (such as gasoline, diesel, or motor oil) or oil-based product (CDPHE, 2003). Soil contamination commonly occurs when petroleum storage or/and handling systems leak and fuel spills contaminate surrounding soils (SERM, 1995).

As an introduction to investigating the possibility of using oil lake residue in stabilising Sabkha soils, its effect on their properties should be examined. Since previous studies on contaminated Sabkha soils are limited, other contaminated soil investigations will be presented in this section. Most studies in this field have been undertaken to investigate the migration of the contaminants, dissolution and bonding characteristics, and to propose suitable remediation methods.

Oil contaminated soils in Kuwait are the results of surface accidental spills that occur during petroleum production, storage or transportation (Bufarsan et al., 2002). These soils cause major environmental and geotechnical problems. The durability of oil contaminated soil as foundation material is one of the problems encountered by soil engineers (Al-Shakarji and Al-Rasool, 1999). Contaminated soils have attracted considerable attention for remediation and investigation of possible usages. The physical and mechanical properties of contaminated soils are affected by their contaminants, since contaminated soils show completely different behaviour from clean soil (Meegoda and Ratnaweera, 1995). Foundation failures and cracking of industrial buildings have been recorded in different locations where soil has been contaminated by oil (Shah et al., 2003; Shin et al., 1999; and Shroff, 1997). Several researchers (Al-Sanad et al., 1995; Evgin et al., 1989; Evgin and Das, 1992; Puri et al., 1994; and Singh et al., 2006) have studied the behaviour of oil-contaminated soils in recent years using different types of petroleum products mixed with different types of soil. Variations in these properties have been investigated by comparing differences in the behaviour between contaminated and clean soils.

The main physical and geotechnical properties that will be discussed in this section are grain size distribution, specific gravity, consistency limits, compaction parameters, compressibility characteristics, strength characteristics and hydraulic conductivity.

2.4.1 Particle size distribution

Meegoda and Ratnaweera (1995) found experimentally that oil addition of 3% and 6% to clay soil reduced clay fraction from 96% to 87% and 87% to 84%, respectively, indicating an increase in soil aggregation with oil addition. The effect of oil contamination on the gradation of alluvial soil was investigated by Srivastava and Pandey (1998). An increase in particle size because of coating by oil was observed. A recent study carried out by Caravaca and Roldan (2003) to assess changes in the physical properties of contaminated clay loam sand by oil sludge revealed a variation in soil gradation. The clay and silt contents decreased from 33.3% and 21.7% to 21.3% and 20.5%, respectively, while the sand content increased from 45% to 58%. This change in the constituent content altered the classification of the soil from clay loam to sandy clay loam. However, Andrade et al. (2004) observed that oil addition did not alter the particle size distribution of the contaminated soil.

Due to the viscosity of oil, oil contaminated soils tend to get aggregated due to the suction pressures caused by the surface tension between the oil and water (Meegoda and Ratnaweera, 1995). Aggregation behaviour is more pronounced for soil size up to silt size (Srivastava and Pandey, 1998). When a sufficient amount of oil coats the surfaces of soil particles, aggregates smaller than 2μm will become glued together, forming dense agglomerates of larger size (Karimi and Gray, 2000). The changes in fine contents have been attributed by (Caravaca and Roldan, 2003) to the adsorption of hydrocarbons onto soil minerals colloids which modify their rate of sedimentation.

Field and experimental investigations on oil-contaminated soils in Kuwait have demonstrated the formation of soil grain aggregation due to oil contamination (Al-Houty et al., 1993). This supports Meegoda and Ratnaweera's, (1995) conclusion that a clay soil acts as a granular soil without plasticity.

Balba et al. (1998) stated that most contaminated soil has a dark brown colour and oily and sticky texture, since the oil generally acts as a bonding agent when mixed with non-cohesive granular soil (Winterkon1975). Several researchers have concluded that standard tests developed for the identification and classification of soils should not be used to identify and classify contaminated soils, since fine-grained oil-contaminated soils are often identified and classified as granular soils with large particle sizes and this classification may result in the selection of inappropriate treatment techniques (Balba et al. 1998 and Meegoda and Ratnaweera, 1995).

2.4.2 Specific gravity

Due to the lower specific gravity of oil, adsorbed hydrocarbons on soil particles will reduce the specific gravity of contaminated soil (Tarefder et al., 2003). Similar results were obtained by Srivastava and Pandey (1998) during their investigation of different soils, where they found experimentally that the specific gravity of tested soil samples decreased with oil addition.

2.4.3 Consistency limits

Consistency limits of oil contaminated soil are expected to be affected by the addition of a polar compound (Arora, 1997 and Winterkorn, 1975). Meegoda and Ratnaweera (1995) during their investigation of clay soil with different plasticity values and silty sands noted that the plasticity index (PI) and plasticity increase with the increase of oil content up to a certain value and then decrease with the increase of oil content. Srivastava and Pandey (1998) reported that the liquid limit and plasticity index of alluvial soil increase with the increase of oil content in the mix while the plastic limit and shrinkage limit decrease with oil content. Shah et al. (2003) noticed that fuel-oil contamination caused significant change in the consistency limits of contaminated soils. This was indicated by the conspicuous increase of the liquid limit (11%), plastic limit (34%) and decrease in the plasticity index. They also observed that the contaminated soil exhibited a wide range of liquid limits (41-46.5%), and attributed this to inhomogeneous distribution of non-polar liquid (fuel oil) to soil.

Attom and Al-Sharif (1998) attributed the reduction in the PI of clayey and silty sands to the addition of non-plastic material to the soil. The non-plastic material reduced the plasticity index of the new mixture. On the other hand, the increase in LL and PL limits of contaminated clayey soils is mainly attributed to the increase in the double layer thickness of clay minerals (Shah et al., 2003). In general, contaminants may alter the mechanics of the consistency limits test when used for contaminated soils. The consistency limits test was originally developed for the natural soil-water system (Meegoda and Ratnaweera, 1994).

2.4.4 Compaction

The compaction parameters, namely, maximum dry density and optimum moisture content, are affected by different types of oil contaminants (Attom and Al-Sharif, 1998; Srivastava and Pandey, 1998). The density curves for oil-contaminated soil displayed a similar trend to that of natural soil in that the dry density of the oil contaminated soil starts to increase with moisture content up to a maximum value and then it starts to decrease with further increase in the moisture content (Aiban, 1998).

In a study conducted by (Al-Sanad et al., 1995) on contaminated sandy soils, the maximum dry density increased from 1.9 g/cm^3 for natural soil to 1.94 g/cm^3 at 4% crude oil content, and decreased to 1.83 g/cm^3 at 6% oil addition. Similarly, in a recent experimental study carried out by Al-Rawas et al. (2005) on petroleum contaminated soil, shows that the oil contaminated soil exhibited a maximum dry density of 1.97 g/cm^3, whereas the natural soil showed a lower dry density of 1.722 g/cm^3. Evgin et al. (1989) found experimentally that oil is more effective in reducing the friction between sand grains, thus helping them to occupy closer configurations resulting in higher dry unit weight. Shah et al. (2003) investigated the effect of fuel oil contamination on the compaction parameters of contaminated soil. Results revealed a reduction in the maximum dry density of the contaminated soil which supported previous findings where the percentage of contamination ranged from 7% to 10%. Field observations have revealed that contaminated areas exhibit a compacted crust with significantly lower porosity (Andrade et al., 2004).

Al-Sanad et al. (1995) noted a reduction in the optimum moisture content (OMC) value with oil addition. In their experimental investigations, the OMC decreased from 12% for natural soil to 7.5% and 6.9% at crude oil contents of 4% and 8%, respectively. Similarly, the optimum moisture content for clayey soil reduced due to petroleum contaminant from 14.8% for natural soil to 11.8% for 10% contaminated soil. The reduction in optimum moisture content value at different oil percentages has been mainly attributed to the lubrication effect of the oil which reduces the friction between the soil grains (Evgin et al., 1989). The reduction in the friction facilitates the sliding of soil grains relative to each other into more compact configurations leading to higher densities at lower moisture content (Al-Sanad et al., 1995). Similar findings were obtained by Shah et al. (2003), who observed a reduction in optimum moisture content from 16.5% to 12.5% with 7% fuel oil contamination.

2.4.5 Strength characteristics

Several studies have been carried out on contaminated soils to investigate their stability and resistance to deformation (Al-Sanad et al., 1995; Evgin et al., 1989; Evgin and Das, 1992; Puri et al., 1994; and Singh et al., 2006). Most of these studies concentrated on the physical behaviour and geotechnical properties of contaminated soils. Naturally deposited tar sands, which are located at varying depths under overburden pressure were studied by Carrigy (1967) and Ola (1991). They reported that these deposits have lower strength than comparable clean sands with possible presence of the cohesion intercept. Strength related tests most often carried out in these studies are direct shear, triaxial, California Bearing Ratio (CBR) and unconfined compression tests.

2.4.5.1 Shear strength

Evgin and Das (1992) carried out triaxial tests on clean and oil-contaminated sand. They found that full saturation with motor oil caused a significant reduction in the friction angle of both loose and dense sands and a drastic increased of the volumetric strains. They also showed using finite-element analysis that settlement of footing increases due to oil contamination.

Several studies reported that the friction angles of different soils undergo a reduction when the soils become contaminated with oils (Shin et al., 1999, and Puri et al., 1994). Singh et al. (2006) found that angle of internal friction of gasoline contaminated clay decreased while the cohesion intercept increased.

In an investigation of oil contaminated sands in Kuwait, Al-Sanad et al. (1995) reported that the reduction in shear strength was dependent on the viscosity of the contaminant and was noticeable at all the tested relative density ranges. Their study on crude oil contaminated sand indicated that no cohesion intercept was obtained under different test conditions. Their findings contradict those of Al-Rawas et al. (2005) and Mohammed et al. (1995) who noted that the addition of 4% of oil residue to soil samples had the simultaneous effect of increasing the cohesion and slightly reducing the frictional resistance. Similarly, Al-Rawas et al. (2005) reported a reduction in the friction angle in an oil-contaminated soil from 61.9° to 46.1° and an increase in the cohesion intercept from 6 kN/m^2 for natural soil to $64kN/m^2$ due to oil addition. Similar results were achieved by Srivastava and Pandey (1998) in their experimental study on alluvial soils and sands from India, contaminated by petroleum products. They concluded that the reduction in shear strength of soils might lead to reduced bearing capacity and possible slope stability problems should construction in such contaminated soils be undertaken.

A reduction in shear strength of 23% to 27%, due to 1.3% oil addition, was recorded by Shin et al. (1999), and was attributed to the oil coating of soil grain surfaces which resulted in soil grains slipping over each other. Shah et al. (2003) reported that the shear strength parameters, angle of internal friction and cohesion intercept, were reduced from 18° and 58.84 kPa, to 16° and 19.69 kPa respectively, due to fuel oil contamination of 10%.

The cohesion of contaminated soil is expected to be affected by the increase and decrease in temperature due to changes in oil viscosity. At a low temperature high viscosity increases the cohesion and at high temperature low viscosity increases the distribution of oil around soil particles (Aiban, 1998). Al-Sanad and Ismael (1997) concluded that the strength and stiffness of oil contaminated sands increase with ageing and reduction in oil content.

The author of this thesis anticipated no contradiction with previous findings, where the friction angle of different types of soil reduced due to oil addition. On the other hand, oil addition is expected to increase the cohesion up to a certain oil percentage after which cohesion is expected to start to decrease with oil addition.

2.4.5.2 California Bearing Ratio (CBR)

The soil bearing capacity of oil contaminated soils, as measured by the California Bearing Ratio test, will probably be affected due to oil contamination. In an investigation of oil contaminated sands in Kuwait, Al-Sanad et al. (1995) found the CBR values of sands increased by about 25% with the addition of up to 4% oil content. However, with a further oil addition content of up to 6%, a dramatic drop in the CBR values occurred. The authors attributed the reduction in the CBR values to the low maximum dry density value due to excess oil content.

Mohammed (1995), however, recorded conflicting findings, since his test results on natural and oil-mixed Sabkha soils from Bahrain revealed the CBR values of 4% oil mixed Sabkha soil decreased by approximately 20% compared to clean Sabkha. It should be noted that the latter carried out the CBR test using smaller moulds than the standard size due to a shortage in raw materials. In addition, he did not compact the oil-mixed samples to the maximum dry densities due to the addition of water to a level higher than the optimum moisture content. An amount of water higher than the optimum moisture content may reduce the CBR value of the compacted soil due to oil solidification that will minimise its lubrication effect (Aiban, 1998).

2.4.5.3 Unconfined compressive strength

Mohammed (1995) investigated the effect of Arabian oil addition on the geotechnical properties of Sabkha soil from Bahrain. Mohammed recorded a significant increase of 120% to 300% in the unconfined compressive strength at 4% oil addition. Such increase was attributed to the increase in cohesion properties that resulted from the oil addition. However, with more oil addition, a reduction in unconfined compressive strength was observed. Reduction in unconfined compressive strength at high oil addition percentage was also observed by Shah et al. (2003) in their research on a loamy silt soil contaminated with 10% fuel oil. They noticed that unconfined compressive strength of the contaminated soil was lower than that of natural soil. The unconfined compressive strength was reduced from 0.58kPa for natural soil to 0.38kPa for 7% oil fuel contaminated soil. Similarly, Al-Rawas et al. (2005) found higher oil content in contaminated soil resulted in a further reduction in unconfined compressive strength.

2.4.6 Compressibility characteristics

Several investigations on oil-contaminated soils have revealed an increase in the compressibility and anticipated settlement of contaminated soils. This has been attributed to bearing capacity reduction due to oil presence (Shin et al., 1999). Reduction in the friction angle with oil contamination may lead to the reduction in ultimate bearing capacity (Shin et al., 1999).

Al-Sanad et al. (1995) found the compressibility of crude-oil contaminated soils in Kuwait more than double the value of clean soils. The increase in compressibility was mainly attributed to mechanical and physiochemical factors, where the addition of contaminants to a soil changes its pore-fluid properties (Meegoda and Ratnaweera, 1994). They concluded that mechanical factors, such as viscosity, facilitate the sliding of soil particles due to lubrication. This, in turn, increases the compression index with an increase in viscosity, which is an indication of increasing compression index value and higher proneness of the soil towards settlement (Srivastava and Pandey, 1998). A case study of oil contaminated soil and its effect on compressibility in India was presented by Shroff (1997). According to Shroff, oil leakages and spills which occurred resulted in excessive settlement of oil storage tanks. Evgin and Das (1992) carried out triaxial tests on clean and oil-contaminated quartz sand. They found that full saturation with motor oil caused a significant reduction in the friction angle of both loose and dense sands and a drastic increase in the volumetric strains. They also showed using finite- element analysis that settlement of footing increases with oil contamination.

2.4.7 Coefficient of permeability

The coefficient of permeability of oil contaminated sandy soils is expected to be lower than that of uncontaminated soils, since oil contaminants occupy pore spaces and reduce soil porosity (Slattery 1990; and Andrade et al., 2004). Anderson (1992) observed that the coefficient of permeability of clay liner in landfills may alter as a result of prolonged contact with organic fluids. Contamination of soil with petroleum derivatives has been found to significantly affect the hydraulic conductivity of sandy soils. A reduction of about 10% and 40% for compacted and loose soils, respectively, has been reported by investigators (Garbulewski and Zakowicz, 1998; and Puri et al., 1998).

Slattery (1990) attributed the reduction in coefficient of permeability of sandy soils with increasing oil content to the occupation of some pore spaces by oil. Measurement of the hydraulic conductivity of clean and contaminated sands from Kuwait has revealed a reduction in the coefficient of permeability of about 20% due to oil contamination (Al-Sanad et al., 1995 and Al-Sanad and Ismael, 1997). Constant-head permeability tests were carried out on sand classified as poorly graded (SP). The aforementioned researchers, test results indicated that the coefficient of permeability was $k = 1.72\times10^{-5}$ m/s and $k = 1.38\times10^{-5}$ m/s for clean and contaminated sand, respectively. Similarly, Singh et al. (2006) reported a reduction in the permeability of gasoline contaminated sand.

2.4.8 The use of oil contaminated soil in construction

The use of contaminated soils provides inexpensive, locally available construction materials. This also minimises waste disposal costs by providing an alternative to landfill disposal. Furthermore, in addition to the benefits derived from the disposal of petroleum contaminated soils (PCSs), there will be cost saving in using petroleum contaminated soils as an aggregate replacement in asphalt concrete (Meegoda,1999).

Many environmental governmental organisations have set different guidelines, regulations, rules and policies to encourage and promote the treatment and reuse of oil contaminated soils in different types of constructions (DEQ, 2006; SERM, 1995). These contaminated soils should meet the appropriate level of cleanup considered adequate to protect the surrounding environment. The US Department of Agriculture provides guidance and assistance in protecting the environment against accidental oil spills. In these guidelines, oil-soaked gravel is disposed by hauling to an approved landfill or by spreading on gravel roads (USDA, 1993).

The Massachusetts Landfill Department of Environmental Protection (MLDEP, 1997) has set out the allowable contaminant levels of concentrations of contaminants for soil reuse at landfills in Massachusetts. The Department has determined that contaminated soils below these levels of concentrations may be reused as daily cover, intermediate cover and pre-capping contour material.

The Iowa Waste Reduction Centre has recommended reusing of petroleum-contaminated soil as a filling material at the original excavation site or alternative cover material at sanitary landfill (IWRC, 2003).

The Minnesota Pollution Control Agency (MPCA, 2005) has set the contaminant limits for thermally treated contaminated soils. The MPCA has indicated that thermally treated soils can be used in controlled fill if the post-burn concentration is less than 5 mg/kg and for road embankment if the post-burn concentration is less than 20 mg/kg (MPCA, 2005).

Consequently, contaminated soil and hydrocarbon-contaminated soil has been utilised in many applications. For example, hydrocarbon-contaminated soil has been used as an ingredient of asphalt pavement materials for secondary roads construction (Ellison, 1991). Meegoda (1992) discussed the possibility of reusing petroleum-contaminated soils in the production of asphalt concrete. He reported that up to 35% petroleum contaminated soil (based on total weight) could be mixed with hot mix asphalt to produce asphalt concrete. Meegoda and Muller (1993) mixed 35% of petroleum contaminated soil with hot mix asphalt concrete and subjected the final mixture to different tests. Their leachability tests on the designed mix showed neither significant concentrations nor significant increase in concentrations of contaminants with time.

Mohammed (1995) used crude-oil residue as a stabilising agent for a natural Bahraini soil. The stability and detachability of the mix were of primary concern. His results showed that the addition of 4% oil binder resulted in achieving maximum stability. He also concluded that leaching of oil at this level of oil addition was not significant. Aiban (1998) concluded that sands contaminated with oil to varying degrees could be utilised for construction without the need to make the contamination homogeneous.

Tarefder et al. (2003) formulated a mix design to incorporate the maximum possible amount of hydrocarbon-contaminated soils relative to the volume of product. In an experimental study, results indicated that mixtures containing up to 22% oily sludge met the necessary criteria for a specific asphalt concrete wearing course or bituminous base course (Taha et al., 2001).

Contaminated soil has been used successfully by the US Army Corps of Engineers to construct cold-mix asphalt base courses at different locations, bearing in mind that the type of petroleum contaminant and the amount or degree of contamination are the main parameters governing this usage (Corp of Engineer's, 1998).

Reuse of treated oil-contaminated soil is one of the main environmental objectives for the development of the Fornebu area in Norway (Westby et al., 2004). In a 4-year project, the treated contaminated soil has been used for construction. More than 20,000 tons of contaminated soils have been stabilised with 3% of bitumen and used as foundation for new roads (Westby et al., 2004). Investigations on the final mix have revealed that the stabilisation process has reduced the leached contaminants and their toxicity. The recycling process of these contaminated soils has been successful in reducing the cost of their disposal. The utilisation of oily sludge in asphalt paving mixtures yields considerable savings per ton of asphalt concrete, and concurrently minimises any direct impact on the environment (Taha et al., 2001).

Several investigators have studied the possibility of stabilising contaminated soils using additives such as lime, fly ash, and cement (Shah et al., 2003; and Hassan et al., 2005). The possibility of stabilising petroleum-contaminated drilling wastes using different additives, such as lime or cement, has been investigated by Tuncan et al. (2000). The addition of 5% cement, 10% fly ash and 20% lime showed the best strength values. The stabilisation process produced a physically, mechanically and chemically new stabilised mixture which could be effectively and safely used as a sub-base material for road construction.

In Oman, where petroleum contaminated soil is considered a real disposal problem, investigations have indicated the possibility of using this material in road constructions (Hassan et al., 2005). Chemical analysis of stabilised soils suggests that the concentrations of metals and organic compounds are within acceptable limits. A study was carried out by Shah et al. (2003) to stabilise fuel oil contaminated soil with different types of additives. Results revealed that contaminated soil treated with 7% to 10% different stabilisation agents like lime, fly ash and cement, either independently or as an admixture, showed an improvement in geotechnical properties. Best results were observed when soil was treated with a combination of 10% lime, 5% cement and 5% fly ash. Geotechnical properties were improved and stabilisation resulted in a reduction of leachable oil. Similarly, Al-Rawas et al. (2005) conducted a study to stabilise petroleum-contaminated soil with cement. Results indicated that cement improved the geotechnical properties of oil contaminated soils in terms of unconfined and compressive strength and permeability. The design was finalised using 80% of the affected soil. The end product was checked to ensure it posed no hazard to the environment.

2.4.9 Oil contaminated soil usages in Kuwait

As a result of burning oil wells, huge amounts of contaminated soils surround oil lakes (section 1.3) making them a permanent source of contamination and necessitating a quick solution to minimise the danger posed by them.

Most studies which have been carried out have monitored the status of oil-lakes and polluted zones as well as investigated the environmental effect and treatment methods of oil-lake residue (Section 1.3). Al-Sanad et al. (1995) have stated that use of contaminated sand for road construction is possible from the engineering point of view. However, they also suggest that such material should be capped or enclosed to prevent potential environmental pollution. Al-Mutairi (1995) investigated the effect of oil based pollutants on the strength and integrity of building materials. Samples from different parts of Kuwait were collected and physical, chemical and X-ray fluorescence tests were carried out. The physical testing programme indicated a positive effect with regard to compressive strength and concrete slump made from contaminated aggregate. The possibility of using oil-contaminated sands in asphalt concrete for secondary roads was investigated by Al-Mutairi and Eid (1995).

It is worth mentioning that, to-date, no large scale remediation plan has been implemented to solve the problem of oil lake residue and the associated problem of contaminated land. Although many such plans have been proposed they have not been implemented (Kwarteng, 1999). The need for an economical method to solve this problem is a major priority for planners and regulators.

2.5 Limitations of previous studies

No previous study has investigated the usage of oil lake residue to stabilise Sabkha soils in Kuwait. Studies reviewed in earlier sections have primarily investigated the behaviour of sandy soils mixed with crude or other types of oils. Work closely related to this study is that carried out by Mohammed (1995) who investigated the possibility of using Arabian oil residues to stabilise saline soils in Bahrain. However, Mohammed (1995) study had the following limitations:

- Physical properties of the stabilised soil samples were not investigated, leading to the following:

  - The maximum dry density for both natural and stabilised soils was assumed to be identical. Optimum moisture content was obtained through mathematical calculation for each mixture based on the percentage of added oil. Compaction parameters were obtained without taking into account changes in soil behaviour due to oil addition. The foregoing literature review suggests oil addition changes the compaction parameters of Sabkha soils, and such changes depend on the oil addition percentage. Therefore, the present study will investigate the physical properties of stabilised Sabkha soils in order to obtain a better understanding of their mechanical behaviour.

- No details regarding arid soil characterisation and specifications used to determine optimum moisture content were provided. Salt bearing soils are sensitive to the drying method employed during laboratory tests. Mohammed's study did not mention the drying method, although it is recommended that these soils be oven dried at 60° C (Ismael, 1993-b).

- Leachability results indicated that salt leachability from the stabilised layer was higher than that from the natural soil layer. This contradicts other investigators findings (Al-Sanad et al. 1995; Al-Houty et al., 1993, and Karimi and Gray, 2000) and general agreement on the waterproofing effect of an oil-Sabkha soil mixture. Waterproofing is considered a main property in bitumen and oil stabilisation. The leachability finding in Mohammed's study also contradicted the geotechnical results which suggested the soaked stabilised layer had a higher strength than the natural soil layer, attributed by the author to the waterproofing mechanism of the oil residue. In this author's view, the stabilised soil was not compacted to its maximum dry density and was mixed to a higher moisture content which created a high void and increased the dissolution of salts.

- Mohammed's study was limited to Bahrain's Sabkha soils stabilised with Arabian oil residues and cannot be applied to the Kuwaiti context. Inhomogeneity of Sabkha soil due to the presence of different salts and minerals in Sabkha flats, will lead to variability in Sabkha soil behaviour (Al-Amoudi et al., 1992-a; and Ismael, 1993-b). Arabian oil residues have different properties to those of oil lake residue.

- CBR and other geotechnical tests were conducted by Mohammed using moulds smaller than the standard size due to a shortage in raw materials. This may have had some bearing on the accuracy of the results of the tests.

2.6 Summary

The foregoing literature review has identified limitations in using different methods (mechanical, cement and lime) to stabilise Sabkha soil, mainly due to the high saline content of the soil, which aggressively attacks these stabilisers. However, bitumen is effective in Sabkha soil stabilisation, since it acts as a waterproofing and binding agent (Basma et al., 1994). But this type of stabilisation is not as common as other methods, mainly because of its relatively high cost in some locations and the considerable expertise required in controlling the temperature and viscosity at high bitumen temperature (Hausmaun, 1990).

The literature review highlighted variation in the geotechnical properties of oil contaminated soils and indicated that the effects of the contaminants in the soil mainly depend on the soil type and properties and percentage of the oil present. Oil in small quantities acts as a lubricant, helping to achieve a high degree of compaction; whereas higher oil content has been reported to have an adverse effect by some investigators as mentioned earlier in this chapter. The literature review suggests oil acts similarly to bitumen on soils in terms of cohesion and waterproofing effect.

Contaminated soils have, as previously mentioned, been used successfully in various countries for different construction usages, taking into account possible impacts on the environment due to migration of contaminants from the stabilised layer to the deeper underlying soil layer. The use of oil-contaminated soils in road construction is a well established approach and has been carried out in several locations in the world. Major factors that have to be carefully considered before using this approach are:

- Type and percentage of contaminant in the soil.
- The mixture satisfies the engineering requirements for the specified purposes.
- Minimum impact on the environment.

2.7 Present work

The literature review has indicated that the major problem in Sabkha soil is the existence of high concentrations of different salt types. Moreover, Sabkha soils strength, volume stability and permeability are highly affected by soaking due to the dissolution of salts. This dissolution of and aggressive attacks on construction materials are the main parameters that must be controlled in any stabilisation technique. Several researchers have pointed to the difficulty of using cement and lime as stabilisation methods due to their high salt contents, including sulphate.

The waterproofing and bonding mechanisms of bituminous materials are more effective in stabilising Sabkha soils than other stabilisation methods. Oil lake residue is a highly viscous material and might provide the stabilised layer with waterproofing and bonding mechanisms. Further, oil lake residue has a lower viscosity than bituminous materials which can be considered advantageous for making it more workable in the field.

This study is expected to shed some light on the potential beneficial use of oil lake residue for stabilising weak collapsible soils. Both oil residues and weak soils are viewed as waste materials that need careful disposal and management.

2.8 References

Abduljauwad, S.N. and Al-Amoudi, O.S.B., 1995. Geotechnical Behaviour of Saline Sabkha Soils. *Geotechnique*, 45(3): 425-445.

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Aiban, S.A., Al-Ahmadi, H.M., Asi, I.M., Siddique, Z.U. and Al-Amoudi, O.S.B., 2006. Effect of Geotextile and Cement on the Performance of Sabkha Subgrade. *Building and Environment*, 41(6): 807-820.

Aiban, S.A. and Ali, S.M., 2001. Nonwoven Geotextile-Sabkha and Sand Interface Friction Characteristics Using Pull-Out Tests. *Geosynthetics International*, 8(3): 193-201.

Akili, W., 1981. On Sabkha Sands of Eastern Saudi Arabia. In Proceedings of the Symposium on Geotechnical Problems in Saudi Arabia. King Saud University, Riyadh, Saudi Arabia, 2: 775-779.

Akili, W. and Torrance, J.K., 1981. Development and Geotechnical Problems of Sabkha, with Preliminary Experiments on the Static Penetration Resistance of Cemented Sands. *Quarterly Journal of Engineering Geology*, 14(1): 59-73.

Al-Abdul Wahhab, H.I. and Asi, I.M., 1997. Improvement of Marl and Dune Sand for Highway Construction in Arid Areas. *Building and Environment*, 32(3): 271-279.

Al-Amoudi, O.S.B., 1994. Chemical Stabilisation of Sabkha Soils at High-Moisture Contents. *Engineering Geology*, 36(3-4): 279-291.

Al-Amoudi, O.S.B., 1995-a. A Review of the Geotechnical and Construction Problems in Sabkha Environments and Methods of Treatment. *The Arabian Journal of Science and Engineering*, 20(3): 405-432.

Al-Amoudi, O.S.B., 1995-b. Soil Stabilisation and Durability of Reinforced Concrete in Sabkha Environment, Proceedings of the 4th Saudi Engineering Conference, King Abdulaziz University, Jeddah, Saudi Arabia, pp. 313-338.

Al-Amoudi, O.S.B., 2002. Characterisation and Chemical Stabilisation of Al-Qurayyah Sabkha Soil. *Journal of Materials in Civil Engineering*, 14(6): 478-484.

Al-Amoudi, O.S.B., Abduljauwad, S., El-Naggar, Z.R. and Safar, M.M., 1991. Geotechnical Consideration on Field and Laboratory Testing of Sabkha, Proceedings, Symposium on Recent Advances in Geotechnical Engineering III, Premier Conference, Singapore, 1: 1- 6.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1994-a. Modified Odometer for Arid, Saline Soils. *Journal of Geotechnical Engineering*, 120(10): 1892-1897.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1994-b. Suggested Modifications to ASTM Standard Methods When Testing Arid, Saline Soils. *Geotechnical Testing Journal*, 17(2): 243-253.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-a. Compressibility and Collapse Characteristics of Arid Saline Sabkha Soils. Engineering Geology, 39(3-4): 185-202.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-b. Strength Characteristics of Sabkha Soils. *Geotechnical Engineering*, 26(1): 73-92.

Al-Amoudi, O.S.B., Abduljauwad, S.N., El-Naggar, Z.R. and Rasheeduzzafar, 1992-a. Response of Sabkha to Laboratory Tests - A Case-Study. *Engineering Geology*, 33(2): 111-125.

Al-Amoudi, O.S.B., Abduljauwad, S.N., Rasheeduzzafar and Maslehuddin, M., 1992-b. Effect of Chloride and Sulphate Salts in Sabkha on Performance of Concrete. Proceedings of Buildings Deterioration in the Arab World and Methods of Repair. Ministry of Public work, Riyadh, Saudi Arabia, pp. 79-88.

Al-Amoudi, O.S.B. and Asi, I.M., 1991. An Investigation on Improvement of Sabkha Soil Properties, Proceedings Symposium on Recent Advances in Geotechnical Engineering III, Singapore, 1: 7-12.

Al-Amoudi, O.S.B., Asi, I.M. and El-Naggar, Z.R., 1995. Stabilisation of an Arid, Saline Sabkha Soil Using Additives. *Quarterly Journal of Engineering Geology*, 28: 369-379.

Al-Bader, B.R., 1989. Leaching of a Calcareous Soil from Kuwait. MSc Thesis, Kuwait University, Kuwait.

Al-Eesa, A. and Hasan, A., 1979. Highway Embankment over Sabkha in the Qassim of Saudi Arabia, Riyadh, Saudi Arabia.

Al-Homoud, A.S., Khedaywi, T. and Al-Ajlouni, A.M., 1996. Engineering and Environmental Aspects of Cutback Asphalt (MC-70) Stabilisation of Swelling and Collapsible Soils. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstract*, 33(7).

Al-Houty, W., Abdal, M. and Zaman, S., 1993. Preliminary Assessment of the Gulf War on Kuwait Desert Ecosystem. *Environmental Science Health*, A28(8): 1705-1726.

Al-Hurban, A. and Gharib, I., 2004. Geomorphological and Sedimentological Characteristics of Coastal and Inland Sabkhas, Southern Kuwait. *Journal of Arid Environments*, 58(1): 59-85.

Ali, G.A. and Youssef, A.F., 1981. Stabilisation of Silt: A Case Study for Low-Volume Roads in Saudi Arabia, 3rd International Conference on Low-Volume Roads. TRP, Arizona.

Al-Mutairi, N.M., 1995. Kuwait Oil-Based Pollution-Effect on Building Material. *Journal of Materials in Civil Engineering*, 7(3): 154-160.

Al-Mutairi, N.M. and Eid, W.K., 1995. Utilization of Oil-Contaminated Sands in Asphalt Concrete for Secondary Roads. *Materials and Structures*, 30(202): 497-505.

Al-Nouri, I. and Saleam, S., 1994. Compressibility Characteristics of Gypseous Sandy Soils. *Geotechnical Testing Journal*, 17(4): 465-474.

Al-Rawas, A., Hassan, H. F., Taha, R., Hago, A., Al-Shandoudi, B. and Al-Suleimani, Y., 2005. Stabilisation of Oil-Contaminated Soils Using Cement and Cement By-Pass Dusts. *Management of Environmental Quality*, 16(6): 670-680.

Al-Saad, A., 1993. Oil Lakes, Lecture Presented at Kuwait Engineering Society, Kuwait, p.32.

Al-Sanad, H. and Bindra, S.P., 1984. Soil Mechanics for Road Engineering in Arabian Peninsula. Kuwait University, Kuwait.

Al-Sanad, H.A., 1986. Characterisation of Salt-Bearing Soils (Sabkha) for Pavement Design Purposes in the State of Kuwait. *Journal of the University of Kuwait-Science*, 13(1): 29-41.

Al-Sanad, H.A. and Al-Bader, B., 1990. Laboratory Study on Leaching of Calcareous Soil from Kuwait. *Journal of Geotechnical Engineering*, 116(12): 1797-1809.

Al-Sanad, H.A., Eid, W.K. and Ismael, N.F., 1995. Geotechnical Properties of Oil - Contaminated Kuwaiti Sand. *Journal of Geotechnical Engineering-ASCE*, 121(5): 407-412.

Al-Sanad, H.A. and Ismael, N.F., 1997. Aging Effects on Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3): 290-293.

Al-Sanad, H.A. and Shaqour, F.M., 1987. The Effect of Groundwater Level Fluctuation on the Engineering Properties of Desert Sands. Final Report EE 556, Kuwait University, Kuwait.

Al-Sanad, H.A., Shaqour, F.M., Hencher, S.R. and Lumsden, A.C., 1989. The Shear Strength of Salt-Cemented Sand from Kuwait, Proceedings of the 1stRegional Conference of Civil Engineering, Bahrain.

Al-Sanad, H.A., Shaqour, F.M., Hencher, S.R. and Lumsden, A.C., 1990. The Influence of Changing Groundwater Levels on the Geotechnical Behaviour of Desert Sands. *Quarterly Journal of Engineering Geology*, 23(4): 357-364.

Al-Shakarchi, Y.J. and Rasool, H.A., 1999. Durability of Soil Contaminated by Oil, 8th International Conference on Durability of Building Materials and Compressibility, Vancouver; Canada. pp.1377-1381.

Al-Shamrani, M.A. and Dhowian, A.W., 1997. Preloading for Reduction of Compressibility Characteristics of Sabkha Soil Profiles. *Engineering Geology*, 48(1-2): 19-41.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North-Western Spain). *Journal Environmental Quality*, 33: 2103-2110.

Andreason, M.W., 1992. Coastal Siliciclastic Sabkhas and Related Evaporative Environments of the Permian Yates Formation, North Ward-Estes Field, Ward County, Texas. AAPG *Bulletin-American Association of Petroleum Geologists*, 76(11): 1735-1759.

Arora, 1997. Soil Mechanics and Foundation Engineering. Standard Publishers Distributors, Delhi, p.852.

Asi, I.M., 2001. Stabilisation of Sabkha Soil Using Foamed Asphalt. *Journal of Materials in Civil Engineering*, 13(5): 325.

Asi, I.M., Al-Abdul Wahhab, H.I., Al- Amoudi, O.S.B., Khan, M.I. and Siddiqi, Z., 2002. Stabilisation of Dune Sand Using Foamed Asphalt. *Geotechnical Testing Journal*, 25(2): 168-176.

Atkinson, J.H., 1994. General Report: Classification of Arid Soils for Engineering. In: P.G. Fooks and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Soils, Balkema, Rotterdam, pp. 57-64.

Attom, M.F. and Al-Sharif, M.M., 1998. Soil Stabilisation with Burned Olive Waste. *Applied Clay Science*, 13(3): 219-230.

Balba, M.T., Al-Daher, R. and Al-Awadhi, N., 1998. Bioremediation of Oil-Contaminated Desert Soil: The Kuwait Experience. *Environment International*, 24(1/2): 163-173.

Basma, A.A., Al-Homoud, A.S., Khedwayi, T.S. and Al-Ajlouni, A.M., 1994. Effect of Bitumen Content and Curing Condition on Strength Characteristics of Asphalt Stabilised Soils. *Geotechnical Engineering*, 25(1): 93-104.

Basma, A.A. and Tuncer, E.R., 1992. Evaluation and Control of Collapsible Soils. *Journal of Geotechnical Engineering*, 118(10): 1491-1504.

Bell, F.G., 1996. Lime Stabilisation of Clay Minerals and Soils. *Engineering Geology*, 42(223-237).

Bissada, A.F., 1974. Low Pavement Situation in Kuwait. In: A.E. Federation (Editor), Proceedings of Conference on Low-Cost Roads, Kuwait.

Bufarsan, A., Barker, C., Wavrek, D.A. and Al-Sarawi, M., 2002. Compositional Changes Induced by Evaporation of Burgan Crude Oil Spilled into the Desert of Southern Kuwait. *Environmental Geosciences*, 9(1): 8-16.

Caravaca, F. and Roldan, A., 2003. Assessing Changes in Physical and Biological Properties in a Soil Contaminated by Oil Sludges under Semiarid Mediterranean Conditions. *Geoderma*, 117: 53-61.

Carrigy, M.A., 1967. The Physical and Chemical Nature of Typical Tar Sand: Bulk Properties and Behaviour, Proceedings of the 7th International World Petroleum Congress, 1: 573-581.

CDPHE, 2003, Colorado Department of Public Health and Environment. Hazardous Materials and Waste Management. Colorado-USA.

CORP, 1984, U.S. Army CORP of Engineers. Soil Stabilisation for Pavements Mobilisation Construction. EM 1110-3-137, Department of the Army, Washington, D. C.

CORP, 1998, U.S. Army Corps of Engineers. Use of Petroleum Contaminated Soil in Cold-Mix Asphalt Stabilised Base Course. ETL 1110-3-487, Technical Letter No. 1110, Department of the Army, Washington, D. C.

DANA, 1994, Department of the Army. Soil Stabilisation of Pavement. Army TM 5-822-14, Air Force AFJMAN 32-109, The Navy and Air Force, Washington, D. C.

Das, B.M., 2003. Chemical and Mechanical Stabilisation. A2J02: Committee on Chemical and Material Stabilisation, California State University, San Francisco.

DEQ, 2006. Department of Oregon Environmental Quality. Fact Sheets. Petroleum-Contaminated Soils Policy for Reuse, http://www.deq,state.or.us/wmc/tank/toc-fct.htm.

Doshi, S.N. and Gurguis, H.R., 1983. Correlation of CBR with Density and Moisture. *Indian Geotechnical Journal*, 12(4): 281-287.

Ellison, R., 1991. Comparison and Critical Review of Onsite Treatment of Petroleum Contaminated Soils. In: E. Calabrese and Paul Kostecki (Editors), Hydrocarbon Contaminated Soils. Lewis Publishers Inc., Chelsea, MI, pp. 301-337.

Enu, E.I., 1985. Textural Characteristics of the Nigerian Tar Sands. *Sedimentary Geology*, 44(1-2): 65-81.

Evgin, E., Amor, F.B., Altaee, A., Lord, S. and Konuk, I., 1989. Effect of an Oil Spill on Soil Properties. Proceedings of the 8th International Conference of Offshore Mechanics and Arctic Engineering (OMAE), 1: 715-720.

Evgin, E. and Das, B.M., 1992. Mechanical Behaviour of an Oil Contaminated Sand, Environmental Geotechnology, Proceedings of the Mediterranean Conference, Usman and Acar, Eds., Balkema Publishers, Rotterdam. The Netherlands, 101-108.

Fatani, M.N.Y., Bauer, G.E. and Al-Joulani, N., 1991. Reinforcing Soil with Aligned and Randomly Oriented Metallic Fibers. *Geotechnical Testing Journal*, 14(1): 78-87.

Garbulewski, K. and Zakowicz, S., 1998. Influence of Hydrocarbon Contaminants on Hydraulic Conductivity of Drainage System, Contaminated and Derelict Land, Materials Properties and Measurement. Thomas Telford, London, pp. 198-203.

Giffen, J.C., Williams, J.R. and Walter, P.D., 1978. Stabilisation of Non-Standard Gravel with Tar, Proceedings ARB, pp. 14-20.

Hassan, H., Taha, R., Al-Rawas, A., Al-Shandoudi, B., Al-Gheithi and Barami, A., 2005. Potential Uses of Petroleum-Contaminated Soil in Highway Construction. *Construction and Building Materials*, 19(8): 646-652.

Hausmann, M.R., 1990. Engineering Principles of Ground Modification, McGraw-Hill Publishing Company, New York.

Hossain, D. and Ali, K.M., 1988. Shear-Strength and Consolidation Characteristics of Obhor Sabkha, Saudi Arabia. *Quarterly Journal of Engineering Geology*, 21(4): 347-359.

Huddleston, J.H., 1996. How Soil Properties Affected Groundwater Vulnerability to Pesticide Contamination. EM 8559, Oregon State University, Extension Services.

Hunter, D., 1988. Lime-Induced Heave in Sulphate-Bearing Clay Soils. *Journal of Geotechnical Engineering*, 114(2): 150-167.

Ingles, O.G. and Metcalf, J.B., 1972. Soil Stabilisation: Principles and Practice. Butterwoths & Co. Ltd., Melbourne, Australia.

Ismael, N.F., 1984. Cement Stabilisation of Kuwait Soils. *Arab Gulf Journal of Scientific Research*, 2(1): 349-360.

Ismael, N.F., 1993-a. Laboratory and Field Leaching Tests on Coastal Salt-Bearing Soils. *Journal of Geotechnical Engineering-ASCE*, 119(3): 453-470.

Ismael, N.F., 1993-b. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035, Washington, D. C.

Ismael, N.F. and Jeragh, A.M., 1986. Static Cone Tests and Settlement of Calcareous Desert Sands. *Canadian Geotechnical Journal*, 23: 297-303.

Ismael, N.F., Jeragh, A.M., Mollah, M.A. and Al-Khaldi, O., 1986-a. A Study of the Properties of Surface Soils in Kuwait. *Geotechnical Engineering*, 17: 67-87.

Ismael, N.F., Jeragh, A.M., Mollah, M.A. and Al-Khalidi, 1990. Expansive Behaviour of Subgrade Soils in Arid Areas. Transportation Research Record.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Ismael, N.F., Mollah, M.A. and AL-Khaldi, O., 1986-b. Geotechnical Properties of Cemented Soils in Kuwait. Australian Road Research, 16(2): 94-104.

IWRC, 2003, Iowa Waste Reduction Centre. Beneficial Reuse of Solid Waste, University of Northern Iowa.

Jeragh, A.M. and Ismael, N.F., 1984. Corrosion of Reinforced Concrete Foundation in Kuwait. In: V. Ashworth (Editor), Proceedings of the 1st Arabian Conference on Corrosion: Industrial Problems, Treatment and Control Techniques. Pergamon Press, Oxford, Kuwait, pp. 523-537.

Juillie, Y. and Sherwood, D.E., 1983. Improvement of Sabkha Soils of the Arabian Gulf Coast, Improvement of Ground, Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, pp. 781-788.

Kamon, M., 1992. Recent Developments of Soil Improvement and Pile Foundation, Nanjing, China, pp. 1-16.

Kamon, M. and Nontananandh, S., 1991. Compressibility of Clay. *Soil Mechanics and Foundation Engineering*, 117: 1-17.

Karimi-Lotfabad, S. and Gray, M.R., 2000. Characterisation of Contaminated Soils Using Confocal Laser Scanning Microscopy and Cryogenic-Scanning Electron Microscopy. *Environmental Science & Technology*, 34(16): 3408-3414.

Kedzi, A., 1974. Handbook of Soil Mechanics. Soil Physics. Elsevier Scientific Publishing Company, Amsterdam, p. 249.

Kwarteng, A.Y., 1999. Remote Sensing Assessment of Oil Lakes and Oil-Polluted Surfaces at the Greater Burgan Oil Field, Kuwait. *International Journal for Applied Earth Observation and Geoinformation*, 1(1): 36-47.

Livneh, M., Livneh, N.A. and Hayati, G., 1998. Site Investigation of Sub-Soil with Gypsum Lenses for Runway Construction in an Arid Zone in Southern Israel. *Engineering Geology*, 51(2): 131-145.

Meegoda, N.J., 1992. Contaminated Soils in Highway Construction. In: L.W. Donald (Editor), Process Engineering for Pollution Control and Waste Minimisation, pp. 553-684.

Meegoda, J.N., 1999. Stabilisation / Solidification of Petroleum-Contaminated Soils with Asphalt Emulsions. *Practice Periodical of Hazardous, Toxic and Radioactive Waste Management*, 3(1): 46-55.

Meegoda, J.N. and Muller, R.T., 1993. Petroleum Contaminated Soils in Highway Construction, In: Symposium Proceedings: Recovery and Effective Reuse of Discarded Materials and by-Products of Construction of Highway Facilities, p. 4.83 - 4.95, Denver, Colorado, USA.

Meegoda, N.J. and Ratnaweera, P., 1994. Compressibility of Contaminated Fine-Grained Soils. *Geotechnical Testing Journal*, 17(1): 101-112.

Meegoda, N.J. and Ratnaweera, P., 1995. Treatment of Oil-Contaminated Soils for Identification and Classification. *Geotechnical Testing Journal*, 18(1): 41-49.

Mitchell, J.K., 1986. Practical Problems from Surprising Soil Behaviour. *Journal of Geotechnical Engineering*, 112(3): 259-289.

MLDEP, 1997, Department of Environmental Protection. Reuse and Disposal of Contaminated Soil at Massachusetts Landfills. Policy # COMM-97-001, Supersedes Policy # BWP-94-037, Massachusetts.

MOD, 1996, Ministry of Defence. Annual Report. Unpublished Internal Report, Engineering Department for Military Projects, Kuwait.

MOD, 1997, Ministry of Defence. Annual Report. Unpublished Internal Report, Engineering Department for Military Projects, Kuwait.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and its Geoenvironmental Implications. PhD Thesis, McGill University, Montreal, Canada.

MPCA, 2005, Minnesota Pollution Control Agency. Thermal Treatment of Petroleum Contaminated Soil. Guidance Document 3-10.

Naifeng, H., 1994. Corrosiveness of the Arid Saline Soils. In: P.G. Fookes and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Areas. Balkema, Rotterdam, London, pp. 29-34.

Narasimha Rao, S. and Rajasekaran, G., 1996. Reaction Products Formed in Lime Stabilised Marine Clays. *Journal of Geotechnical Engineering, ASCE*, 122: 329-336.

Newill, D. and Connell, M.J.O., 1994. TRL Research on Road Construction in Arid Areas. In: P.G. Fookes and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Areas. Balkema, Rotterdam, Brookfield, London.

Ola, S.A., 1978. Geotechnical Properties and Behaviour of Some Stabilised Nigerian Lateritic Soils. *The Quarterly Journal of Engineering Geology*, 38: 145 -160.

Ola, S.A., 1991. Geotechnical Properties and Behaviour of Nigerian Tar Sand. *Engineering Geology*, 30(3-4): 325-336.

Puri, V.K., Das, B.M., Cook, E.C. and Shin, E.C., 1994. Geotechnical Properties of Crude Oil-Contaminated Sand. In: A. Tracey and B.H. Keith (Editors), Analysis of Soils Contaminated with Petroleum Constituents. ASTM STP1221, Philadelphia, USA, pp. 75-88.

Qahwash, A.A., 1989. Geotechnical Properties of Fine-Grained Calcareous Sediments for Engineering Purposes. *Engineering Geology*, 26(2): 161-169.

Rajasekaran, G., 2005. Sulphate Attack and Ettringite Formation in the Lime and Cement Stabilised Marine Clays. *Ocean Engineering*, 32(8-9): 1133-1159.

Rao, S.M., Reddy, B.V.V. and Muttharam, M., 2001. The Impact of Cyclic Wetting and Drying on the Swelling Behaviour of Stabilised Expansive Soils. *Engineering Geology*, 60(1): 223-33.

Rogers, C.D.F., Dijkstra, T.A. and Smallery, I.J., 1994. Keynote Lecture: Classification of Arid Soils for Engineering Purposes: An Engineering Approach. In: P.G. Fookes and R.H.G. Parry (Editors), Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Areas, Balkema, Rotterdam.

Sabtan, A.A. and Shehata, W.M., 2002. Problematic Sabkha - a Potential Source of Fresh Water. *Bulletin Engineering Geology Environment*, 61(2): 153-159.

Sabtan, A.A. and Shehata, W.M., 2003. Hydrogeology of Al-Lith Sabkha, Saudi Arabia. *Journal of Asian Earth Sciences*, 21(4): 423-429.

Saleh, A., Al-Ruwaih, F., Al-Reda, A. and Gunatilaka, A., 1999. A Reconnaissance Study of an Elastic Coastal Sabkha in Northern Kuwait, Arabian Gulf. *Journal of Arid Environments*, 43(1): 1-19.

SERM, 1995, Saskatchewan Environment and Resources Management. Guidelines and Disposal of Petroleum Contaminated Soils at Municipal Waste Disposal Grounds, Canada.

Shah, S.J., Patel, A.V. and Ramakrishnan, D., 2003. Stabilisation of Fuel Oil-Contaminated Soil-A Case Study. *Geotechnical and Geological Engineering*, 21: 415-427.

Sharif, L.R.L., 1991. Investigations to Assess the Potentialities of Soil Lime Stabilisation in Jordan. Dirasat S.B Pure and Applied Science, 18(4): 127-142.

Shehata, W.M., Al-Saafin, A.K., Harari, Z.Y. and Bader, T.A., 1990. Potential Sabkha Hazards in Saudi Arabia. Proceedings of the 6th International IAEG Congress, Amsterdam, 2003-2010.

Shin, E.C., Lee, J.B. and Das, B.M., 1999. Bearing Capacity of a Model Scale Footing on Crude Oil-Contaminated Sand. *Geotechnical and Geological Engineering*, 17: 123-132.

Shroff, A.V., 1997. Properties of Oil Contaminated Soils and Their Remedial Method by Admixtures-A Case Study, Presented at Workshop on Solid Waste Processing and Disposal at IIT Delhi, India.

Singh, S.K., Srivastava, R.K. and John, S., 2006. Assessment and Remediation of Soils Contaminated with Gasoline. In: H.R. Thomas (Editor), 5th ICEG Environmental Geotechnics. Thomas Telford, Geoenvironmental Research Centre, Cardiff University, Cardiff, UK, pp. 294-301.

Slattery, J.C., 1990. Interfacial Transport Phenomena. Springer-Verlag, New York.1159.

Srivastava, R.K. and Pandey, V.D., 1998. Geotechnical Evaluation of Oil Contaminated Soil. In Thomas Telford (Editor), Contaminated and Derelict Land, Material Properties and Measurement, pp. 204-209.

Stavridakis, E.I., 2005. A Proposed Classification of Anisotropic Engineering Behaviour of Cement Treated Clay Mixture Related to Their Strength and Durability. *Electronic Journal of Geotechnical Engineering (EJGE).*

Swan, L.H., 2003. Improvement of Sabkha Soils by Preloading and Dynamic Compaction at a Housing Site in Saudi Arabia. In: L. Dames & Moore (Editor), Piling and Ground Treatment, Proceedings of the International Conference on Advances in Piling and Ground Treatment for Foundations. Thomas Telford Ltd, London, London.

Taha, R., Ba-Omar, M., Pillay, A.E., Roose, G. and Al-Hamdi, A., 2001. Recycling of Petroleum - Contaminated Sand. *Journal of Environmental Monitoring*, 3(4): 417-420.

Tarefder, R.A., Ruckgaber, M.E., Zaman, M. and Patton, D., 2003. Formulation of Mix Design for Asphaltic Incorporation of Hydrocarbon Contaminated Soil. *Journal of Materials in Civil Engineering*, 15(2): 166-173.

Tenax, 2004. Stabilisation of a Road Embankment on Very Soft Marine Silts and Clay, for the Beheith Military Road Project, Kuwait. Tenax International B.V.

Terrel, R.L., Epps, J.A., Barenberg, E.J., Mitchell, J.K. and Thompson, M.R., 1984. Soil Stabilisation in Pavement Structure, A User Manual. Federal Highway Administration, Washington, D. C.

Tuncan, A., Tuncan, M. and Koyuncu, H., 2000. Use of Petroleum - Contaminated Drilling Wastes as Sub-base Material for Road Construction. *Waste Management and Research*, 18(5): 489-505.

USDA, 1993, United States of Department of Agricultural. Design Guide for Oil Spill Prevention and Control at Substation. *REA Bulletin* 1724E-302.

USEPA, 1996, U. S. Environmental Protection Agency. Vertical Strip Drains to Increase Storage Capacity of Confined Dredged Disposal Facilities, Environmental Effects of Dredging, Technical Note EEDP-02-02, U.S. Army Engineer Waterways Experiment Station.

West, G., 1959. A Laboratory Investigation into the Effects of Elapsed Time after Mixing on the Compaction and Strength of Soil Cement. *Geotechnique*, 9(1): 22.

Westby, T., Systad, R.A. and Ellefsen, V., 2004. Remediation of Contaminated Soil; Stabilisation and Re-Use of PAH-Contaminated.

Winterkorn, H.F., 1975. Soil Stabilisation. In: H.F. Winterkorn and H.Y. Fang (Editors), Foundation Engineering Handbook, Van Nostrand Reinhold, New York.

Yechieli, Y. and Wood, W.W., 2002. Hydrogeologic Processes in Saline Systems: Playas, Sabkhas, and Saline Lakes. *Earth-Science Reviews*, 58(3-4): 343-365.

Chapter 3

Experimental Programme, Sampling Plan and Materials Characterisation

3.1 Introduction

The study objectives will be achieved through implementing an experimental programme consisting of laboratory tests and field work. Initial and final field work will be carried out in Kuwait. This chapter describes the experimental programme and its first phases, namely, the soil survey and sampling strategy. Methods and techniques used to determine and characterise the physical and chemical properties of both Sabkha soils and oil residue are described. Measured parameters will be used in the analysis of Sabkha soil behaviour presented in subsequent chapters.

The experimental programme is descried in Section 3.2. Section 3.3 outlines phases A and B of the programme while soil sampling locations and general soil conditions in the test zone are indicated in section 3.4. The soil survey and its main phases are detailed in Section 3.5. Sections 3.6 and 3.7 detail the soil sampling plan, and site conditions and general features, respectively. Section 3.8 describes the methods and techniques used for materials' characterisation and Sabkha soil analysis results. Oil residue characterisation is provided in section 3.9. Main findings are summarised in section 3.10 and a list of references is provided in the final section, 3.11.

3.2 Experimental programme

To achieve the study objectives stated in section 1.5, a detailed experimental research programme, shown in the schematic diagram as Figure 3.1, was designed. This programme was divided into the following phases:

1- **Phase A:**

Site investigation, selecting the sampling zone, and identifying locations for preliminary soil sampling.

2- **Phase B**

Preliminary investigations to characterise Sabkha soils and oil residue and select representative samples.

3- **Phase C**

Mixing representative soils with different oil residue percentages and investigating the soil gradation, coefficient of permeability, specific gravity, consistency limits, and compaction parameters of oil mixed soils.

4- **Phase D**

Investigating the geotechnical properties of representative soil samples mixed with different oil residue in terms of strength aspects.

5- **Phase E**

Investigating additional geotechnical properties of oil mixed Sabkha soils in terms of bearing capacity and consolidation characteristics.

6- **Phase F**

Investigating leachability aspects of stabilised Sabkha soils.

7- **Phase G**

Field-testing, consisting of geotechnical and leachability tests to investigate the long-term behaviour of stabilised Sabkha soils.

3.3 Phases A and B

An important task in this study was to define and select the test zone, to establish a plan for different soil sampling stages and material characterisation and to select representative samples from the defined study area.

To obtain reliable results on the behaviour of Sabkha soils, tests had to be conducted on representative soil samples that accurately reflected Sabkha flats existing in the test zone.

This part of the experimental work consisted of Phases A and B in the experimental programme shown in Figure 3.2. Main stages of this part of the experimental programme included site investigation, soil surveying, soil sampling, and preliminary and detailed materials' characterisation.

The soil survey, sampling processes and preliminary soil testing were carried out in Kuwait, while laboratory characterisation tests were carried out at Cardiff University, Wales, UK.

3.4 Location of the survey zone

Most of the southern coast of Kuwait is covered with scattered coastal Sabkha flats as explained in section 1.2 and shown in Figure 1.1. Therefore, the selected sampling zone was located in the southern sector of Kuwait as shown in Figure 3.3. The sampling zone covers an area of approximately 2.5 km x 12 km and stretches in a NE-SW direction. This zone was selected for the following reasons:

- Most of this area is covered with scattered coastal Sabkha flats which are typical of other Sabkha soils in the region (Al-Hurban and Gharib, 2004).
- Several large-scale construction projects are expected to be built in this area in the near future.
- It is an easily identifiable and accessible strip, extending to Saudi Arabia and surrounded by the Arabian Gulf in the east and a motorway in the west.

The selected zone is part of the southern Sabkha flats that extend along the southern coastal area of Kuwait. These Sabkha soils occur as scattered, irregular, closed lowland areas of different sizes, i.e. 1-5 km^2 (Al-Hurban and Gharib, 2004). The outer surface of these Sabkha soils is composed of distinctly layered sediments of variable depths. These sediments range from slightly loose to lightly consolidated fine to medium silty sands. The Sabkha surface is enriched with different types of salts, such as carbonates, sulphates and chlorides (Ismael, 1993-b; Ismael and Mollah, 1998). The Sabkha flats within the sampling zone were expected to exhibit stable ground conditions for sampling purposes due to the cementation effect of different salt layers and crystals during dry conditions.

3.5 Soil survey

The main objective of the soil survey was to investigate soil variations within the test zone, to select preliminary sampling locations and reference them on the area map. The soil survey consisted of many phases, including:

- Desk study
- Site reconnaissance.
- Preliminary assessment.

Information derived from the soil survey was especially important to:

- provide a background picture of the test zone,
- exclude locations that presented dangers or difficulties during sampling,
- design a better sampling plan and
- decide the best locations for sampling.

The soil survey extended over a long period of time and required considerable manpower because of the size of the area that had to be covered. Adverse ground and climatic conditions during this stage also contributed to the prolonged time needed to complete the soil survey.

3.5.1 Site reconnaissance

Site reconnaissance was carried out to collect data on the test zone, to identify, assess and characterise Sabkha flats within it and to observe any variations in soil texture, colour and visible salt formations. Site reconnaissance was also undertaken to gain a general understanding of the field conditions, to familiarise the sampling team with characteristics and features of the test zone, and to explore the area before selecting appropriate sampling locations and methods. Construction companies with ongoing construction projects within the test zone were contacted and information about soil conditions, boreholes, and groundwater variations were obtained from them. Locations that were difficult to reach or dangerous due to the presence of land mines or cluster bombs left behind after the Gulf war, were excluded.

Site reconnaissance provided an orderly, on-the-ground field map showing sampling locations and preliminary soil data. In addition, information collected from companies working in the same area was organised, checked and added to the map.

At the end of the site reconnaissance, a preliminary map of the test zone with potential sampling locations was developed. Estimation of manpower and equipment required for the sampling processes was also undertaken.

3.5.2 Preliminary assessment

Preliminary assessment was conducted to identify the initial sampling locations and sample size through reviewing and screening collected information together with data already provided from the site reconnaissance. Preliminary assessment involved a thorough examination of all existing and obtained information relating to the study area, the location of previous soil samplings and a review of sketches and photographs of the test zone. Background information collected from companies in the test zone was evaluated and studies conducted on the test zone were reviewed.

The preliminary assessment resulted in identifying suitable soil sampling locations on the map after:

- Excluding several Sabkha locations close to the shoreline (as shown in Plate 3.1) due to time and resources constraints. Sampling from these locations was viewed as impossible, given limited resources.
- Minimising variability in selected areas.
- Ensuring the safety of the work team; areas thought likely to contain land mines, cluster bombs and other explosive remnants of war were avoided.

Importantly, preliminary sampling locations were selected on the basis of their uniform soil condition and representativeness of the test zone. Assessment of sampling locations and sample size required a considerable amount of collected information in addition to the data already provided from the site reconnaissance.

3.6 Soil sampling plan and methodology

Planned soil sampling was divided into two main phases, namely, preliminary and extensive soil sampling. After completing the surveying process, locations for preliminary sampling were marked on the site map. Preliminary soil sampling was conducted between September and October 2003, while extensive soil sampling from the main selected locations was conducted in November 2003. This time period was selected for the following reasons:

- It is the end of the dry season when the accumulation of different types of salts at the soil surface is at its peak.
- Sabkha flats exhibit stable ground conditions during this period, thus facilitating movement of vehicles and the sampling team and thereby reducing sampling time and risk.

3.6.1 Preliminary soil sampling

This sampling phase was carried out to collect initial samples from the test zone based on soil survey results. During this process, sixty-five representative soil samples weighing about thirty kilograms each were collected from excavated pits at almost the same depth.

Soil testing was undertaken using remoulded samples since the intended use of Sabkha soil materials is as construction materials of different engineering purposes. Sampling pits were prepared by excavating and removing the top 20cm layer of soil to expose fresh soil and avoid the influence of vegetation, as shown in Plate 3.2. Collected samples were transported to the Kuwaiti Ministry of Defence Laboratory for characterisation.

A preliminary testing programme was performed on these samples to study the variability of soil conditions in the selected locations. Preliminary characterisation tests, including particle size distribution, consistency limits, specific gravity, compaction, and X-ray diffraction analysis, were subsequently carried out on the samples.

3.6.2 Extensive soil sampling

After testing, the collected Sabkha soil samples were banded into four main soil sample types. Each type represented a Sabkha flat within the test zone. Soil samples from locations shared relatively uniform soil properties and a narrow range of soil characteristics.

In this sampling phase, larger soil samples were collected from the selected locations in order to ensure their availability for different tests. A shovel was used to excavate the soil after removing the thin surface layer as shown in Plate 3.3. A minimum of 400 kilograms of soil was taken from each location. Bags containing soil samples were labelled in detail to show the location and elevation at which samples had been taken. Each sample was given a number, transcribed on a map, to assist return to the exact location from which it had been taken, should additional samples be required. The final selected locations were Sabkha flats in the following areas: Al-Jailaiaha (J), Al-Zour (Z), Al-Khiran (K) and Benider (B). Designations used to identify the soils, their locations, number of samples and types are presented in Table 3.1

3.7 Site conditions

Data for soil conditions within the survey zone were obtained from a previous investigation undertaken by a private company (INCO, 1999). Soil profiles in general for all the sites revealed a surface layer of mainly silty sand soil. Sand in these layers was fine to medium grained with the percentage of fines varying between 5% and 15%. The surface layer contained random intercalations and different percentages of shells and cemented particles. The presence of gypsum ($CaSO_4.2H_2O$) crystals was noted in the surface areas in all locations, and small accumulation of loose sodium chloride crystals ($NaCl$) due to the evaporation of tidal water at the surface was noted in location 4.

Field measurements of groundwater levels carried out by INCO (1999), a company working in the area, are shown in Figure 3.4. The ground water level is shallow and ranges in depth from 0.6 to1.1m in winter, increasing in depth to a range of 1.0 to 2.2 m, in summer. This level is similar to ground water levels of other Sabkhas in the Gulf region (Sabtan and Shehata, 2003). The rise in groundwater creates many problems, including dissolution of water-soluble salts, weakening of the foundation soil, and sulphate/chloride attack on the foundation of structures (Sabtan and Shehata, 2002).

The natural moisture content of the Sabkha soils was measured during soil sampling. Small weights of soil extracted at different depths were placed in sealed small containers. The natural moisture content of collected soil samples was determined in the laboratory as soon as they arrived from the site.

The natural moisture content of the surface layer of Sabkha soil in Al-Jailaiaha (J), Al-Khiran (K) and Benider (B) ranged from 8% to 28%. Typical variations in natural moisture content for the four locations at different depths are presented in Figure 3.5. It should be noted that these values were recorded in June when temperatures exceeded 35°C. During the winter season, Sabkha flats in Al-Jailaiaha (J), Al-Khiran (K) and Benider (B) are completely wet or flooded. The surface and near-surface soils in Al-Zour (Z) are relatively dry compared to those in other locations, i.e. their moisture content is lower than 5%. The natural moisture content of the soil in Kuwait ranges between 0% and 25% (Al-Sanad and Shaqour 1991; Al-Sanad 1986).

Investigation of different locations within the test zone revealed many important characteristic features of Sabkha flats:

- During the preliminary inspection of different sites, it was noted that the thickness of the soil crust varied between the different sites in the range of few to 10 cm, as a result of the latter being made up of salt-rich layers of different types and concentrations. This variation has been attributed by Akili and Torrance (1981) to the evaporative pumping mechanism, which precipitates soluble minerals as a crust on the surface or at other levels above the shallow water table. It was further noted that almost all sites contained a significant amount of different salts (Plate3.4).

- The groundwater table levels in Al-Jailaiaha (J), Al-Khiran (K) and Benider (B) are shallow, vary between winter and summer, and are similar to those in other Sabkhas (Serhan and Sabtan, 2000; and Sabtan and Shehata, 2002). It was noted during sampling in some locations that groundwater table rose within a relatively short time, increasing sampling difficulty.

- During sampling, it was observed that the hard soil crust was highly susceptible to moisture, losing its strength upon saturation during the rainfall season as had been previously reported by Al-Shamrani and Dhowian (1997).

- Visual examination during excavation revealed a well developed cementing bond in Al-Jailaiaha (J), Al-Khiran (K) and Benider (B) (Plate 3.4). These sites also contained a larger moisture content and percentage of fines than Al-Zour (Z).

- After a rainstorm, the extent of dissolved salts in the runoff inundation water and precipitation of salts on the sides of the excavated pits became apparent, since a white powdery crust remained on the sides of excavated pits upon drying. Difficulty moving within Sabkha flats after rainstorms was commonly experienced in all locations. This was attributed to instability due to strength loss resulting from dissolution of different types of salts, which had provided partial cementation to the crust (Sabtan and Shehata, 2002).

- Large areas of the Sabkha flats were completely covered with flood water (Plate 3.5), mainly because of their flat topography, low elevation, gentle gradient, and relatively low permeability (Sabtan and Shehata 2002). Generally, Sabkha soil surface dips very gently seaward at imperceptible rates. Its elevation does not usually exceed a few centimetres to one and a half metres above the mean high-water level (El-Naggar, 1988).

- Layers of cemented soils were observed at different levels and with different thicknesses and were underlain by weakly cemented silty sands (Plate 3.4). These variations are related to the repeated drying of inundation waters rich in dissolved salts (Livneh et al., 1998; Yechieli and Wood, 2002).

3.8 Characterisation of Sabkha soil samples

The collected quantities of soil materials were air dried and, when required, oven drying was used to a maximum temperature of about 60°C, since salt bearing soils are affected by temperature employed. Drying at high temperature has been found to cause significant changes in the properties of these soils (Ismael, 1993-b). The soils were dried until a state was reached at which they could be crumbled. Soil particles within lumped pieces were gently separated using rubber hammers. The crushing of individual particles was avoided. This process was carried out until all the materials passed through a 2.0 mm test sieve. Sieved materials were thoroughly mixed again, homogenised and placed in a large container. This procedure produced a large quantity of highly consistent material. The collected soil material from each selected location was divided by a mechanical splitter into two portions. One soil portion was shipped to the UK and stored at Cardiff University laboratory, while the other portion was kept in the Ministry of Defence laboratory in Kuwait. The soil preparation method was critically important to achieve reliable and repeatable results.

3.8.1 Physical and Index Properties

Physical characteristics are important factors in evaluating geotechnical properties and in understanding the different behaviours of soil. Sabkha soils were subjected to identification tests to determine their physical properties. Soil tests included in this stage were particle size distribution, consistency limits, specific gravity, compaction and coefficient of permeability.

3.8.1.1 Particle size distribution

Testing of particle size distribution was carried out in two parts: for washed particles > 63μm using the sieve analysis test according to BS 1377: Part 2: 1990:9.2 and for washed particles < 63μm using a hydrometer according to BS1377: Part 2:1990: 9.5.

The sieve analysis test was carried out on all samples in both sampling phases, while the hydrometer test was carried out only on selected soil samples which had a fine percentage higher than 5.0%. Particle size distribution for part of the collected soil samples is shown in Figure 3.6. Upper and lower bounds of the grain size distribution curves for all samples are shown in the same figure. Although the range may be considered wide, taking into account the large area covered, the variation in range may be regarded as narrow. In general, collected samples were composed of sand with no gravel. Grain size distribution curves indicate that the percentage of fines, passing through a 63 μm sieve, ranged from 2% to 12%. Soils from locations B and K had the highest percentage of fines, whereas soils from locations J and Z had the lowest percentage of fines. The clay percentage was found to be very low (less than 1%) but existed at all locations, except location Z.

Based on the preliminary results, collected soils were banded into four main zones of more or less uniform gradations. Particle size distributions for the banded soils are shown in Figures 3.7, 3.8, 3.9 and 3.10 for soils S_J, S_Z, S_K and S_B, respectively, and summarised in Tables 3.2 to 3.5. The uniformity of each zone can be observed from these figures. Moreover, these figures show that sand, with its coarse, medium and fine size fraction, comprised 95%, 96%, 86%, and 84% of soils S_J, S_Z, S_K and S_B, respectively.

Representative soil samples from locations were designated as follows: S_{J-4} (sample No.4) from Al-Jailaiaha (J), S_{Z-5} (sample No.5) from Al-Zour (Z), S_{K-7} (sample No.7) from Al-Khiran (K) and S_{B-8} (sample No.8) from Benider (B).

Particle size distribution curves, shown in Figure 3.11, indicate that soil S_{K-7} and S_{Z-5} have almost similar gradation curves for particle sizes ranging from 0.15 to 0.425mm. Soil S_{B-8} has almost uniform gradation curves for medium size particles ranging from 0.25 to 0.45mm. A clear absence of particle sizes ranging from 0.070mm to 0.10mm and from 0.25 mm to 0.425mm is noticeable in soil sample S_{B-8} Soil sample S_{K-7} represented the upper boundary, while S_{Z-5} and S_{B-8} represented the lower boundary of tested soils.

Soil gradation results are in good agreement with findings reported by Al-Hurban and Al-Gharib (2004), whose investigations of Sabkha soils in southern Kuwait revealed an average sand size percentage of 96%.

3.8.1.2 Consistency limits

Consistency limits tests undertaken were liquid limit and plastic limit, which represent the upper and lower limits of water content over which the soil exhibits plastic behaviour, respectively.

Liquid limit and plastic limit tests for natural Sabkha were carried out in accordance with BS 1377 part 2:1990: 5.3 and 4.3, respectively. Liquid limit tests were carried out using Casagrande's apparatus. The plasticity index (PI) was calculated from these two values.

The plasticity properties of different Sabkha soils are presented in Tables 3.2, 3.3, 3.4, and 3.5. Almost all the soil samples were found to be low to non-plastic. Soils S_{J-4} and

S_{Z-5} had plasticity limit values of less than one, while other soils' PI values were less than four. Collected samples' plasticity results are illustrated on the plasticity chart provided in Figure 3.12, with all results plotted below the A-line. Liquid limit for all samples is well below 30%, indicating the low plastic nature and compressibility of the soils (Mitchell, 1993). The low plasticity of the Sabkha soils is due to low fine contents, which are mostly silt. The PI of a soil increases with an increase in fine content and the amount of clay particles (Arora, 1997). High concentrations of soluble salts can affect the consistency limits of a soil (Mahasneh, 2004). Similar results have been reported by Al-Sanad (1986) and Ismael (1993a; 1993b) in their investigations of soil properties in Kuwait.

3.8.1.3 Soil classification

Sabkha soil samples were classified according to the British, Unified and American Association of State Highway and Transport Officials (AASHTO) soil classification systems. Classifications are based on Atterberg limits and grain size analysis. British classification was conducted in accordance with the procedures described in BS1377 (1990). The Unified Soil Classification System (USCS) was conducted as recommended by the American Society for Testing of Materials, ASTM D-2487 (ASTM, 2000).

Soil classification is based on fine contents, coefficient of uniformity, C_u, and the coefficient of curvature, C_c, defined as $C_u=D_{60}/D_{10}$ and $C_c=(D_{30})^2/(D_{60}\times D_{10})$, where D_{10}, D_{30} and D_{60} refer to the particle-size diameter corresponding to 60%, 30%, and 10% passing, respectively. Calculated C_c and C_u values and classification results of collected soils are summarised in Tables 3.2 to Table 3.5.

Sabkha soils S_{J-4} and S_{Z-5} were generally classified as poorly graded sand (SPu) and (SP) according to the BSI and USCS, respectively. Soils S_{K-7} and S_{B-8} were classified as poorly graded silty sand SPM and (SP-SM) according to BSI and USCS, respectively.

According to the soil classification system of the American Association of State Highway and Transportation Officials (AASHTO, 1993) procedure M145-73, tested Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} were classified as A-2-4.

Soil classification results for the tested soils are in good agreement with those reported by other researchers on soils from Kuwait and the Gulf region (Al-Sanad, 1986).

3.8.1.4 Specific gravity

The specific gravity (G_s) or particle density of different soil samples was determined using a pycnometer as specified by British Standards BS 1377: Part 2: 1990: 8.3. Specific gravity values were determined from an average of two tests. Individual values differed from the mean by less than 0.01. The specific gravity values of the soils are summarised in Table 3.6.

Table 3.6 shows that the specific gravity value of the soils varied from 2.68 to 2.79, within the range of specific gravity values of southern Sabkha soils in Kuwait as reported by Ismael (1993-a; 1993-b). These specific gravity values of Sabkha soils are lower than those of typical sands or silty sands. Similar lower values were reported by Al-Amoudi et al. (1992) in their study on salt-rich soils. They attributed the lower values of specific gravity to the conjoint effect of low oven temperature (60°C) at which the specific gravity was determined and the high salt content of Sabkhas.

3.8.1.5 Soil compaction

This test was conducted to identify the dry density/moisture content relationship for different soil samples from Sabkha locations. The soil compaction test was carried out in accordance with BS1377: Part 4: 1990:3.3. A modified proctor test was performed on specimens of natural Sabkha soils.

Compaction curves for Sabkha soils from different locations are shown in Figures 3.13, 3.14, 3.15, and 3.16, representing soils S_J, S_Z, S_K and S_B, respectively. The similarity of the collected soil samples from different locations is reflected in the narrow range of variation in maximum dry density and optimum moisture content. Optimum moisture content (OMC) and maximum dry density (MDD) values, obtained from the compaction curves, for collected soils from main locations are summarised in Tables 3.2 to 3.5.

Compaction curves for representative Sabkha soil samples from all four main locations are shown in Figure 3.17. The compaction curves of soils S_{J-4}, S_{K-7} and S_{B-8} have clearly defined peaks, whereas soil S_{Z-5} has a flatter compaction curve with a double peak.

The maximum dry density and optimum moisture content values for the four representative soils are tabulated in Table 3.6. Notably, soil S_{Z-5} has a maximum dry density of 1.904 g/cm^3 at an optimum moisture content of 8.80%, the lowest value among the tested soils. Soil S_{K-7} has a maximum dry density of 1.950 g/cm^3 at an optimum moisture content of 9.20%, the highest value among the tested soil samples. The maximum dry densities of soils S_{J-4} and S_{B-8} are 1.932 g/cm^3 and 1.948 g/cm^3, respectively.

The lower dry density value of soil S_{Z-5} may be attributed to its lower fines content which created a higher void in the compacted Sabkha soil. The density of the soil mass is also affected by the degree of cementation between the soil particles, since the percentage of fines in the soil is proportional to the degree of cementation (Ismael, et al., 1986-b). In addition, the lower dry density of soil S_{Z-5} may also be attributed to its lower specific gravity value, since the specific gravity value is a factor that affects the dry density of the compacted soil (Murthy, 1992).

In general, Sabkha soil S_{Z-5} had the lowest maximum dry density, whereas soils S_{K-7} and S_{B-8} had the highest maximum dry densities. Maximum dry density and optimum moisture content values found are in general agreement with results reported in other studies on Sabkha soils in Kuwait and the Gulf region (Al-Sanad, 1986 and Ismael, 1993-b).

3.8.1.6 Coefficient of permeability

In this study, the leaching cell test was used to measure the coefficient of permeability of Sabkha soils, *k*, as described by Mohamed et al. (1994); Mohamed (1995); and Yong et al. (1992). Since the primary aim of the leaching cell test was to investigate the leachability of oil residue from oil mixed Sabkha soils and their long term permeability, this method was used for Sabkha soils.

Leaching cell tests, explained in detail in chapter 7, were undertaken on samples compacted at their optimum moisture content to their maximum dry density obtained from the modified proctor test detailed in Section (3.8.1.5). Distilled water was passed through the soil under a constant applied air pressure of 7.0psi, representing a hydraulic gradient, i, of 40. This applied hydraulic gradient was selected for both natural and stabilised Sabkha soils to compare permeability results under the same conditions. Several trials were carried out to achieve a reasonable hydraulic gradient that would create sufficient leached pore volumes within a specific period of time for oil mixed sample.

The first pore volume of distilled water was allowed to percolate slowly under low pressure of 1.2 psi to saturate the tested soil sample. The quantity of water, Q ml, flowing through a sample in a specific period of time, t seconds, under applied hydraulic gradient effect was measured and the coefficient of permeability subsequently calculated.

The coefficient of permeability results for natural Sabkha soils are presented in Table 3.6. The results indicate that the permeability of the tested Sabkha soils were 7.26×10^{-8} m/sec, 53.7×10^{-8} m/sec, 1.95×10^{-8} m/sec and 1.325×10^{-8} m/sec for soils $S_{J\text{-}4}$, $S_{Z\text{-}5}$, $S_{K\text{-}7}$ and $S_{B\text{-}8}$, respectively. These values fell within the range of low to very low permeability soils (Mitchell, 1993). Measured coefficient of permeability values fell within the range of values cited by different studies investigating different Sabkha soils in the region. These studies had reported coefficient of permeability values ranging from $2.199\text{x}10^{-9}$ m/s (Sabtan and Shehata, 2003) to $2.4\text{x}10^{-6}$ m/s (INCO, 1999). It should be noted that the use of distilled water in the tests caused salts to leach, thereby increasing permeability (Al-Amoudi et al., 1992).

3.8.2 Chemical characteristics

Sabkha soil chemical characterisation tests undertaken in this study were: soil pH, organic contents, carbonate content, cation exchange capacity, and the mineralogy of the soil. Some chemical soil and XRD tests were conducted in accordance with Minton, Treharne and Davies Limited (MTD) laboratory and Kuwait Institute for Scientific Research (KISR).

The soil pH test was conducted in accordance with BS 1377: Part 3: 1990:9. Cations and anions in the soil were analysed using ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) and IC (Ion Chromatography), respectively (HMSO, 1980). Organic contents were determined using the peroxide oxidation method. Carbonate content was identified using the rapid titration method detailed in BS 1377: Part 3:1990:6.3. The Cation Exchange Capacity (CEC) test was carried out using ammonium acetate exchange, following procedures outlined in method 16 in the MAFFL/ADAS (1987).

The chemical analysis results for the tested Sabkha soils are presented in Table 3.7. The test results indicate that Sabkha soils from all locations were moderately alkaline, with the highest pH at location S_{J-4} and the lowest at location S_{Z-5}. pH values were above 8 for most of the soils, which may be attributed to the high calcium carbonate content in the Sabkha soil. These values are in good agreement with those reported for other Sabkhas in Kuwait and the Gulf region (Al-Amoudi et al., 1992; and Ismael et al., 1986-a).

Quartz (SiO_2) was the principal component in soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, its percentage was 54.39%, 72.38%, 59.3% and 34.86%, respectively. Results showed S_{B-8} had the lowest quartz content of 34.86%. The latter percentage is similar to that recorded by Al-Sanad (1986), whose chemical soil tests revealed a quartz percentage of around 30% in soils tested from different coastal locations in Kuwait.

The amount of calcium oxide (CaO) varied between 9.95% for soil S_{Z-5} and 31.99% for soil S_{B-8}. Sodium oxide (Na_2O) ranged from 0.89% to 1.26% in all tested soil samples. The concentrations of potassium and iron oxides were also very low in all tested soil samples.

Total organic carbon content was generally less than 2.75%, due to the semiarid climatological characteristics (low rainfall and high temperatures), which reduce the input of organic matter (Caravaca and Albaladejo, 1999). The light yellowish colour of the tested soils was an indication of low organic content. Similar results were achieved by Ismael et al. (1986-a) during their investigation of soils in Kuwait. It should be mentioned that the ignition method is not suitable for determining the organic content in Sabkha soils due to phase transformations (Ismael, 1993b).

The carbonate (calcium carbonate) content was 23.35%, 19.75%, 26.24% and 39.55% in soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. High carbonate content acts as a weak cementing agent that fills up the pore space between particles (Al-Amoudi and Abduljauwad, 1995-a and b) and reduces the hydraulic conductivity and air filled porosity of the soil.

Sulphate concentration in soils S_{J-4}, S_{K-7} and S_{B-8} ranged from 10.85% to 13.68%, much higher than that in S_{Z-5}. These concentrations of sulphates in Sabkha soils consist of either gypsum or anhydrite. The results supported the visual inspection of the tested soils which revealed the presence of gypsum within the soil mass in the form of lumps (ranging in size from 1 to 5mm in diameter) that cemented the soil particles together at their contact points.

Cation exchange capacity (CEC) is the quantity of exchangeable cations held by the soil and is a measure of the positively charged ions that can be held on negatively charged sites of soil minerals (Yong et al., 2001). CEC is measured in milliequivalents (meq) per 100 grams of soil, and is highly dependent on soil texture, clay and organic matter content (Cameron, 1992). In general, the more clay and organic matter in the soil, the higher the CEC values (Yong et al., 1992). CEC results for the tested soils, listed in Table 3.7, were 11.2, 12.8, 10.7 and 13.3 meq/100g for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. These values were considerably low due to the absence of clay and organic materials, indicative of the low ability of the soils to hold cations.

3.8.2.1 Mineralogy

An XRD test was carried out during the preliminary analysis of soils in some locations in the test zone. The object of this test was to identify variation in minerals between test locations. Soil samples were selected on the basis of texture, colour and their distribution within the test zone, and obtained from different locations at a depth ranging from 40 to 70 cm. This test was conducted at the Kuwait Institute for Scientific Research (KISR) using a XRD Philips, X' Pert diffractometer.

X-ray diffraction patterns of Sabkha soils from the different locations are shown in Figures 3.18 to 3.21. The amount of different compounds identified by the XRD was estimated from the height of the corresponding peaks in the XRD diagram. Main minerals in Sabkhas soils from the four main locations are listed in Table 3.7. The X-ray diffraction diagrams of the Sabkha soil specimens show the soils were characterised by different constituents identified as quartz, gypsum, calcite, halite, and illite. Minerals determined by XRD were in good agreement with chemical analysis results presented previously in section (3.8.2). Importantly, the XRD-analysis revealed that the quantity of clay minerals was very low in the tested soils, confirming the result obtained from particle size distribution analysis (see Section 3.8.1.1). The most common clay mineral detected was illite.

Similar mineralogical results have been reported by Al-Sanad (1986), whose study on south Sabkha soils indicated that the most common minerals are quartz, gypsum and calcite. Results reported by Al-Amoudi and Abduljauwad (1995-a) and (1995-b) show a mineralogical composition similar to that of this study.

3.9 Characterisation of oil residue

In the course of the introduction to this work, reference was made to the composition of oil lakes and difficulties encountered in obtaining representative samples from them (section 1.3). Accordingly, it was then decided that oil residue for use in this research would be atmospheric bottom oil residue provided by the Kuwait Institute for Scientific Research -Petroleum Research (KISR, 2002).

The oil residue has properties similar to those of the oil lakes as demonstrated by investigations conducted by Barker and Bufarsan (2001) and Khan et al. (1995). Properties that affect the behaviour of oil residue and may be used to characterise it are density, viscosity, and chemical composition (Hahn and Associates, 2005).

3.9.1 Chemical composition

According to the chemical analysis report provided by the KISR and reproduced in Table 3.8, total hydrocarbon contents in the oil residue used in this research amounted to

85.5%, most of which (86%) were aromatic and saturated hydrocarbons. Asphaltenes and resins, which have the highest molecular weight fractions, contain most of the polar compounds (Peters and Luthy, 1993), represented 4.5% and 9.5% by weight, respectively. Elements in oil residue other than carbon and hydrogen, such as sulphur, nitrogen, vanadium, nickel and sodium, are called heteroatoms. These elements, as presented in the table, were in low concentrations.

Hydrocarbon analysis results indicate the low polarity of the oil residue due to the dominance of non-polar fractions (aromatic and saturated) and low content of polar compound (asphaltenes and resins) (Yong and Rao, 1991).

3.9.2 Physical and chemical properties

Physical properties of the used oil residue are summarised in Table 3.8. The oil residue used was a black coloured oily liquid. It was a non-volatile highly viscous material with a boiling point > 350°C. The flash point according to ASTM D-56, D-92, and D-93 is the temperature to which the oil residue must be heated under specified conditions to give off sufficient vapour to form a mixture with air that can be ignited momentarily by a flame (ASTM, 1993; 1994). The flash point of the used oil residue was 210°C. Work with hydrocarbons in the field involves different processes such as transportation, mixing and compaction with different machines. The flash point of the oil residue was relatively high and therefore, can be considered safe material for working within the field, while observing the usual safety precautions.

One of the significant properties of the oil residue if it is going to be used for stabilisation of Sabkha is its workability on site and immobility under the conditions of temperature and pressure. By definition, the pour point according to ASTM D-97 (ASTM, 1993) is the lowest temperature at which oil can be poured or flows when it is chilled without disturbance under definite conditions. The pour point value for the tested sample of oil was 20°C, which is lower than average temperature in Kuwait.

The density of the oil residue at 15°C, listed in Table 3.8, was 0.9764 g/ml. The solubility of the oil residue was found to be less than 1 mg/l, which is considered very low. Since the density of the oil residue was lower than that of water and it was not soluble, it could be classified as a light non-aqueous phase liquid (LNAPL) that exists as a separate fluid phase in an aqueous environment.

3.10 Conclusion

The objectives of this chapter were to describe the experimental programme and to present the steps taken to select the sampling zone, the sampling procedure and the preliminary tests undertaken to characterise the materials used in this research namely, Sabkha soil and oil residue.

The zone selected for study purposes comprises part of the southern Sabkha flats in Kuwait. Preliminary soil tests were conducted on 65 collected soils and detailed soil tests were carried out on samples obtained from four main study areas. The study areas were characterised by different common features. Soil in these Sabkha areas ranged from calcareous non-plastic to slightly plastic soils composed mainly of quartz and calcium, with low organic matter. X-ray analysis of the mineral content of different Sabkha soils, indicated that quartz was the predominant mineral in all tested soils with varying percentages. The principal cementing agents at all sites were the same, with different percentages, namely; gypsum and calcite.

Based on characterisation tests, the following observations were made with respect to consistency limits, maximum dry density, and optimum moisture contents:

- Fine percentages in the tested soils ranged from 2.5% to 12%.
- The soils were composed mainly of fine sands (86% to 95%).
- The soils showed low plasticity and specific gravity.
- Soils S_{K-7} and S_{B-8} had the highest maximum dry densities, whereas soil S_{Z-5} had the lowest value.

The depth of groundwater fluctuated between summer and winter, and was very shallow (less than 2.5 m). The coefficient of permeability of the soil ranged of 1.325×10^{-8} m/sec to 53.7×10^{-8} m/sec. The soils investigated in the study zone fell into the SM, SP, and SM-SP categories according to the Unified Soil Classification system.

Atmospheric bottom oil residue, a light non-aqueous phase liquid (LNAPL) was used in this study to represent the oil lake residue. This oil was relatively insoluble, non-volatile, and with a slightly lower density than that of water. The used oil was non-polar because of the dominance of saturates and aromatic hydrocarbons, with small percentages of asphaltenes and resins.

The results reported were essentially preliminary characterisation tests for the used materials. The outcome properties were used as a benchmark in the comparison with the oil mixed Sabkha soils properties.

3.11 References

AASHTO, 1993, American Association of State Highway and Transportation Officials. Standard Method of Test for the Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. Part I Specifications, 16th Edition, Designation: M145-82.

Akili, W. and Torrance, J.K., 1981. Development and Geotechnical Problems of Sabkha, with Preliminary Experiments on the Static Penetration Resistance of Cemented Sands. *Quarterly Journal of Engineering Geology*, 14(1): 59-73.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-a. Compressibility and Collapse Characteristics of Arid Saline Sabkha Soils. *Engineering Geology*, 39(3-4): 185-202.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-b. Strength Characteristics of Sabkha Soils. *Geotechnical Engineering*, 26(1): 73-92.

Al-Amoudi, O.S.B., Abduljauwad, S.N., El-Naggar, Z.R. and Rasheeduzzafar, 1992. Response of Sabkha to Laboratory Tests - A Case Study. *Engineering Geology*, 33(2): 111-125.

Al-Hurban, A. and Gharib, I., 2004. Geomorphological and Sedimentological Characteristics of Coastal and Inland Sabkhas, Southern Kuwait. *Journal of Arid Environment*s, 58(1): 59-85.

Al-Sanad, H.A., 1986. Characterisation of Salt-Bearing Soils (Sabkha) for Pavement Design Purposes in the State of Kuwait. *Journal of the University of Kuwait-Science*, 13(1): 29-41.

Al-Sanad, H.A. and Shaqour, F.M., 1991. Geotechnical Implications of Subsurface Water Rise in Kuwait. *Engineering Geology*, 31(1): 59-69.

Al-Shamrani, M.A. and Dhowian, A.W., 1997. Preloading for Reduction of Compressibility Characteristics of Sabkha Soil Profiles. *Engineering Geology*, 48(1-2): 19-41.

Arora, 1997. Soil Mechanics and Foundation Engineering. Standard Publishers Distributors, Delhi, p.852.

ASTM, 1993, American Society for Testing and Materials, ASTM International. Analytical Testing Services, http://www.wetestit.com/astm_test_methods.htm.

ASTM, 1994, Annual Book of ASTM Standards. ASTM E-1321 Standard Test Method of Material Ignition and Flammability, vol. 0407. 1055-1077.

ASTM, D2487. 2000. Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International. 12.

Barker, C. and Bufarsan, A., 2001. Evaporative Losses from the Surfaces Oil Lakes of Southern Kuwait. *Environmental Geosciences*, 8: 123-129.

BSI, 1377:1990. British Standards and Methods of Tests for Soils for Civil Engineering Purposes. British Standard Institute.

Cameron, R.E., 1992. Guide to Site and Soil Description for Hazardous Waste Site Characterisation. NV 89119, Contract Number 68-C0-0049, Environmental Monitoring Systems Laboratory, Office of Research and Development U.S. Environmental Protection Agency, Las Vegas.

Caravaca, F., Lax, A. and Albaladejo, J., 1999. Organic Matter, Nutrient Contents and Cation Exchange Capacity in Fine Fractions from Semi-arid Calcareous Soils. Geoderma, 93(3-4): 161-176.

El-Naggar, Z.R., 1988. Foundation Problems in Sabkha Deposits. In: Abdul-Jauwad, S. (Coordinator). In: King Fahad University O.P.M. (Editor), Short Course on Foundation Engineering for Practicing Engineer, Dhahran, pp. SD1-SD54.

Hahn and Associates, I., 2005. Summary Report-Former MGP Operations and Dense Non-Aqueous Phase Liquid Occurrence. HAI Project No.2708, NW Natural, Portland, Oregon.

Head, K.H., 1981. Manual of Soil Laboratory Testing, 1. Pentech Press, London, p. 387.

HMSO, 1980. Emission Spectrophotometric Multielement Methods of Analysis for Waters, Sediments and other Materials of Interest to Water Industry. ISBN NO. 0117500151, Environment Department, London.

INCO, 1999. Soil Investigation for Al-Khiran Residential Pearl City Project, La'ala Al-Kuwait Real Estate Company-Al-Shaheen Consltants (ASCO/BURO HAPPOLD, Kuwait.

Ingles, O.G. and Metcalf, J.B., 1972. Soil Stabilisation: Principles and Practice. Butterwoths & Co. Ltd., Melbourne, Australia.

Ismael, N.F., 1993-a. Laboratory and Field Leaching Tests on Coastal Salt-Bearing Soils. *Journal of Geotechnical Engineering*, 119(3): 453-470.

Ismael, N.F., 1993-b. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035. Washington, D.C.

Ismael, N.F., Jeragh, A.M., Mollah, M.A. and AL-Khaldi, O., 1986-a. A study of the Properties of Surface Soils in Kuwait. *Geotechnical Engineering*, 17: 67-87.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Ismael, N.F., Mollah, M.A. and AL-Khaldi, O., 1986-b. Geotechnical Properties of Cemented Soils in Kuwait. Australian Road Research, 16(2): 94-104.

Khan, Z.H., AbuSeedo, F., Al-Besharah, J. and Salman, M., 1995. Improve of the Quality of Heavily Weathered Crude Oils. *Fuel*, 74(9): 1375-1995.

KISR, 2002, Kuwait Institute for Scientific Research-Petroleum Department. Chemical Analysis Report-Oil Residue.

Livneh, M., Livneh, N.A. and Hayati, G., 1998. Site Investigation of Sub-Soil with Gypsum Lenses for Runway Construction in an Arid Zone in Southern Israel. *Engineering Geology*, 51(2): 131-145.

MAFF/ADAS, 1987. The Analysis of Agricultural Materials. Reference Book 427. Ministry of Agricultural, Fisheries and Food/Agricultural Development and Advisory Services.

Mahasneh, B.Z., 2004. Dead Sea Water as a Soil Improvement Agent. *Electronic Journal of Geotechnical Engineering* (EJGE), 9: http://www.ejge.com/2004/Pro0401.htm.

Mitchell, J.K., 1993. Fundamentals of Soil Behaviour. 2nd ed., John Wiley and Sons, Inc., New York, p. 437.

Mohammed, A.O.M., Yong, R.N., Tan, B.K., Farkas, A. and Curtis, L.W., 1994. Geoenvironmental Assessment of a Micaceous Soil for its Potential Use as an Engineering Clay Barrier. *Geotechnical Testing Journal*, 17(3): 291-304.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and its Geoenvironmental Implications. PhD Thesis, McGill University, Montreal, Canada.

Murthy, 1992. A Text Book of Soil Mechanics and Foundation Engineering. Sai Kripa Technical Consultants, Bangalore.

Peters, C.A. and Luthy, R.G., 1993. Coal-Tar Dissolution in Water-Miscible Solvents-Experimental Evaluation. *Environmental Science & Technology*, 27(13): 2831-2843.

Sabtan, A.A. and Shehata, W.M., 2002. Problematic Sabkha - A Potential Source of Fresh Water. *Bulletin Engineering Geology Environment*, 61(2): 153-159.

Sabtan, A.A. and Shehata, W.M., 2003. Hydrogeology of Al-Lith Sabkha, Saudi Arabia. *Journal of Asian Earth Sciences*, 21(4): 423-429.

Serhan, T.N. and Sabtan, A.A., 2000. Geotechnical and Geochemical Properties of Al-Nekhala Sabkha, South of Jeddah. *Journal of King Abdulaziz University, Earth Sciences*, 11.

Yechieli, Y. and Wood, W.W., 2002. Hydrogeologic Processes in Saline Systems: Playas, Sabkhas, and Saline Lakes. *Earth-Science Reviews*, 58(3-4): 343-365.

Yong, R.N., Mohamed, A.M.O. and Warkentin, B.P., 1992. Principles of Contaminant Transport in Soils, Developments in Geotechnical Engineering 73. London: Elsevier Science Publications.

Yong, R.N. and Rao, S.M., 1991. Mechanistic Evaluation of Mitigation of Petroleum Hydrocarbon Contamination by Soil Medium. *Canadian Geotechnical Journal*, 28: 84-91.

Yong, R.N., Yaacob, W.Z.W., Bentley, S.P., Harris, C. and Tan, B.K., 2001. Partitioning of Heavy Metals on Soil Samples from Column Tests. *Engineering Geology*, 60: 307-322.

Table 3.1. Sampling locations and number of collected samples

Sampling Location	Location Name	Geographical Position		Number of Preliminary Soil Samples	Number of Detailed Soil Samples	Number of Rejected Soil Samples	Designation
		E	N				
1	Al-Jailaiaha	816919.782	3196034.322	15	1	2	$S_{J\text{-}X}$
2	Al-Zour	829999.009	3168932.132	14	1	3	$S_{Z\text{-}X}$
3	Al-Khiran	821788.401	3179747.870	12	1	0	$S_{K\text{-}X}$
4	Benider	822462.049	3177263.062	16	1	3	$S_{B\text{-}X}$

***X-refers to the soil sample number from the area**

Table 3.2. Physical characterisation of Sabkha soil samples from Al-Jailaiaha (J)

Soil sample	D_{10}	D_{30}	D_{60}	C_U	C_c	Fines %	Clay %	PL %	LL %	PI %	Soil Classification			Gs	OMC %	MDD g/cm^3
											British System	Unified System	AASHTO System			
S_{J-1}	0.075	0.13	0.27	3.60	0.83	3.50	0.50	21.0	21.5	0.50	SPu	SP	A-2-4	2.54	11.0	1.9155
S_{J-2}	0.075	0.095	0.20	2.60	0.60	3.50	0.50	20.2	21.0	0.80	SPu	SP	A-2-4	_	9.10	1.9250
S_{J-3}	0.075	0.09	0.25	3.30	0.43	2.75	_	21.5	22.0	0.50	SPu	SP	A-2-4	_	9.35	1.9150
S_{J-4}	0.075	0.12	0.22	2.93	0.87	4.50	0.50	21.3	22.0	0.70	SPu	SP	A-2-4	2.68	9.80	1.9320
S_{J-6}	0.075	0.15	0.30	4.00	1.00	3.00	0.50	22.2	23.0	0.80	SPu	SP	A-2-4	_	11.5	1.9430
$S_{J-1}0$	0.075	0.17	0.38	5.06	1.01	2.50	0.50	20.4	21.0	0.60	SPu	SP	A-2-4	_	9.80	1.9320

Table 3.3. Physical characterisation of Sabkha soil samples from Al-Zour (Z)

Soil sample	D_{10}	D_{30}	D_{60}	C_u	C_c	Fines %	Clay %	PL %	LL %	PI %	Soil Classification			Gs	OMC %	MDD g/cm^3
											British System	Unified System	AASHTO System			
S_{Z-1}	0.10	0.175	0.330	3.30	0.927	4.00	0.0	19.2	19.5	0.30	SPu	SP	A-2-4	_	8.10	1.9070
S_{Z-2}	0.12	0.160	0.320	2.67	0.667	5.00	0.0	18.5	19	0.5	SPu	SP	A-2-4	_	8.20	1.905
S_{Z-5}	0.095	0.180	0.390	4.10	0.875	4.00	0.0	20.5	21	0.5	SPu	SP	A-2-4	2.68	8.80	1.9043
S_{Z-6}	0.10	0.180	0.330	3.30	0.982	4.00	_	_	_	0.00	SPu	SP	A-2-4	_	9.90	1.9050
S_{Z-8}	0.12	0.180	0.450	3.75	0.600	4.50	_	_	23	_	SPu	SP	A-2-4	_	8.90	1.9050
S_{Z-9}	0.09	0.180	0.460	5.11	0.782	5.00	_	_	18.5	_	SPu	SP	A-2-4	_	9.85	1.9055

Table 3.4. Physical characterisation of Sabkha soil samples from Al-Khiran (K)

Soil sample	D_{10}	D_{30}	D_{60}	C_u	C_c	Fines %	Clay %	PL %	LL %	PI %	Soil Classification			Gs	OMC %	MDD g/cm^3
											British system	Unified system	AASHTO system			
S_{K-1}	0.05	0.11	0.320	6.40	0.75	11.0	0.5	17.0	19.0	2.00	SPM	SP-SM	A 2 -4	_	11.75	1.9465
S_{K-2}	0.05	0.09	0.320	6.40	0.50	9.0	_	15.0	18.0	3.00	SPM	SP-SM	A 2 -4	_	8.250	1.938
S_{K-3}	0.05	0.09	0.285	5.70	0.56	10.0	_	16.5	18.5	2.00	SPM	SP-SM	A 2 -4	_	11.00	1.950
S_{K-4}	0.06	0.12	0.330	5.50	0.72	11.0	_	17.0	18.0	1.00	SPM	SP-SM	A 2 -4	_	8.85	1.9655
S_{K-5}	0.05	0.10	0.320	6.40	0.63	10.5	_	_	_	_	SPM	SP-SM	A 2 -4	_	11.10	1.950
S_{K-7}	0.075	0.15	0.320	4.27	0.94	11.0	1.0	17.0	19.0	2.00	SPM	SP-SM	A 2 -4	2.78	9.20	1.950

Table 3.5. Physical characterisation of Sabkha soil samples from Benider (B)

Soil sample	D10	D30	D60	Cu	Cc	Fines %	Clay %	PL %	LL %	PI %	Soil Classification			Gs	OMC %	MDD g/cm3
											British system	Unified system	AASHTO system			
S_{B-1}	0.075	0.155	0.385	5.13	0.83	10.0	–	19.50	22.5	3.0	SPM	SP-SM	A-2-4	–	10.125	1.9425
S_{B-2}	0.055	0.140	0.375	6.82	0.95	12.0	–	19.00	21.5	2.5	SPM	SP-SM	A-2-4	–	11.860	1.9400
S_{B-4}	0.068	0.115	0.300	4.41	0.64	12.0	0.50	17.50	19.5	2.0	SPM	SP-SM	A-2-4	–	13.125	1.9375
S_{B-5}	0.060	0.095	0.375	6.25	0.40	11.0	–	18.00	21.0	3.0	SPM	SP-SM	A-2-4	–	9.800	1.9350
S_{B-6}	0.05	0.125	0.380	7.60	0.82	12.0	0.50	17.00	19.0	2.0	SPM	SP-SM	A-2-4	–	9.95	1.9450
S_{B-7}	0.065	0.16	0.350	5.38	1.12	10.1	10.5	19.0	22.0	3.0	SPM	SP-SM	A-2-4	–	13.00	1.9300
S_{B-8}	0.075	0.25	0.380	5.10	2.2	10.5	–	19.0	22.0	3.0	SPM	SP-SM	A-2-4	2.79	12.20	1.9480

Table 3.6. Physical characterisation of soil samples from the main locations

Soil Location	Selected Soil Sample	Designation	G_S	$k \times 10^{-8}$ m/sec	PL %	LL %	PI %	Soil Classification		MDD g/cm^3	OMC %
								British system	Unified system		
Al-Jailaiaha	$S_{J\ -4}$	S_{J-4}	2.68	7.26	21.30	22.00	0.70	SPu	SP	1.932	9.800
Al-Zour	$S_{Z\ -5}$	S_{Z-5}	2.68	53.70	20.50	21.00	0.50	SPu	SP	1.904	8.800
Al-Khiran	$S_{K\ -7}$	S_{K-7}	2.78	1.95	17.00	19.00	2.00	SPM	SP-SM	1.950	9.200
Benider	$S_{B\ -8}$	S_{B-8}	2.79	1.325	19.00	22.00	3.00	SPM	SP-SM	1.948	12.20

Table 3.7. Chemical and mineralogical composition of Sabkha soil samples from the main locations

Soil Sample	pH	Organic Content %	SiO_2 %	CaO %	MgO %	Fe_2O_3 %	Al_2O_3 %	K_2O %	Na_2O %	SO_4^{2-} %	$CaCO_3$ %	CEC Meq/100g	XRD
S_{J-4}	8.30	1.35	54.39	16.7	2.13	1.76	4.51	0.97	1.24	12.27	23.35	11.20	Quartz- Aragonite- Gypsum Calcite
S_{Z-5}	8.05	1.05	72.38	9.95	1.11	1.69	4.53	0.99	1.11	1.920	19.75	12.80	Quartz-Albite-Calcium carbonate- Gypsum-
S_{K-7}	8.20	2.66	59.3	12.48	1.56	1.52	3.69	0.81	0.89	13.68	26.24	10.70	Quartz- Gypsum Albite-calcium carbonate
S_{B-8}	8.18	2.75	34.86	31.99	2.68	1.95	2.96	0.91	1.26	10.850	39.55	13.30	Gypsum- Aragonite - Quartz- calcite

Table 3.8. Physical and chemical characterisation of oil residue (Source: KISR, 2002)

Physical Properties	**Physical State and Colour**	Oily Liquid / Black		
	Boiling Point	°C		> 350
	Gravity	API		13.3
	Pour Point	°C		20
	Density	@ 15°C	g/ml	0.9764
	Kinematic Viscosity	@ 50°C	cSt	1162
	Flash Point	@ 20°C	°C	210
	Solubility	mg/l		< 1.0
	Vapour Pressure	@ 20°C	kPa	0.01
Chemical Composition	**Nickel**	Wt (ppm)		21
	Vandium	Wt (ppm)		69
	Nitrogen	Wt (%)		0.24
	Hydrogen	Wt (%)		11
	Sulphate	Wt (%)		3.62
	Resins	Wt (%)		9.5
	Asphaltenes	Wt (%)		4.5
	Aromatic and Saturate Hydrocarbons	Wt (%)		86
	pH			Neutral

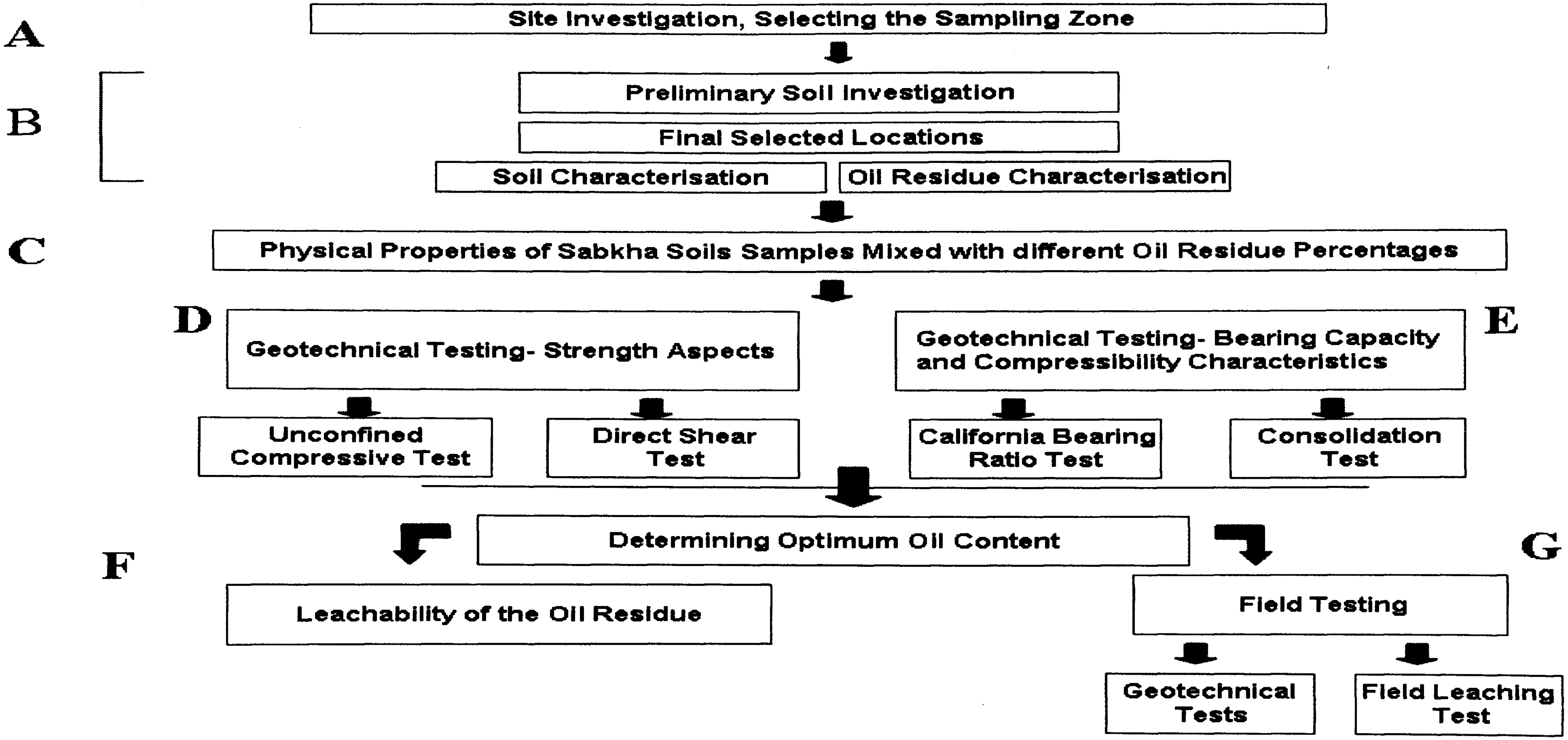

Figure 3.1. Designed experimental programme

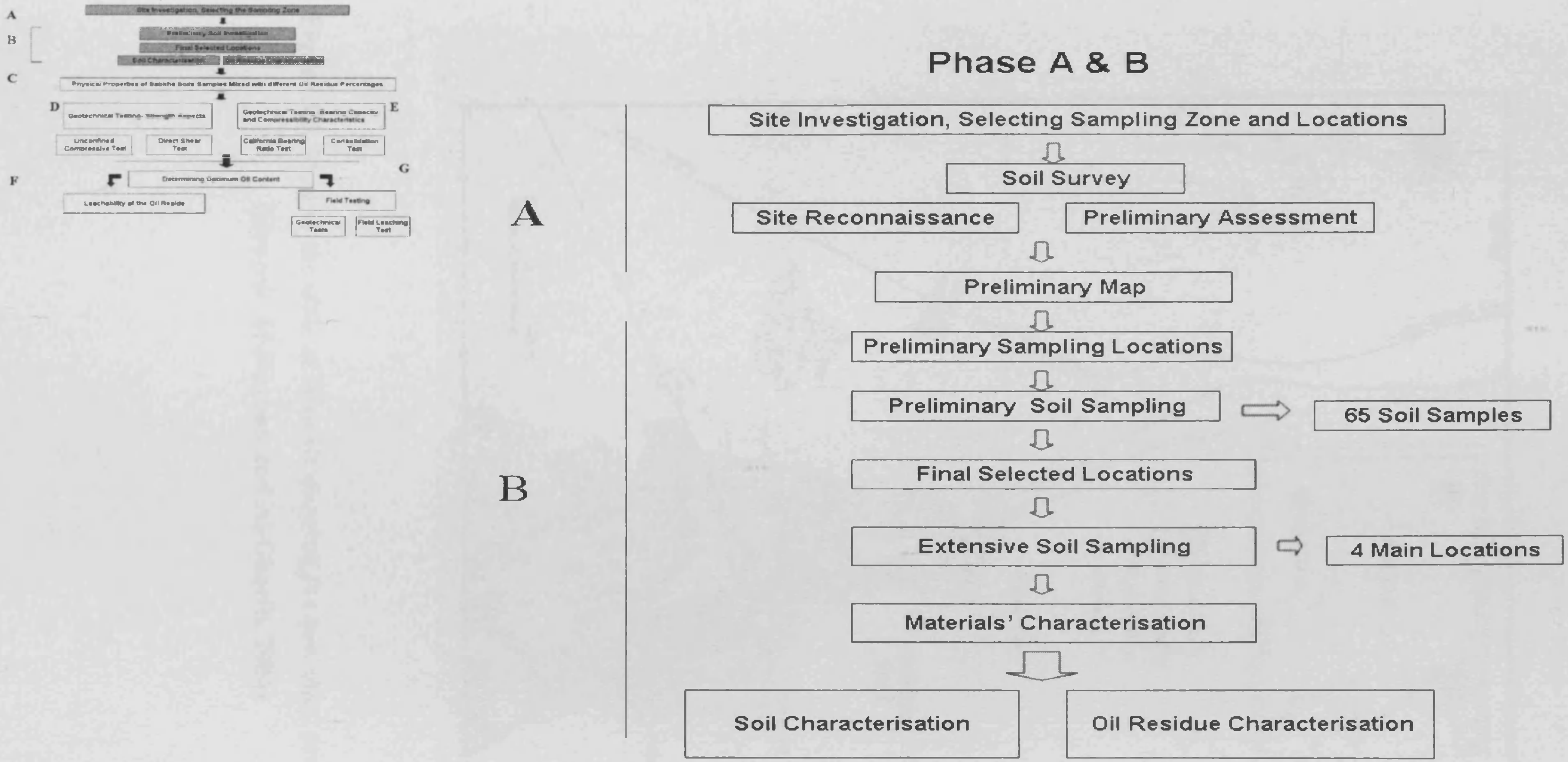

Figure 3.2. Phases A and B of the experimental programme

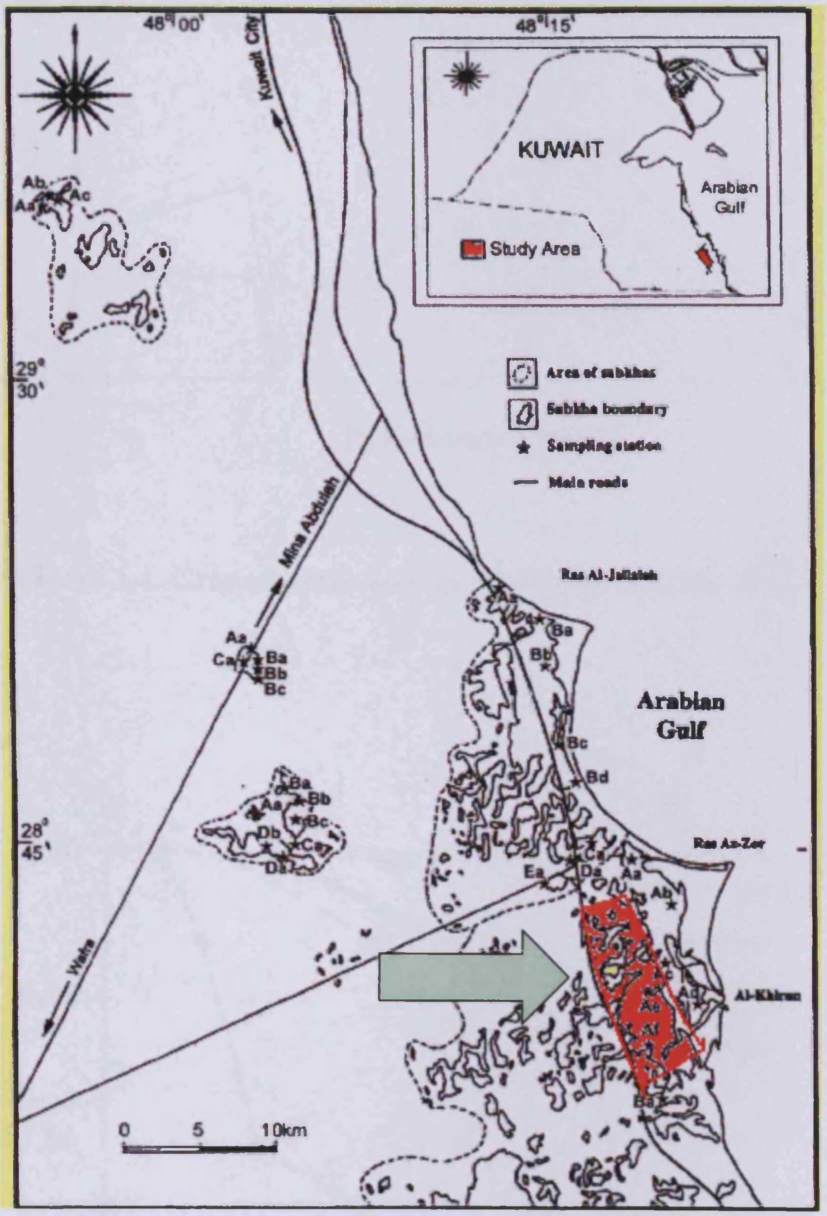

Figure 3.3. Map of the state of Kuwait showing the test zone, south Kuwait (Source: Al-Hurban and Al-Gharib, 2004)

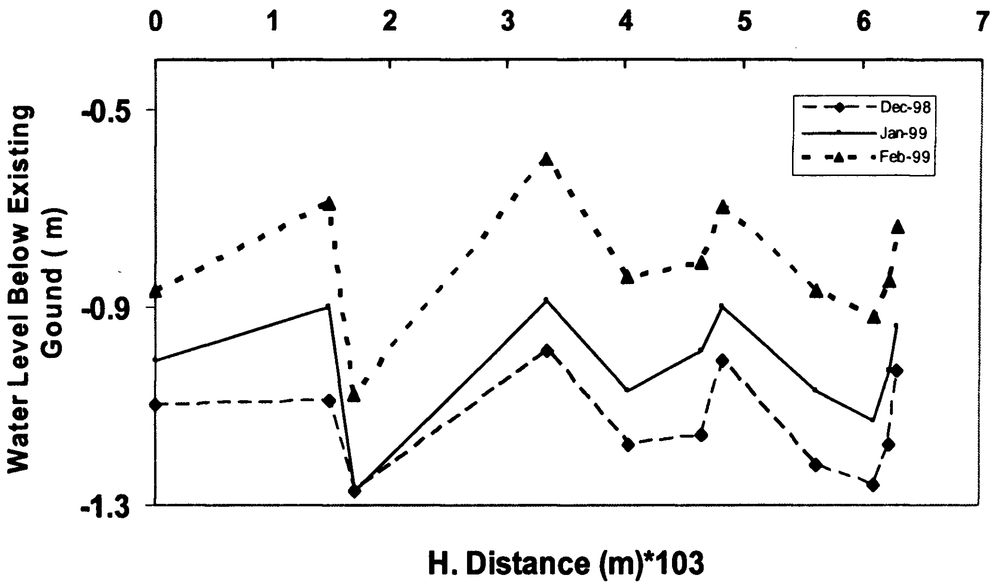

Figure 3.4. Groundwater level in Al-Khiran (INCO, 1999)

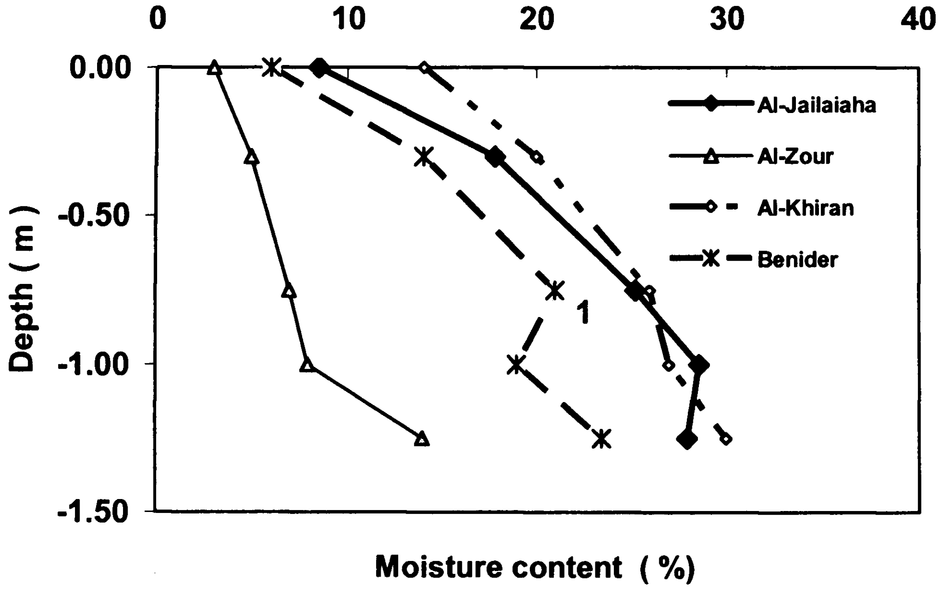

Figure 3.5. Variation of natural moisture content by depth for the main locations

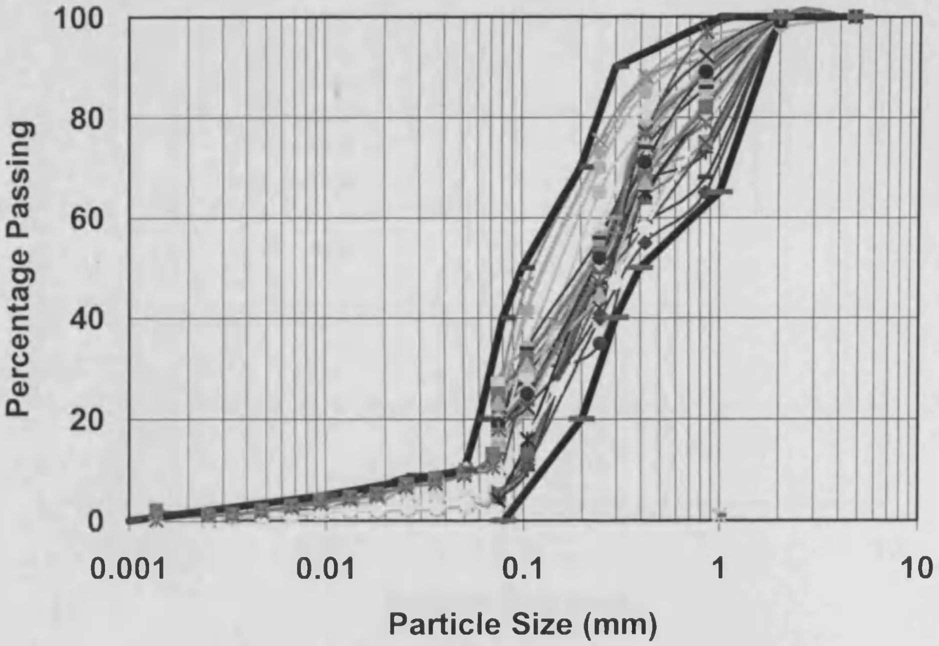

Figure 3.6. Range of particle size distribution curves for collected Sabkha soils

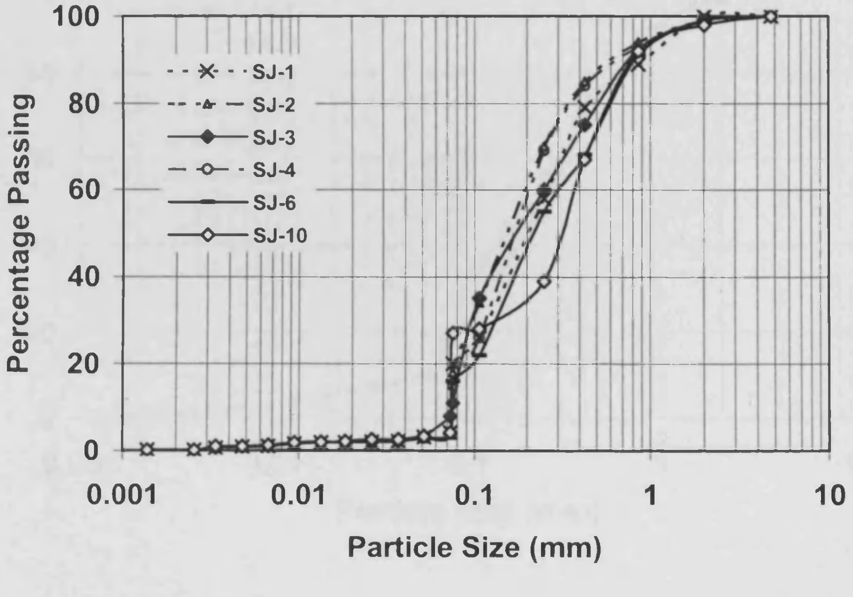

Figure 3.7. Particle size distribution curves for Sabkha soils from Al-Jailaiaha

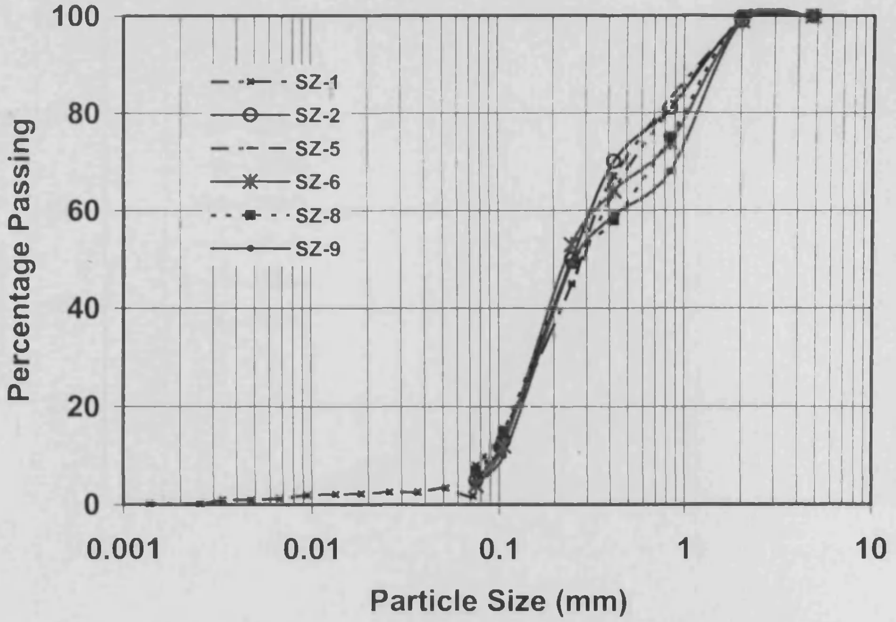

Figure 3.8. Particle size distribution curves for Sabkha soils from Al-Zour

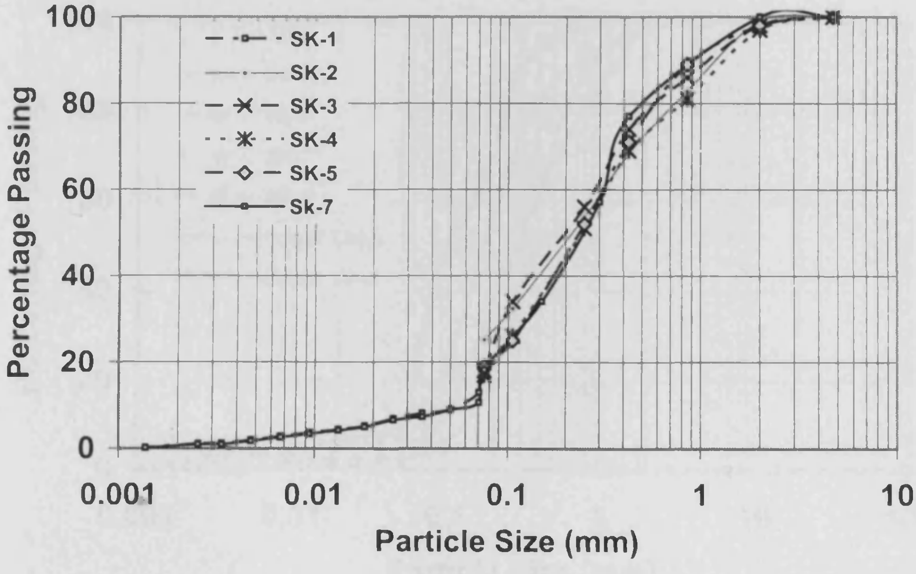

Figure 3.9. Particle size distribution curves for Sabkha soils from Al-Khiran

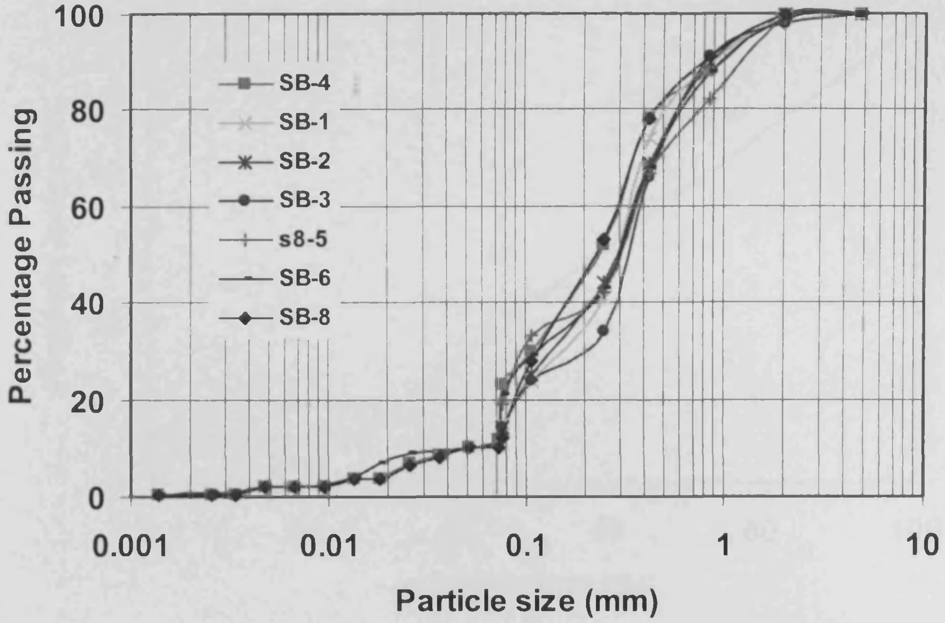

Figure 3.10. Particle size distribution curves for Sabkha soils from Benider

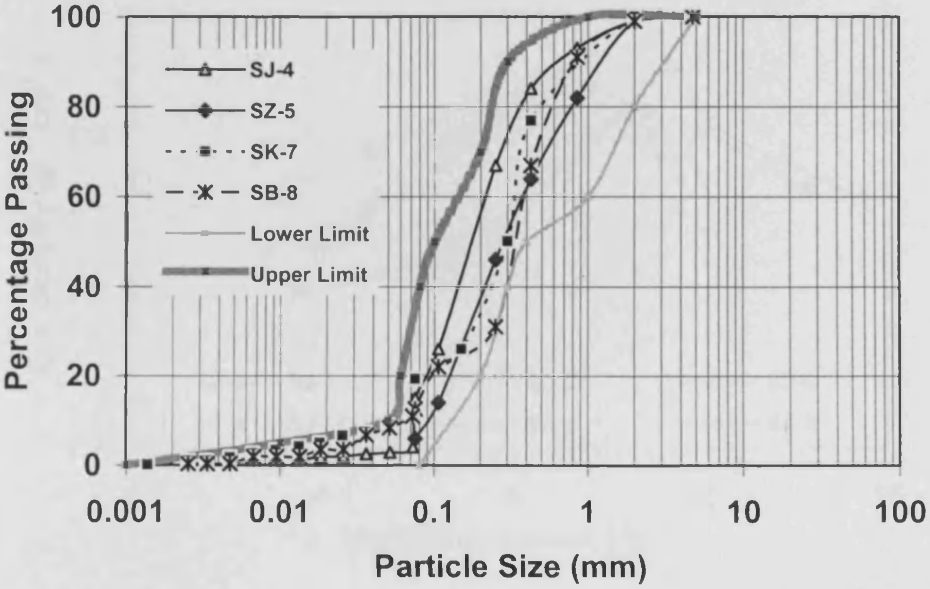

Figure 3.11. Particle size distribution curves for Sabkha soils from main locations

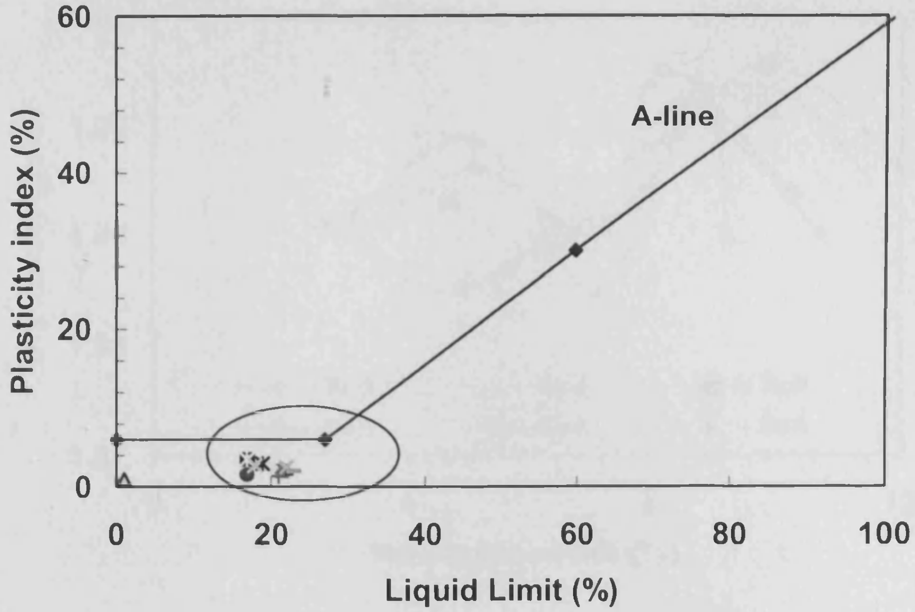

Figure 3.12. Collected samples illustrated on the plasticity chart

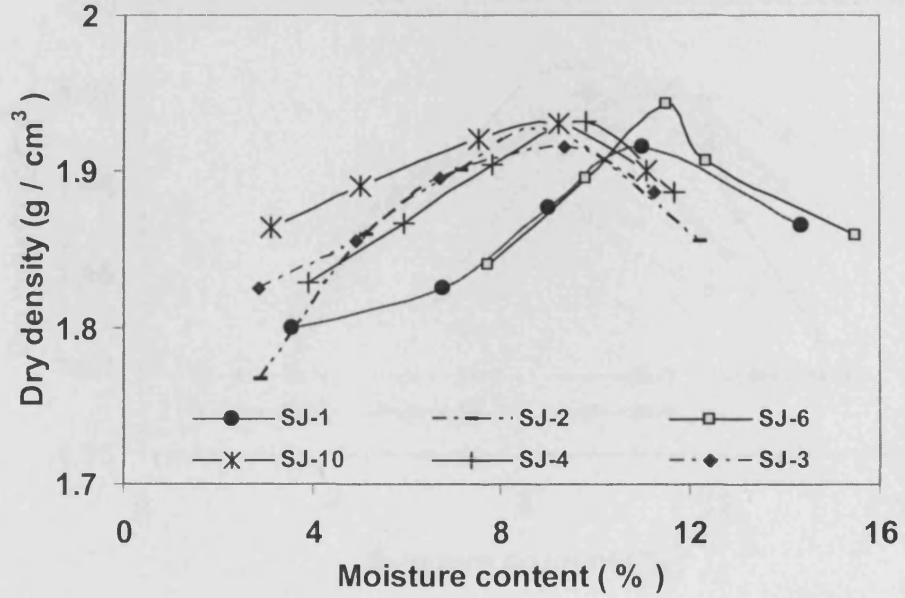

Figure 3.13. Compaction curves for Sabkha soils from Al-Jailaiaha

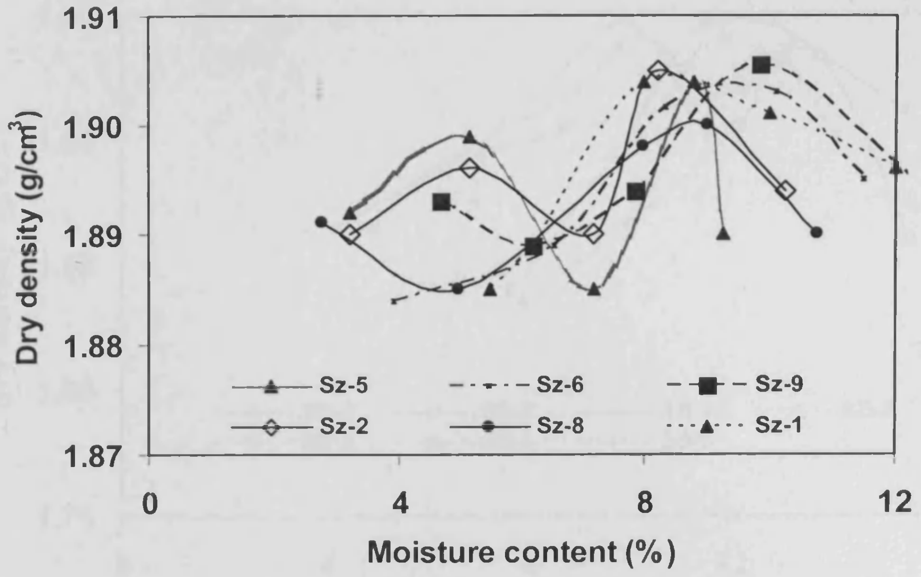

Figure 3.14. Compaction curves for Sabkha soils from Al-Zour

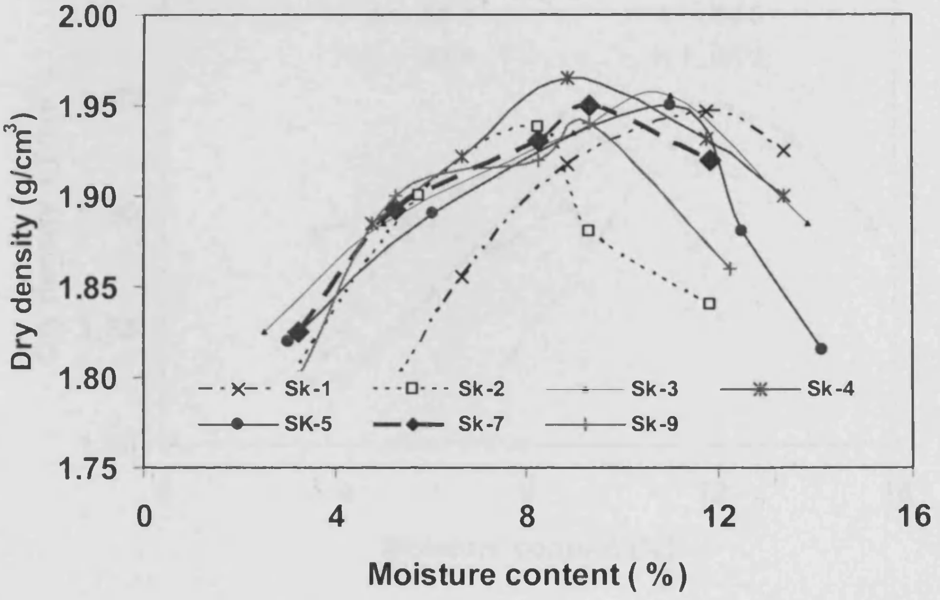

Figure 3.15. Compaction curves for Sabkha soils from Al-Khiran

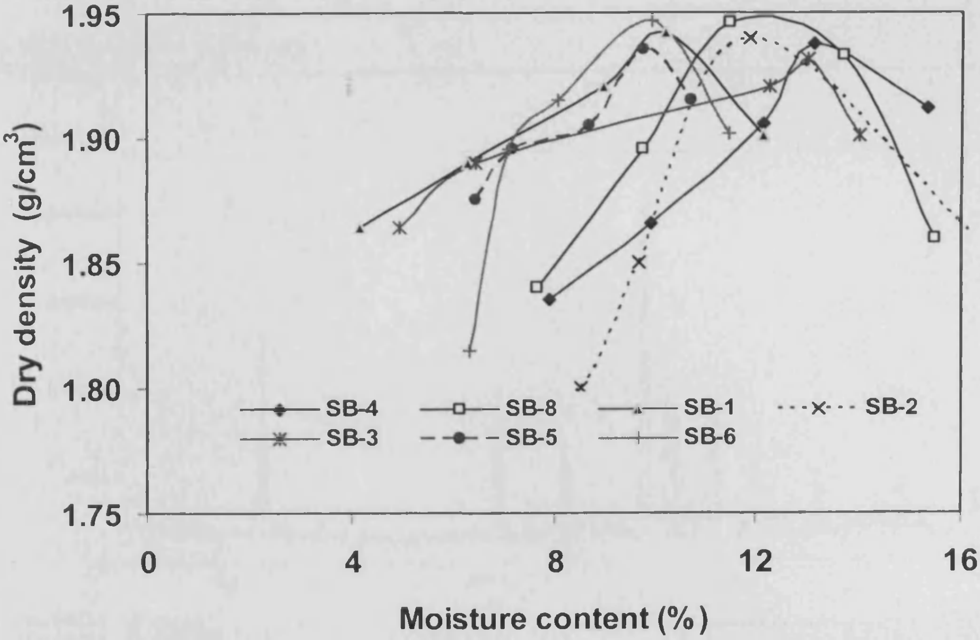

Figure 3.16. Compaction curves for Sabkha soils from Benider

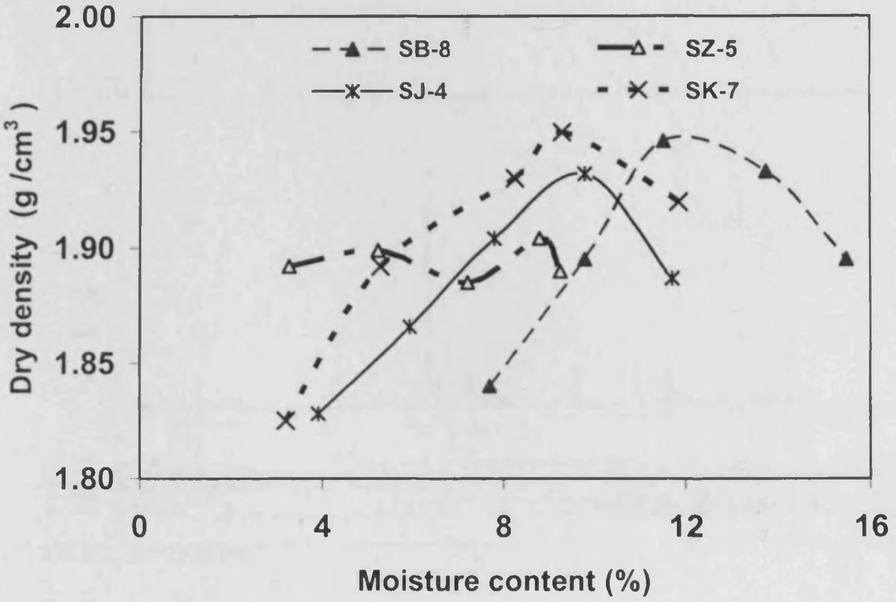

Figure 3.17. Compaction curves for Sabkha soils from main locations

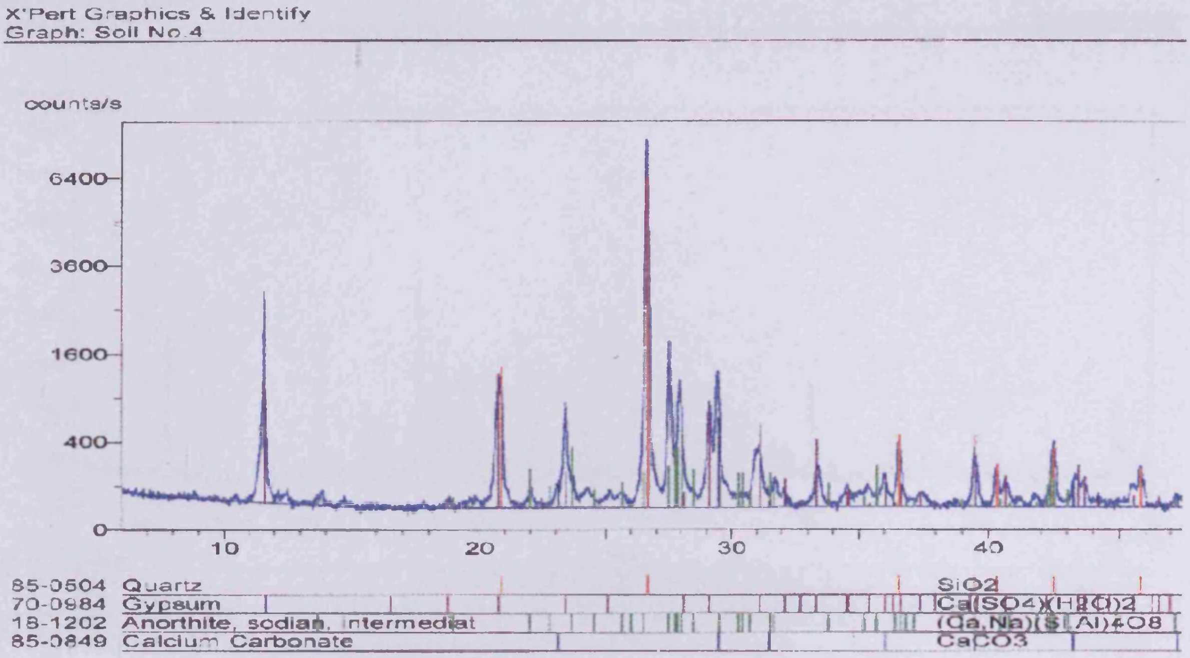

Figure 3.18. Representative X-ray diffraction pattern of Sabkha Soil S_{J-4}

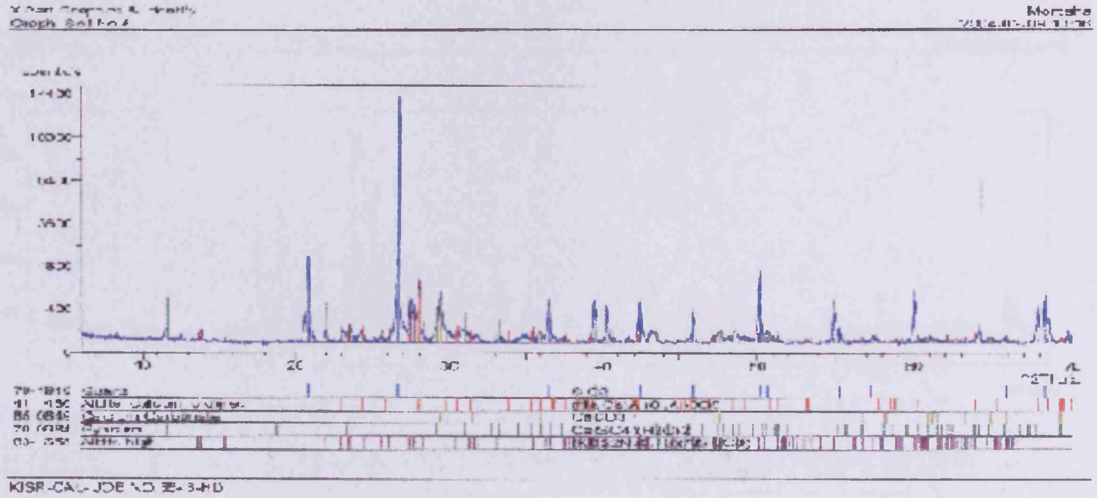

Figure 3.19. Representative X-ray diffraction Pattern of Sabkha Soil S_{Z-5}

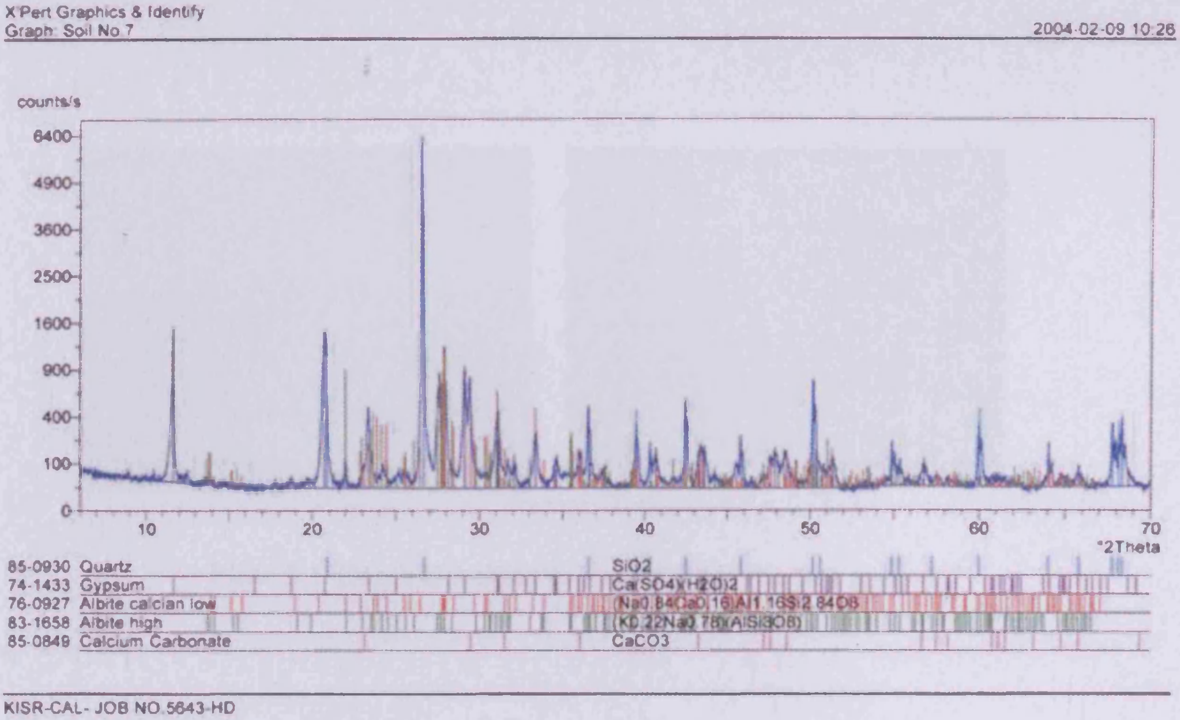

Figure 3.20. Representative X-ray diffraction Pattern of Sabkha Soil S_{K-7}

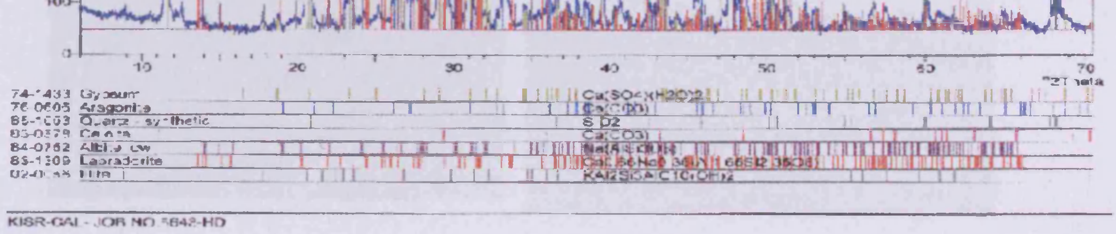

Figure 3.21. Representative X-ray diffraction Pattern of Sabkha soil S_{B-8}

Plate 3.1. Some locations excluded from the test zone

Plate 3.2. Preliminary soil sampling

Plate 3.3. Detailed soil sampling

Plate 3.4.Cored pit section

Plate 3.5. Flooded Sabkha flats during the rainfall season

Chapter 4

Physical Properties of Sabkha Soils Mixed with Oil Residue

4.1 Introduction

A review of the literature in chapter 2 indicated that very few studies have been previously carried out on contaminated Sabkha soils, hence the necessity to undertake a programme of tests to assess the effect of oil residue on the physical properties of these soils. This chapter presents the work carried out in phase C of the experimental programme to understand and establish the basic properties and behaviour of Sabkha soil mixed with different oil residue percentages as a preliminary to evaluating the geotechnical behaviour of natural and oil mixed Sabkha soils in the following chapters. The physical properties investigated in this chapter include particle size distribution, consistency limits, compaction parameters, coefficient of permeability and specific gravity.

The testing programme for soil test is described in section 4.2. Section 4.3 and section 4.4 detail testing procedures and results, respectively. Main findings are reviewed in section 4.5 and a list of references is provided in section 4.6.

4.2 Testing programme

This part of the testing work covered phase C of the experimental programme, as detailed in Figure 4.1. A series of soil tests were carried out on Sabkha soils mixed with different oil percentages. Soil samples from the test sites were mixed with between 0% to 10% of oil residue by weight of dry soil. This wide range of oil residue addition was necessary to understand the behaviour of oil mixed Sabkha soils.

Tested soils were designated as follows: SJ-4-0% (or 0%) represented natural soil from Al-Jailaiaha (J), to which no oil residue had been added, SJ-4-2% (or 2%) represented soil from Al-Jailaiaha mixed with 2% oil residue, and so on for other locations and other oil residue percentages. The first character after "S" represented the location, the first number referred to the sample number from the location, and the second number and percentage sign referred to the percentage of oil residue.

4.3 Testing procedures

The soil, which had been prepared previously, was initially air-dried. The oil residue percentage (by weight of dry soil) was then added to the dried soil. The mixture preparation method used in this research followed previous procedures used by Aiban (1998) and Basma et al. (1994). The mixture was initially mixed manually and then mixed in a mechanical mixer for at least two minutes until a uniform mixture was obtained.

The moisture content in the compaction test was selected as a percentage from 1% to 15% for each soil sample at different oil residue percentages. Water was added to the mixture in the mixing bowl, which was remixed for one minute to obtain a homogeneous mix. This mix was then covered with a plastic sheet to minimise water evaporation during handling.

Each soil sample from a main location was mixed with a different oil percentage and subjected to characterisation tests similar to those carried out in section 3.8.1 to determine its engineering properties.

4.3.1 Oven drying temperature effect

This test was carried out to investigate the percentage loss of oil residue from the mixture as a result of drying temperature. As mentioned previously in section 3.8, oven drying was used to a maximum temperature of 60°C in order to prevent significant changes in the properties of the Sabkha soils (Ismael, 1993-b). It was important to measure the amount of ioss in the oil (volatilized) during the drying process.

An amount of Sabkha soil S_{J-4} was dried, weighed, and mixed thoroughly with 5% of oil residue (by dry weight of the soil). The mixture was divided into eight subsamples which were weighed individually and then left in a loose condition in metal containers in order to create more exposed soil surfaces and represent the same condition as had existed when measuring moisture content. Alternative subsamples were placed in a different oven. Ovens were heated at constant temperatures of 50°C, 60°C, 65°C, and 80°C. Samples were weighed at different time intervals of 2, 4, 6, 24, 36, 48, 60 and 70 hours. The average percentage loss at different temperatures was calculated at the specified time intervals and is shown in Figure 4.2.

Figure 4.2 shows similar results at constant temperatures of 50°C, 60°C, 65°C but a big difference as the temperature increased to 80°C. Figure 4.2 indicates that weight loss at 60°C after three days was less than 0.4%. This percentage was considered negligible and not thought to affect moisture content calculations. It was therefore decided to use 60°C as the drying temperature for the oil mixed Sabkha soils mixed with oil residue.

4.4 Results and discussion

4.4.1 Particle size distribution

Particle size distribution curves for Sabkha soils mixed with different oil percentages are shown in Figures 4.3, 4.4, 4.5 and 4.6, for S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively. The percentage of particles passing through different sieves is presented in Table 4.1. As can be seen from the Figures and the Table, the percentage of particles passing through different sieve sizes reduced with oil addition. Moreover, the grain size distribution of each soil was affected by oil residue addition at different rates. With more oil addition, an increase in particle size was noted in all Sabkha soils. This was due to particle aggregation as a result of the addition of viscous oil residue (see plate 4.1). A close examination of Figure 4.3 shows that fines (<75 μm) in Sabkha soil S_{J-4} reduced to less than 50% at an oil residue percentage of 4%, and almost disappeared with further oil addition.

Results summarised in Table 4.1 clearly show a reduction in soil particles passing through different sieves at different oil residue content. For example, fine sands (<106 μm) in natural Sabkha soil S_{J-4}, reduced from 28% to 15% and 3.0% with 4% and 8% oil residue content, respectively, and completely disappeared with 10% oil addition. Similar results were achieved when mixing oil residue with Sabkha soils S_{Z-5}, S_{K-7} and S_{B-8}.

Calculated values of the uniformity coefficient C_u and concavity coefficient C_c are also summarised in Table 4.1. The table shows that the slope of the curves, i.e. C_u values, reduced with continuous oil residue addition. For example, the C_u value for natural Sabkha soil S_{K-7} was 4.27 and reduced to 3.96 at an oil residue content of 10.0%. The reduced C_u value suggests that the range of particle sizes became smaller with more oil addition, indicative of uniformity in particles' size. The reduction in C_u value is reflected in the sharp slope of the grain size distribution curve, and is mainly attributed to the aggregation of fine particles. A similar trend is noted for Sabkha soils S_{J-4}, S_{Z-5} and S_{B-8}.

Soil aggregation may be attributed to the effect of the adsorbed oil residue on the surfaces of the soil. The adsorption process is considered the major mechanism for the retention of organic contaminants in soils (Bayard et al., 2000). The immiscible oil residue (non-aqueous phase liquid or NAPL) consisted mainly of 20% polar (asphaltenes) and weakly polar (resin) compounds (section 3.9.1). On the other hand, clay and organic contents were very low in the Sabkha soils. The cation exchange capacity values of the tested soils were 11.2, 12.8, 10.7, and 13.3 meq/100g for S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively. Asphaltenes adsorbed rapidly and, to a large extent, were affected by the exchangeable cation of the soil constituents (Gaboriau and Saada, 2001). The larger the molecular size, the higher the boiling point (>350° C) and the viscosity of the oil residue, the larger the van der Waals' forces between the molecules and soil surfaces, consequently the greater the extent of adsorption (Semer and Reddy, 1998). Weakly-polar compounds have higher adsorption capacity onto soil surfaces than non-polar compounds due to the attractive forces. In addition, high viscosity is a major factor in fine soil aggregations. The adsorbed viscous oil layer is expected to reduce fine soil fractions. With more oil, the thicker adsorbed viscous layer causes more fine soil aggregations and, consequently, coarser soil gradation.

Similar findings have been reported by Meegoda and Ratnaweera (1995) and Srivastava and Pandey (1998) in their work on contaminated clay and alluvial soil. They observed that oil contaminated soil becomes coarser due to the reduction of clay fractions. Meegoda and Ratnaweera (1995) attributed the aggregation to the oil-coated soil tending to become aggregated due to the suction pressures caused by the surface effects of oil and water (surface tension). Similar results were achieved in a recent study carried out by Caravaca and Roldan (2003) on contaminated clay loam, where clay and silt contents decreased from 33.3% and 21.7% to 21.3% and 20.5%, respectively. Oil residue covers the surface of the aggregate and fills the accessible interaggregate, and the viscous NAPL material acts as a gluing agent and holds the aggregate together (Karimi and Gray, 2000). Andrade et al. (2004) similarly concluded that oil coating fine materials facilitate their entry and permanence in the larger pores and channels of the soil, resulting in the gluing together of larger particles.

Soil aggregations have been observed in contaminated soils in Kuwait, where investigations have revealed the formation of completely oily covered soil aggregations (Al-Houty et al., 1993), the diameters of which ranged from >0.25 mm up to 1-2 mm (Al-Sarawi et al., 1998). Enu (1985) also observed soil grains in contaminated locations in Nigeria being held together largely by tarry oil.

4.4.2 Consistency limits

Liquid limit (LL), plastic limit (PL), and plasticity index (PI) results for natural and oil mixed Sabkha soil samples are summarised in Table 4.2, while Figures 4.7, 4.8, 4.9, and 4.10 show consistency limits for natural and oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively.

Figures 4.7, 4.8, and 4.9 indicate that liquid limit increased as oil content increased, since values increased from 22, 21 and 19 for natural soils to 24, 22.5 and 22 for 4% oil mixed Sabkha soils S_{J-4}, S_{Z-5}, and S_{K-7}. On the other hand, the liquid limit for soil S_{B-8} decreased with more oil addition.

Plastic limit results varied between the tested samples. Plastic limit values for Sabkha soils S_{J-4}, S_{Z-5} and S_{B-8} decreased from 21.3, 20.5 and 19 for natural soils to 18.5, 20 and 14 for 4% oil mixed soils. Plastic limit for soil S_{K-7} shows increasing trend in the plastic limit as presented in Figures 4.9.

The increase in the liquid limit for Sabkha soils with oil addition may be attributed to the increase in oil mixed particles bonding (cohesion) due to oil adsorption and viscosity as explained in the previous section. Higher soil bonding due to oil addition may cause an increase in the liquid limit due to higher resistance to soil flow.

The reduction in the plasticity of Sabkha soils mixed with oil residue may be attributed to the addition of non-polar compounds (Arora, 1997), which may change the soil affinity for water (Kaiser, et al., 2000). Due to the low CEC of the Sabkha soil samples (section 3.8.2), added oil residue probably satisfied the soil surface charges and enhanced the water-repellent characteristics of the oil mixed Sabkha soil (Salem, et al., 1985), causing a reduction in its plasticity. This reduction may also be attributed to the fine particle aggregation observed previously in section (4.4.1). The different trend of soil S_{K-7}, may be attributed to the inhomogeneous distribution of non-polar compounds (Shah et al., 2003).

The plasticity index (PI), which is a measure of the cohesiveness of Sabkha soils, is an important parameter for evaluating the physical properties of natural as well as chemically treated soil (Murthy, 1992; and Nalbantoglu and Gucbilmez, 2001). The plasticity index (PI) was calculated as the numerical difference between liquid limit (LL) and plastic limit (PL). Plasticity indices for Sabkha soils increased with oil residue addition as shown in Figures 4.7 to 4.10.

Similar findings were reported by Meegoda and Ratnaweera (1995), Srivastava and Pandey (1998) and Shah et al. (2003) in their investigations of different contaminated soils. According to Meegoda and Ratnaweera (1995), the addition of oil to the soil changes its pore-fluid properties and causes a change in the mechanical and physiochemical factors which control the liquid limit.

Generally, natural and oil mixed Sabkha soils fall in the low plasticity chart suggesting that oil addition does not have much effect on the plasticity of the soil. The oil residue coating of soil particles appears to increase the bonding between particles and may reduce their surface activity, in turn affecting the consistency limits of the oil mixed Sabkha soil. Moreover, the mechanics of the consistency limits test may be altered when used for contaminated soils as this test was originally developed for oil-water systems

(Meegoda and Ratnaweera, 1995). Arguably, the oil residue in the oil mixed soils facilitated slippage of the samples in the cup during soil testing and this may have affected the results.

4.4.3 Soil classification:

It was reported in the previous sections that soil gradation and consistency limits were affected by oil residue addition. As a result, soil classification of oil mixed Sabkha soil is expected to vary from that of natural soil.

Soil classifications of natural and oil mixed Sabkha soils are presented in Table 4.2. It can be observed from the Table that natural Sabkha soils S_{B-8} and S_{K-7} are classified as silty sands (SPM) while the oil mixed samples of the same soils are classified as poorly graded sand (SP) according to the British Soil Classification System. According to the Unified Soil Classification System, the same soils are classified as poorly graded silty sands (SP-SM) in their natural condition while the oil mixed samples are classified as poorly graded sand (SP). These findings are in general agreement with those findings of Meegoda and Ratnaweera (1995) in the context of clays and silty sand soils. They concluded that oil-coated soil tends to become aggregated, the gluing effects of the adsorbed NAPL (Karimi and Gray, 2000) cause soil aggregation, and fine-grained oil contaminated soils are often identified and classified as granular soils with a large particle size, which may result in the selection of unsuitable treatment techniques. Thus, standard tests developed for the identification and classification of soils should not be used to identify and classify contaminated soils for the selection of type of treatment methods (Meegoda and Ratnaweera, 1995).

4.4.4 Specific gravity

Specific gravity tests were carried out on natural and oil mixed Sabkha soils with 2%, 5%, and 10% oil residue. There were some difficulties in carrying out the specific gravity experiment on the stabilised Sabkha soils. Due to the entrapment of air, mixed soil samples floated at the top of the pycnometer with air bubbles attached to their surfaces, which affected the test results. Several trials were carried out to reduce this effect. Similar difficulties were encountered by Meegoda and Ratnaweera (1995) in their investigation of contaminated soils.

Specific gravity values for natural and oil mixed Sabkha soils are shown in Tables 4.3, 4.4, 4.5 and 4.6 for soils S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively, and presented graphically in Figure 4.11. Specific gravity values for Sabkha soils with oil content follow a similar trend, in that there is a reduction in specific gravity value with oil content addition. The specific gravity of oil residue is lower than 1 (section 3.9.2). The specific gravity of oil mixed Sabkha soil was expected to be lower than that of natural Sabkha, mainly due to the low specific gravity of the oil mixed Sabkha soil and, to some extent, to the possible entrapment of air bubbles in the interior aggregate pores by the oil residue.

Similar results were reported by Srivastava and Pandey (1998) in their experimental study on contaminated alluvial soils and sands from India. Tarefder et al. (2003) attributed this to the absorption of hydrocarbons to the surface of soil particles, since the specific gravity of contaminated soil was lower than that of natural soil.

Theoretical specific gravity values for oil mixed Sabkha soils were calculated using the specific gravities of mixed materials and their percentages. Theoretical and experimental values for Sabkha soils S_{J-4} with different oil content are shown graphically in Figure 4.12. Notably, the theoretical specific gravity values are lower than the experimental values. A similar finding was observed in the experimental results of Srivastava and Pandey (1998).

4.4.5 Compaction test

Modified proctor compaction tests were carried out on Sabkha soil mixed with different oil residue percentages in order to establish the maximum dry density (MDD) and optimum moisture content (OMC) values for the range of oil residue addition. A compaction test was also necessary in order to adopt these parameters as the target values for the preparation of mixed soil samples with different oil percentages for other soil tests in this research programme.

The compaction test was carried out according to BS1377: Part 4: 1990:3.3. Results of modified Proctor tests incorporating the effects of oil residue addition are shown in

Figures 4.13, 4.14, 4.15 and 4.16. Maximum dry density and optimum moisture content values for natural and oil mixed Sabkha soils are summarised in Tables 4.3, 4.4, 4.5, and 4.6 for soils S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively.

Compaction test results presented in Figures 4.13 to 4.16 indicate that natural and oil mixed Sabkha soils have clearly defined peaked curves. Close examination of different curves in the Figures shows that all density curves show a similar trend, in that the dry density value increases up to a maximum dry density value (MDD) at optimum moisture content (OMC), after which the dry density value drops as the moisture content increases. Aiban (1998) attributed the increase in dry density value to a reduction in capillary effect due to moisture addition, which enhances particles' rearrangement up to a limit, after which the dry density value starts decreasing.

It can also be observed that, for all tested soils, better compaction characteristics are achieved with continuous oil addition up to 8%, since the compaction curves in general tend towards the upper left side of others. For example, maximum dry density value for natural Sabkha soil S_{J-4} is 1.932 g/cm^3 at an optimum moisture content of 9.8%. At oil residue addition of 5% and 8%, the maximum dry density value increases to 2.005 g/cm^3 and 2.037 g/cm^3, respectively, and optimum moisture content reduces by 6.3% and 4%, respectively. The difference between oil mixed curves and the natural curve reflect the effect of oil residue addition. Similar results were found for other Sabkha soils mixed with oil residue percentages at different rates. Visual inspection of oil mixed Sabkha soils extracted from the compacting mould revealed they had become more resistant to hammering and deformation as shown in Plate 4.2.

Variation in maximum dry density values for natural and oil mixed Sabkha soils is shown in Figure 4.17. The Figure shows a general increase in maximum dry density as oil residue addition increases up to 8%. With oil addition beyond 8%, the maximum dry density (MDD) starts to decrease. Variations in maximum density values due to oil residue addition are summarised in Table 4.3, 4.4, 4.5, and 4.6, for soils S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively. A close look at Figure 4.17 reveals a large increase in the maximum dry density value for soil sample S_{Z-5}, from 1.9043 g/cm^3 for natural soil to 2.1425 g/cm^3 for 8% oil mixed soil, which represents an increase of 12.5%. An increase in the maximum dry density of oil mixed soils is an indication of the higher compactness of these soils than natural soils. The adsorbed viscous oil residue layer on soil particles (section 4.4.1) facilitated the sliding of soil particles over each other, which resulted in a denser compacted soil.

Field investigations in Kuwait to investigate oil contaminated sand revealed it exhibited higher bulk density than uncontaminated soil (Al-Sarawi et al., 1998). Similar behaviour to that of the oil mixed Sabkha soil in this study was reported by Tarefder et al. (2003) who found experimentally that maximum dry density value increases as emulsion content increases, until it reaches an optimum value where the dry density decreases with increasing emulsion content.

The reduction in dry density value with more oil addition beyond 8% could be attributed to the combined effect of the following:

- The reduction in the specific gravity value with oil content addition as reported, since a specific gravity value is a factor that affects the dry density of compacted soil (Murthy, 1992),
- Higher oil residue addition resulted in thicker oil layers around soil particles preventing their interlocking, as was concluded by Ingles and Metcalf (1972) in their work on bituminous stabilised soils.
- The build up of oil pressure in the soil voids during soil compaction and the lubrication effect that facilitated slippage of soil particles and pushed part of the soil out of the compaction mould during the compaction process (observed during compaction and shown in Plate 4.3). This was supported by other observed phenomenon. It was noted that at high oil residue content, the surface of the compacted soil cylinder after extraction from the mould was greasier than the internal section of the soil, indicating that part of the oil residue, which was filling the voids between particles, was being pushed out to the external surfaces of the soil mould. The replacement of soil in the mould with oil residue resulted in the reduction of soil mass, which eventually reduced the maximum dry density value of the compacted soil.

Shah et al. (2003) noted that at oil content of 10%, contaminated soil's dry density value became lower than that of natural uncontaminated soil. Singh et al. (2006) similarly reported that the dry density of sandy soil reduced with presence of gasoline as pore fluid. At high oil residue content, the soil behaved as a sponge and became very soft and sticky, making compaction difficult. Al-Sanad et al. (1995) also stated that with increasing oil percentage, field compaction becomes extremely difficult.

Variations in optimum moisture content values for natural and oil mixed Sabkha soils are presented in Figure 4.18 and summarised in Tables 4.3, 4.4, 4.5, 4.6. Figure 4.18 shows a general decrease in optimum moisture content (OMC) with an increase in oil addition. It can also be noted from the Figure and tabulated values in the Tables that the decrease in OMC values increased as oil residue addition increased. This implies that the increase in oil residue percentage reduced the amount of water required to achieve good compaction. Similar results have been reported by Al-Sanad et al. (1995) in their studies on contaminated sand, and in the field of bitumen stabilisation, where a decrease in the optimum moisture content of stabilised soils, mainly due to a reduction of particles' adsorption, was viewed as an advantage in very arid conditions (Ingles and Metcalf, 1972). This is considered to be one of the primary reasons for using bitumen stabilisation for soil since the percentage of absorption reduces as the percentage of stabiliser increases (Basma et al., 1994; Justo and Dayal, 1967 and Katti et al., 1960).

Although it was observed that the lubrication effect of the oil residue reduced the optimum moisture content (OMC) needed to reach the maximum dry density (MDD), it is clear that the total amount of fluids added (water and oil residue) actually rose. Figures 4.19, 4.20, 4.21 and 4.22 show the variation in fluid content with oil residue content for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. The fluid content is defined as the sum of the optimum moisture and oil residue contents.

In general, findings are in good agreement with other studies carried out on contaminated soils (Shah et al., 2003; Al-Sanad et al., 1995; Hausman, 1990; and Ingles and Metcalf, 1972), but contradict Mohammed's (1995) assumption that the maximum dry density of stabilised Sabkha soil is similar to that of natural Sabkha soil. Mohammed (1995) used optimum moisture content for natural soil to obtain the optimum moisture content for stabilised Sabkha soils in his study and the dry density. In the present study, compaction tests for Sabkha soils from different locations indicated that the compaction parameters varied with different oil residue contents.

4.4.6 Coefficient of permeability

The coefficient of permeability is a major soil property considered in soil modification. Oil residue addition was expected to affect the coefficient of permeability (*k*) of Sabkha soils. This phase of the testing programme was carried out to investigate the effect of oil residue addition on the coefficient of permeability of oil mixed Sabkha soils at specific oil addition percentages. Coefficient of permeability measurements were performed using the column leaching test. This test was carried out in two series of testing. The first series of testing was carried out on natural and 5% oil mixed Sabkha soils from the four main locations. The second series of testing was carried out to investigate the effect of 0%, 2%, 5% and 7% oil residue addition on Sabkha soil S_{J-4}.

A leaching column test, described in detail in chapter 7, was used to measure the permeability of natural and oil mixed Sabkha soil samples compacted at their optimum moisture content. A pressure of 7 psi was applied in this test, which represented a hydraulic gradient *i* of 40. Each stabilised sample was compacted into layers in the leaching cell. The degree of compaction of the soil in the cell was calculated to check its closeness to the corresponding dry density value for each sample. Each soil sample was saturated by allowing the water to percolate slowly under pressure of 1.2 psi.

The coefficient of permeability results for natural and oil mixed Sabkha soil samples are summarised in Tables 4.3, 4.4, 4.5, and 4.6 for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. Results indicate that the coefficient of permeability for the 5% oil mixed Sabkha soils was lower than that for natural soil, due to oil addition. The coefficient of permeability for natural Sabkha soil S_{J-4} decreased from 7.26×10^{-8} m/sec to 1.288×10^{-8} m/sec at an oil addition of 5%, representing a reduction percentage of 82%. The reduction in the coefficient of permeability of the 5% oil mixed Sabkha soils from different locations was 31%, 35%, and 55% for Sabkha soils S_{Z-5}, S_{K-7} and S_{B-8}, respectively. The adsorbed oil residue on soil particles was thought to have filled the voids between these particles, In addition, fine soil aggregation previously explained in section 4.4.1, resulted from the entry of fine particles into voids between larger particles, which partially or fully closed channels in the soil skeleton. The reduction in the void ratio and the closing of void channels resulted in the reduction of the coefficient of permeability of the oil mixed soil. In addition, oil residue viscosity, which is a measurement of the ability of fluid to flow (Hahn and Associates, 2005), was high, indicative of an immobile liquid which will reduce the transportation characteristics of the matrix and decrease conductivity in oil mixed soil (Fine et al., 1997; Gerstel et al., 1994)

Similar findings were reported by Al-Sanad et al. (1995) and Al-Sanad and Ismael (1997) during their investigations of oil contaminated sand in Kuwait. It is likely that oil coating of fine particles facilitated their entry into the larger pores and channels of the soil and glued the larger particles together, resulting in reduced porosity and permeability (Andrade et al., 2004 and Slattery, 1990). In Garbulewski and Zakowicz's (1998) study on contaminated sand, the coefficient of permeability of well compacted contaminated soil was reduced by 10%, while a reduction of 40% was found for loose soil. However, a higher decrease of about 90% in the coefficient of permeability value has been recorded for contaminated loamy silt with 10% oil (Shah et al., 2003). Singh et al.(2006) reported a reduction of 10% and 19% in the sandy soil coefficient of permeability in the presence of 6% and 9% gasoline, respectively.

In order to compare the results and to investigate the effect of increasing oil residue percentage, Sabkha soils $S_{J\text{-}4}$ were mixed with 2%, 5%, and 7% oil residue. Results, which are summarised in Figure 4.23, indicate that the coefficient of permeability k=7.26 $\times 10^{-8}$ m/sec for natural Sabkha soil was reduced to k=6.04$\times 10^{-8}$ m/sec, 1.288$\times 10^{-8}$ m/sec and to 1.077$\times 10^{-8}$ m/sec for Sabkha soils mixed with 2%, 5% and 7% oil residue, respectively. Noticeably, the coefficient of permeability of oil mixed Sabkha soils decreased with increasing oil residue percentage. Percentage reduction was 17%, 82% and 85% for 2%, 5%, and 7% oil residue, respectively. Percentage reduction was particularly noticeable for oil residue addition of 2% to 5%, possibly due to the reduction in pore volume due to the existence of oil residue. As the oil residue increased to 5%, a high percentage of voids were filled with the residue. In contaminated gasoline sandy soil the reduction in the void ratio was reported (Singh et al., 2006)

The reported effect of oil residue on soil permeability may also be due to the increasing dry density of the compacted stabilised soil samples, resulting in a decreased void ratio and, subsequently, a decrease in the permeability of the soil. Results are in good agreement with those reported by Al-Sanad et al. (1995) in their research on contaminated sand.

It is acknowledged that an in-depth investigation of chemical bonding mechanisms at the soil-oil-water interface is necessary for a better interpretation of the physical and geotechnical behaviour of composite materials. Similarly, detailed consideration needs to be given to the high salt concentration in the system. However, such investigations are beyond the scope of the present study.

4.5 Conclusion

This chapter has detailed the laboratory testing programme undertaken to investigate the effect of oil residue addition on the physical properties of Sabkha soils at the four main testing locations. The investigated properties were grain size distribution, consistency limits, specific gravity, compaction parameters, and coefficient of permeability. The amount of oil residue investigated varied from 2% to 10%. The following conclusions were drawn from this part of work;

- With continuous oil addition, soils showed significant particle aggregation.

- Consistency limits were slightly affected by oil residue addition. Liquid limits were increased while plasticity was decreased. Plasticity indices for oil mixed Sabkha soils were increased, taking into consideration the lower values of the plasticity indices for the natural tested soil samples, which were mainly due to apparent cohesion.

- Classification of the oil mixed Sabkha soils was affected by oil residue addition.

- The specific gravity of the Sabkha soil was reduced with continuous oil residue addition.

- Coefficient of permeability of oil mixed Sabkha was decreased with oil addition in the range of 31% to 82% indicating a modification of this property. A noticeable reduction occurred at oil residue content of 5%. This reduction was mainly due to the reduction of the void ratio of the compacted oil mixed Sabkha soils.

- Compaction characteristics were modified with oil residue addition of up to 8%, since the maximum dry density values were increased in the range of 5.5% to 12.5% and the optimum moisture content values were decreased in the range of 30% to 78%. Beyond this percentage, the maximum dry density values for the compacted oil mixed Sabkha soils were decreased.

The results reported are obviously essentially preliminary characterisation tests. The outcome is sufficiently encouraging to merit further development of the experimental programme.

4.6 References

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Al-Houty, W., Abdal, M. and Zaman, S., 1993. Preliminary Assessment of the Gulf War on Kuwait Desert Ecosystem. *Journal of Environmental Science and Health*, A28(8): 1705-1726.

Al-Sanad, H.A., Eid, W.K. and Ismael, N.F., 1995. Geotechnical Properties of Oil - Contaminated Kuwaiti Sand. *Journal of Geotechnical Engineering-ASCE*, 121(5): 407-412.

Al-Sanad, H.A. and Ismael, N.F., 1997. Aging Effects on Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3): 290-293.

Al-Sarawi, M., Massoud, M.S. and Wahba, S.A., 1998. Physical Properties As Indicators of Oil Penetration in Soils Contaminated with Oil Lakes in the Greater Burgan Oil Fields, Kuwait. *Water, Air and Soil Pollution*, 102(1-2): 1-15.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North - Western Spain). *Journal of Environmental Quality*, 33: 2103-2110.

Arora, 1997. Soil Mechanics and Foundation Engineering. Standard Publishers Distributors, Delhi, p.852.

Basma, A.A., Al-Homoud, A.S., Khedwayi, T.S. and Al-Ajlouni, A.M., 1994. Effect of Bitumen Content and Curing Condition on Strength Characteristics of Asphalt Stabilised Soils. *Geotechnical Engineering*, 25(1): 93-104.

Bayard, R., Barna, L., Mahjoub, B. and Gourdon, R., 2000. Influence of the Presence of PAHs and Coal Tar on Naphthalene Sorption in Soils. *Journal of Contaminant Hydrology*, 46(1-2): 61-80.

BSI, British Standard, 1990. 1377: Methods of Test for Soils for Civil Engineering Purposes. British Standards Institution, London.

Caravaca, F. and Roldan, A., 2003. Assessing Changes in Physical and Biological Properties in a Soil Contaminated by Oil Sludges under Semi-Arid Mediterranean Conditions. *Geoderma*, 117: 53-61.

Enu, E.I., 1985. Textural Characteristics of the Nigerian Tar Sands. *Sedimentary Geology*, 44(1-2): 65-81.

Fine, P., Graber, E.R. and Yaron, B., 1997. Soil Interactions with Petroleum Hydrocarbons: Abiotic processes. *Soil Technology*, 10(2): 133-153.

Gaboriau, H. and Saada, A., 2001. Influence of Heavy Organic Pollutants of Anthropic Origin on PAH Retention by Kaolinite. *Chemosphere*, 44(7): 1633-1639.

Garbulewski, K. and Zakowicz, S., 1998. Influence of Hydrocarbon Contaminants on Hydraulic Conductivity of Drainage System, Contaminated and Derelict Land, Materials Properties and Measurement. Thomas Telford, London, pp. 198-203.

Gerstel, Z., Galin, T. and Yaron, B., 1994. Mass Flow of a Volatile Organic Liquid Mixture in Soils. *Journal of Environmental Quality*, 23: 487-493.

Hahn and Associates, I., 2005. Summary Report-Former MGP Operations and Dense Non-Aqueous Phase Liquid Occurrence. HAI Project No.2708, NW Natural, Portland, Oregon.

Hausmann, M.R., 1990. Engineering Principles of Ground Modification, McGraw-Hill Publishing Company, New York.

Ingles, O.G. and Metcalf, J.B., 1972. Soil Stabilisation: Principles and Practice. Butterworths & Co. Ltd., Melbourne, Australia.

Ismael, N.F., 1993-b. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035, Washington, D.C.

Justo, C.E. and Dayal, R., 1967. Effect of Mixing and Aeration on Soil-Cutback Mix Design. Indian Road Congress, 32(3): 444-456.

Kaisar, K., Haumaier, L. and Zeck, W., 2000. The Sorption of Organic Matter in Soils as Affected by the Nature of Soil Carbon. *Soil Science*, 165(277-304).

Karimi-Lotfabad, S. and Gray, M.R., 2000. Characterisation of Contaminated Soils Using Confocal Laser Scanning Microscopy and Cryogenic-Scanning Electron Microscopy. *Environmental Science & Technology*, 34(16): 3408-3414.

Katti, R.K., Davidson, D.T. and Sheeler, J.B., 1960. Water in Cutback Asphalt Stabilisation of Soil. Highway Research Board Bulletin, 241.

Meegoda, N.J. and Ratnaweera, P., 1995. Treatment of Oil-Contaminated Soils for Identification and Classification. *Geotechnical Testing Journal*, 18(1): 41-49.

Mercer, J. and Cohen, R.M., 1990. A Review of Immiscible Fluids in the Subsurface: Properties, Models, Characterisation and Remediation. *Journal of Contaminant Hydrology*, 6(2): 107-163.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and its Geoenvironmental Implications. PhD Thesis, McGill University, Montreal, Canada.

Murthy, K., 1992. A Text Book of Soil Mechanics and Foundation Engineering. Sai Kripa Technical Consultants, Bangalore, India.

Nalbantoglue, Z. and Gucbilmez, E., 2001. Improvement of Calcareous Expansive Soils in Semi-Arid Environments. *Journal of Arid Environmens*, 47: 453-463.

Salem, N., Verloo, M. and DeBoodt, M., 1985. Effects of Bituminous Emulsion on Retention and Release of Some Chemical Elements in Two Soil Samples. *Geoderma*, 35(3): 241-249.

Semer, R. and Reddy, K.R., 1998. Mechanisms Controlling Tolune Removal from Saturated Soils during In Situ Air Sparging. *Journal of Hazardous Materials*, 57: 209-230.

Shah, S.J., Patel, A.V. and Ramakrishnan, D., 2003. Stabilisation of Fuel Oil - Contaminated Soil - A Case Study. *Geotechnical and Geological Engineering*, 21: 415-427.

Singh, S.K., Srivastava, R.K. and John, S., 2006. Assessment and Remediation of Soils Contaminated with Gasoline. In H.R. Thomas (Editor), 5th ICEG Environmental Geotechnics. Thomas Telford, Geoenvironmental Research Centre, Cardiff University, Cardiff, UK, pp. 294-301.

Slattery, J.C., 1990. Interfacial Transport Phenomena. Springer-Verlag, New York.1159.

Spangler, M.G., 1953. *Soil Engineering*. International Text Book Company, Scranton.

Srivastava, R.K. and Pandey, V.D., 1998. Geotechnical Evaluation of Oil Contaminated Soil. In L. Thomas Telford (Editor), Contaminated and Derelict Land, Material Properties and Measurement, pp. 204-209.

Tarefder, R.A., Ruckgaber, M.E., Zaman, M. and Patton, D., 2003. Formulation of Mix Design for Asphaltic Incorporation of Hydrocarbon Contaminated Soil. *Journal of Materials in Civil Engineering*, 15(2): 166-173.

Zhang, B., Peng, X.H., Zhago, Q.G. and Hallett, P.D., 2004. Eluviation of Dissolved Organic Carbon Under Wetting and Drying and Its Influence on Water Infiltration in Degraded Soils Restored with Vegatation. *European Journal of Soil Science*, 55: 725-737.

Table 4.1. Particle size distribution results for natural and oil mixed Sabkha soils from main locations

Soil	Oil (%)	Percent Passing					Fine (%)	D_{60}	D_{30}	D_{10}	C_C	C_U
		Sieve Openings (mm)										
		2.0	**0.85**	**0.425**	**0.25**	**0.106**						
S_{J-4}	0.0	98	94	85	69	28	4.50	0.22	0.1200	0.075	0.873	2.930
	4.0	95	92	78	53	15	2.00	0.28	0.1550	0.095	0.903	2.950
	8.0	93	87	68	45	3.0	0.00	0.34	0.1800	0.130	0.733	2.620
	10	95	82	58	30	0.0	0.00	0.43	0.2500	0.150	0.969	2.870
S_{Z-5}	0.0	98	82	65	45	13	4.00	0.39	0.1800	0.095	0.874	4.100
	2.0	90	79	58	39	9.0	0.00	0.45	0.1970	0.115	0.750	3.900
	4.0	85	75	47	21	0.0	0.00	0.57	0.3150	0.180	0.970	3.170
	8.0	83	71	42	18	0.0	0.00	0.57	0.3150	0.180	0.970	3.170
S_{K-7}	0.0	100	98	77	48	26	11.0	0.32	0.1500	0.075	0.937	4.270
	5.0	97	88	67	42	17	2.00	0.35	0.1750	0.085	1.030	4.110
	7.0	92	79	58	38	9.0	0.00	0.45	0.2055	0.120	0.780	3.750
	10	88	67	48	30	3.0	0.00	0.61	0.2500	0.154	0.660	3.96
S_{B-8}	0.0	98	91	67	30	22	10.50	0.380	0.2500	0.075	2.200	5.060
	5.0	98	85	60	28	12	3.00	0.410	0.2600	0.080	2.070	5.125
	10	95	73	58	19	7.0	1.00	0.45	0.2750	0.150	1.120	3.00

Table 4.2. Consistency limits and classification for natural and oil mixed Sabkha soils from main locations

Soil sample		S_{J-4}					S_{Z-5}				S_{K-7}				S_{B-8}		
Oil content (%)		0	2	3	4	5	0	2	3	4	0	2	3	4	0	2	4
Consistency Limits	Liquid Limit	22.0	18.9	23.0	24.0	24.5	21	21.5	20.0	22.5	19	21	21.6	22	22	22	19
	Plastic Limit	21.3	16.8	21.3	18.5	19.0	20.5	19	19.5	20	17	19	19.0	19	19	17	14
	Plasticity Index	0.70	2.1	2.5	4.50	5.50	0.5	2.5	0.50	2.5	2.0	2.0	2.60	3.0	3.0	5.0	5.0
Soil Classification	British System	SP_U	SP_U	SP_U	SP_U	SP_U	SP_U	SP_U	SP_U		SPM	SP	SP	SP	SPM	SP	SP
	Unified System	SP	SP	SP	SP	SP	SP	SP	SP		SP-SM	SP	SP	SP	SP-SM	SP	SP

Table 4.3. Specific gravity, coefficient of permeability and compaction parameters for natural and oil mixed soils (S_{J-4})

Oil %		G_S	OMC (%)	Δ OMC (%)	MDD (g/cm^3)	Δ MDD (%)	FC (%) = OMC+ Oil	*k* (m/sec)
S_{J-4}	**0%**	2.68	9.8	0.00	1.932	0.00	9.800	7.26×10^{-8}
	2%	2.65	9.0	-8.00	1.924	-0.31	11.00	6.04×10^{-8}
	3%	_	9.2	-6.00	1.918	-0.62	12.20	_
	4%	_	6.8	-31.00	2.005	3.89	10.80	_
	5%	2.62	6.3	-36.00	2.005	3.89	11.30	1.288×10^{-8}
	6%	_	5.8	-40.80	2.030	5.20	11.80	_
	7%	_	6.7	-31.60	2.035	5.40	13.70	1.07×10^{-8}
	8%	_	4.0	-59.10	2.037	5.50	12.00	_
	10%	2.58	2.7	-72.40	2.010	4.140	12.7	_

Table 4.4. Specific gravity, coefficient of permeability and compaction parameters for natural and oil mixed soils (S_{Z-5})

Oil %		G_S	OMC (%)	Δ OMC (%)	MDD (g/cm^3)	Δ MDD (%)	FC (%) = OMC+ Oil.	*k* (m/sec)
S_{Z-5}	0%	2.68	8.8	0.000	1.9043	0.00	8.800	5.37×10^{-7}
	2%	2.66	8.2	-7.300	1.9755	3.700	10.20	–
	3%	–	5.0	-43.00	2.020	6.100	8.000	–
	4%	–	6.8	-22.40	2.055	7.900	10.80	–
	5%	2.63	4.4	-50.0	2.060	8.200	9.400	3.727×10^{-7}
	6%	–	7.9	-10.39	2.080	5.600	13.90	–
	7%	–	2.8	-68.3	2.1310	11.90	9.800	–
	8%	–	1.95	-78.3	2.1425	12.50	9.95	–
	10%	2.53	2.8	-68.3	2.0225	6.200	12.80	–

Table 4.5. Specific gravity, coefficient of permeability and compaction parameters for natural and oil mixed soils (S_{K-7})

Oil %		G_S	OMC (%)	Δ OMC (%)	MDD (g/cm^3)	Δ MDD (%)	FC (%) = OMC+ Oil.	k (m/sec)
S_{K-7}	**0%**	2.78	9.20	0.000	1.9500	0.00	9.200	1.95×10^{-8}
	2%	2.74	10.00	8.600	1.9040	-2.40	12.00	_
	3%	_	10.40	13.00	1.9430	-0.360	13.40	_
	4%	_	8.400	-8.500	1.9730	1.180	12.40	_
	5%	2.73	8.810	-4.430	1.9723	1.140	13.81	1.27×10^{-8}
	6%	_	9.260	0.650	1.9722	1.080	15.28	_
	7%	_	7.000	-23.93	1.9724	1.800	14.00	_
	8%	_	6.490	-29.50	1.9770	1.380	14.49	_
	10%	2.66	5.040	-45.34	1.9540	0.210	15.04	_

Table 4.6. Specific gravity, coefficient of permeability and compaction parameters for natural and oil mixed soils (S_{B-8})

Oil %		G_S	OMC (%)	Δ OMC	MDD (g/cm^3)	Δ MDD (%)	FC (%) = OMC+ Oil.	*k* (m/sec)
S_{B-8}	0%	2.79	12.20	0.000	1.948	0.00	12.20	1.325×10^{-8}
	2%	2.76	9.400	-23.00	2.004	2.87	11.40	_
	3%	_	11.00	-9.800	2.000	2.67	14.00	_
	4%	_	9.750	-20.00	1.993	2.30	13.75	_
	5%	2.74	8.200	-32.80	1.997	2.52	13.20	5.96×10^{-9}
	6%	_	8.300	-32.00	2.020	3.69	14.30	_
	7%	_	6.300	-48.70	2.028	4.60	13.30	_
	8%	_	5.600	-54.10	2.030	5.11	13.60	_
	10%	2.68	3.800	-68.60	2.020	3.70	13.80	_

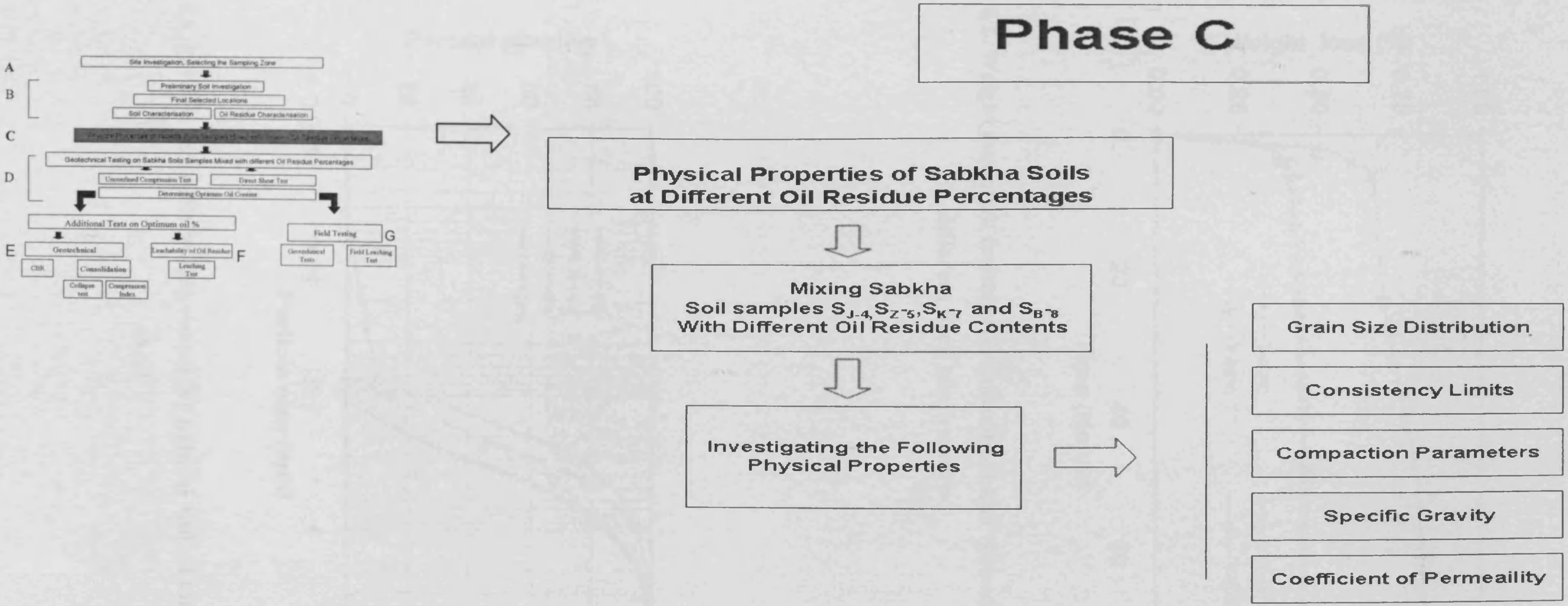

Figure 4.1. Phase C of the experimental programme

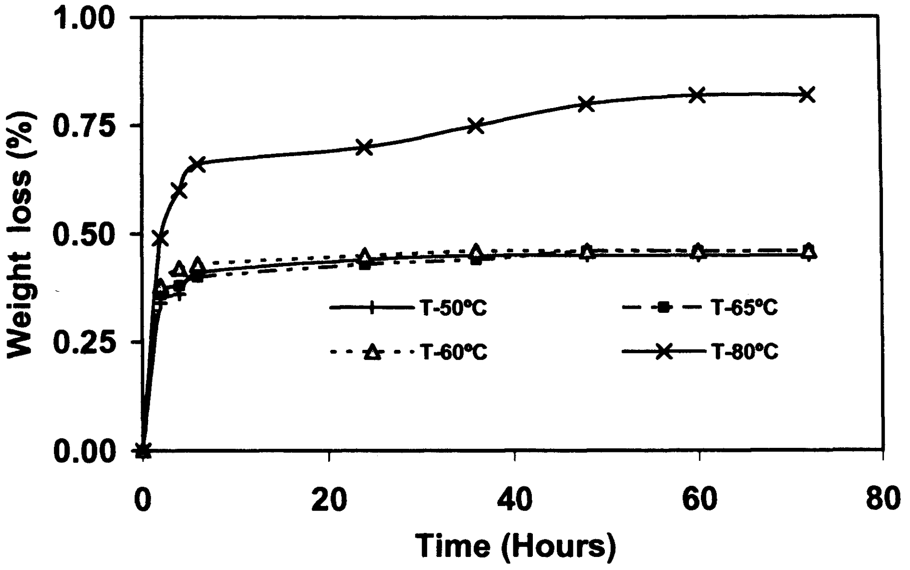

Figure 4.2. Weight loss of oil residue from mixed Sabkha with oil residue dried at different oven temperatures

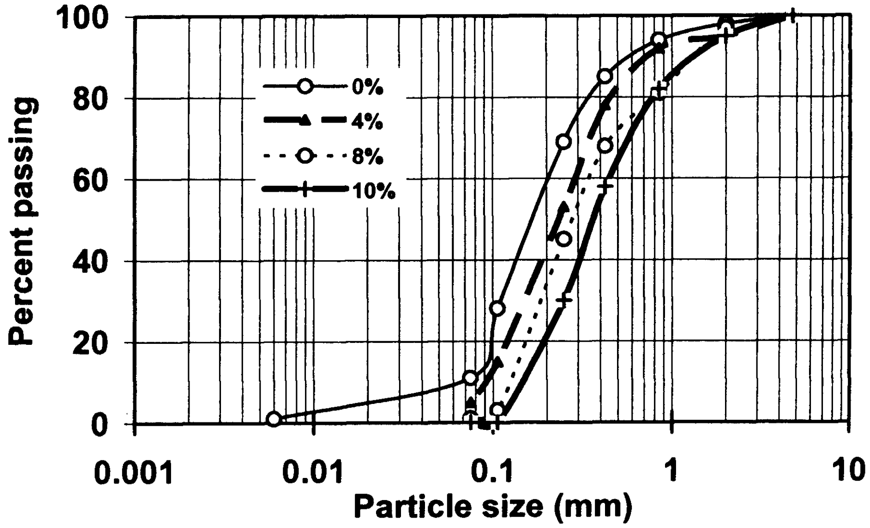

Figure 4.3. Particle size distribution curves for natural and oil mixed Sabkha soils (S_{J-4})

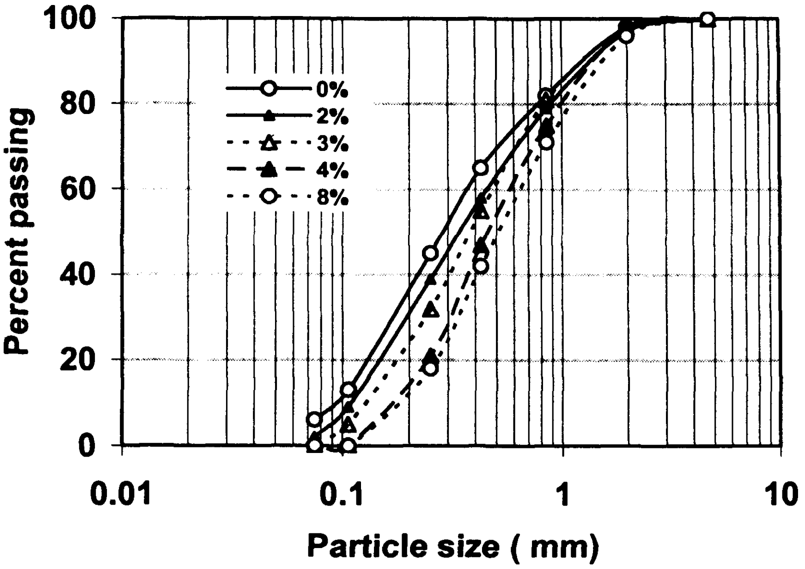

Figure 4.4. Particle size distribution curves for natural and oil mixed Sabkha soils

($S_{Z\text{-}5}$)

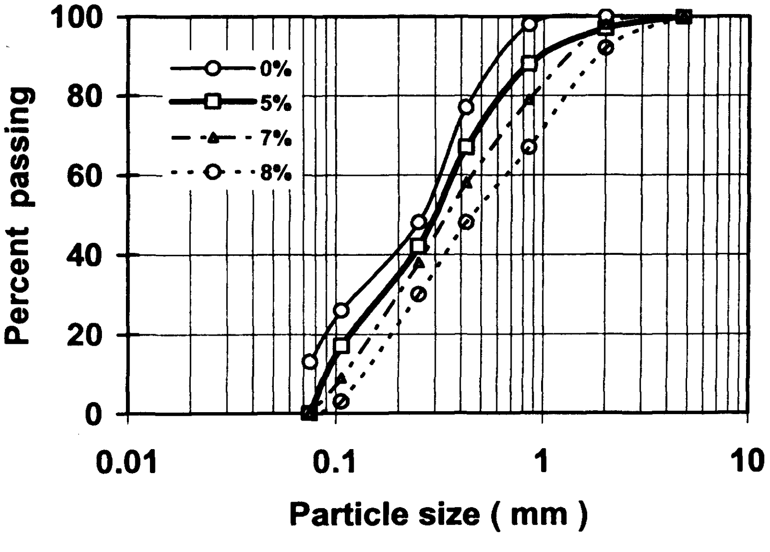

Figure 4.5. Particle size distribution curves for natural and oil mixed Sabkha soils

($S_{K\text{-}7}$)

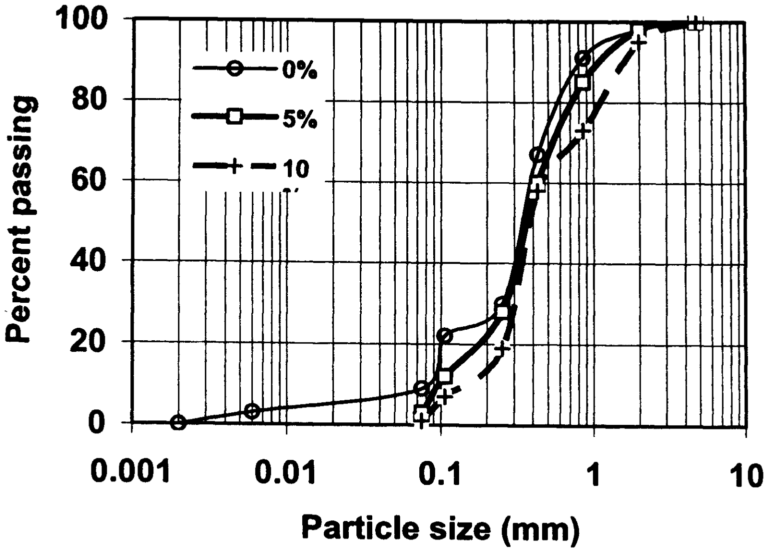

Figure 4.6. Particle size distribution curves for natural and oil mixed Sabkha soils (S_{B-8})

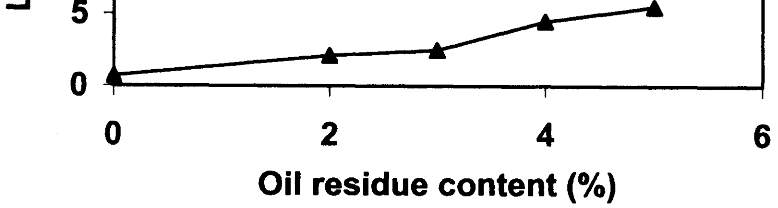

Figure 4.7. Consistency limits for natural and oil mixed Sabkha soils (S_{J-4})

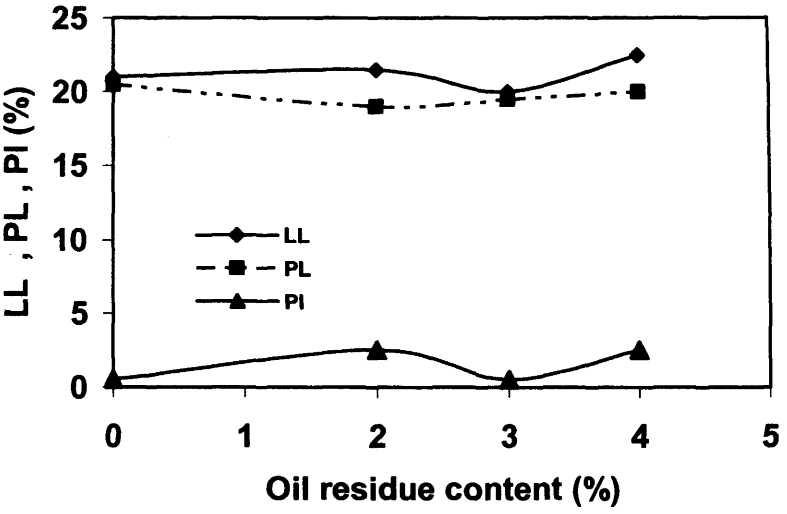

Figure 4.8. Consistency limits for natural and oil mixed Sabkha soils (S_{Z-5})

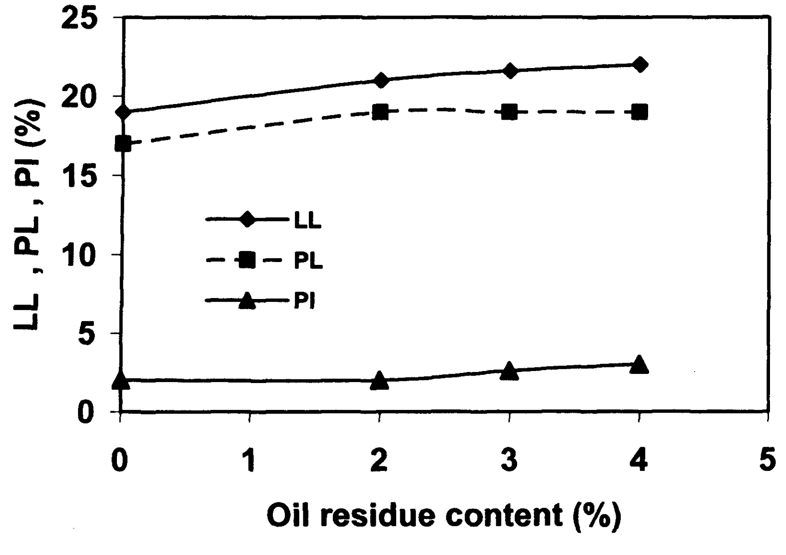

Figure 4.9. Consistency limits for natural and oil mixed Sabkha soils (S_{K-7})

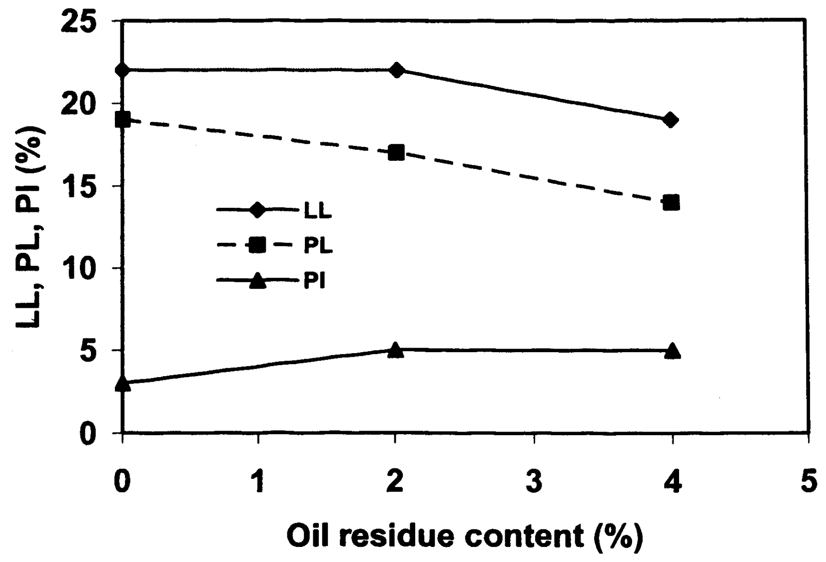

Figure 4.10. Consistency limits for natural and oil mixed Sabkha soils (S_{B-8})

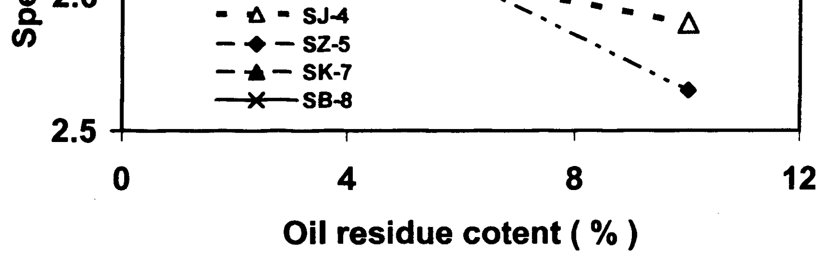

Figure 4.11. Specific gravity of natural and oil mixed Sabkha soils for the four main locations

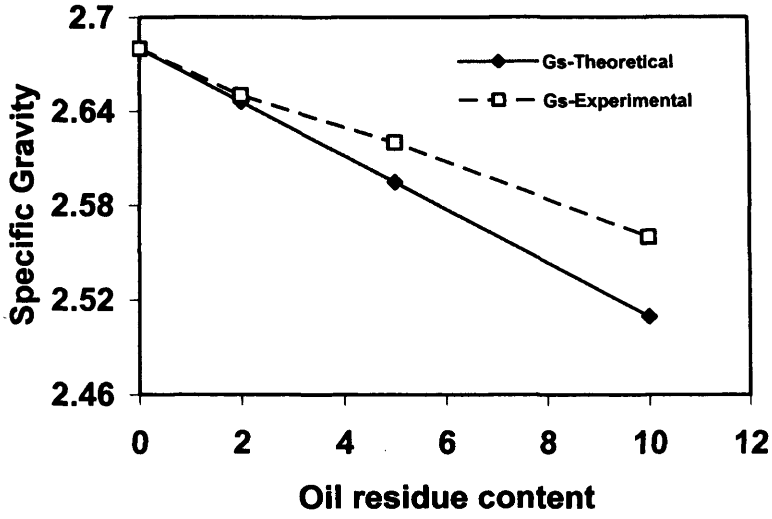

Figure 4.12. Experimental and theoretical specific gravity for natural and oil mixed Sabkha soils (Soil S_{J-4})

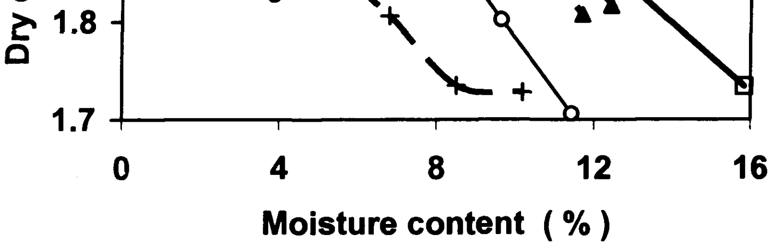

Figure 4.13. Compaction curves for natural and oil mixed Sabkha soils (Soil S_{J-4})

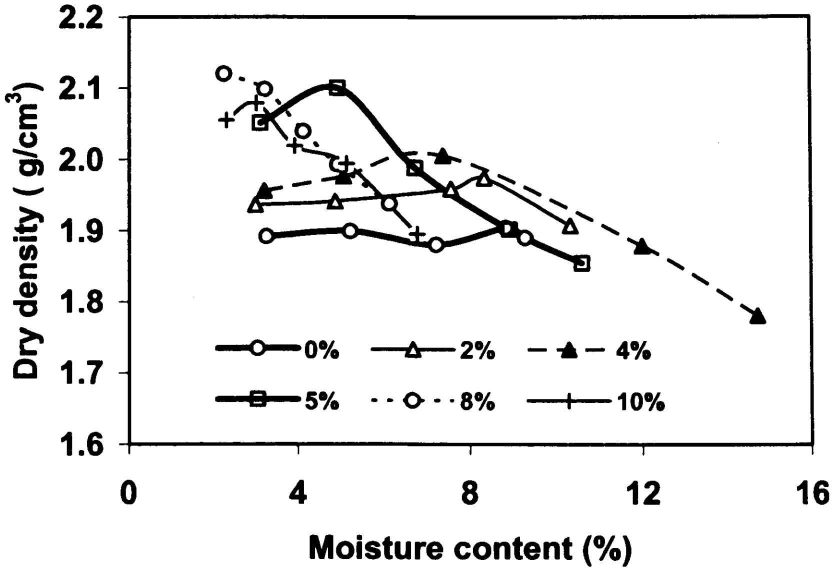

Figure 4.14. Compaction curves for natural and oil mixed Sabkha soils (Soil S_{Z-5})

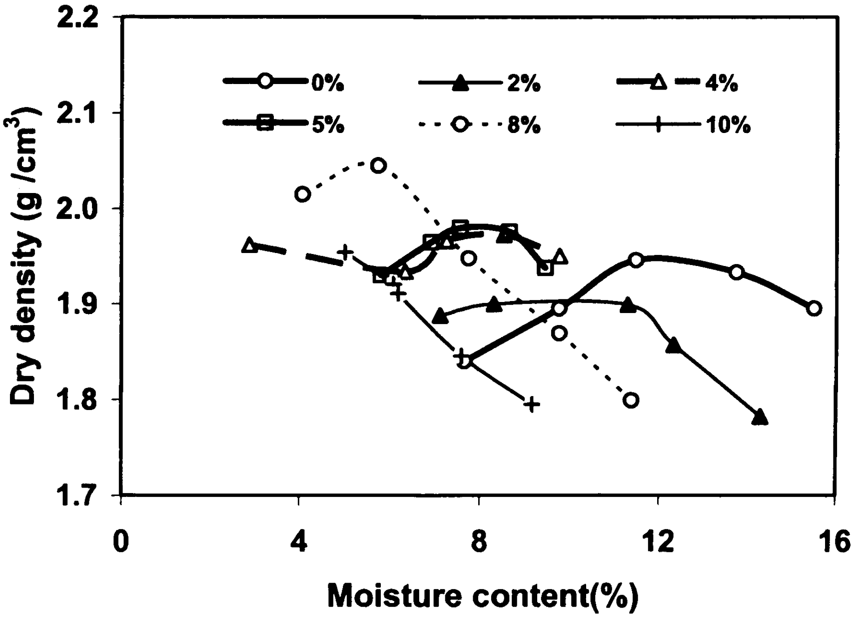

Figure 4.15. Compaction curves for natural and oil mixed Sabkha soils (Soil S_{K-7})

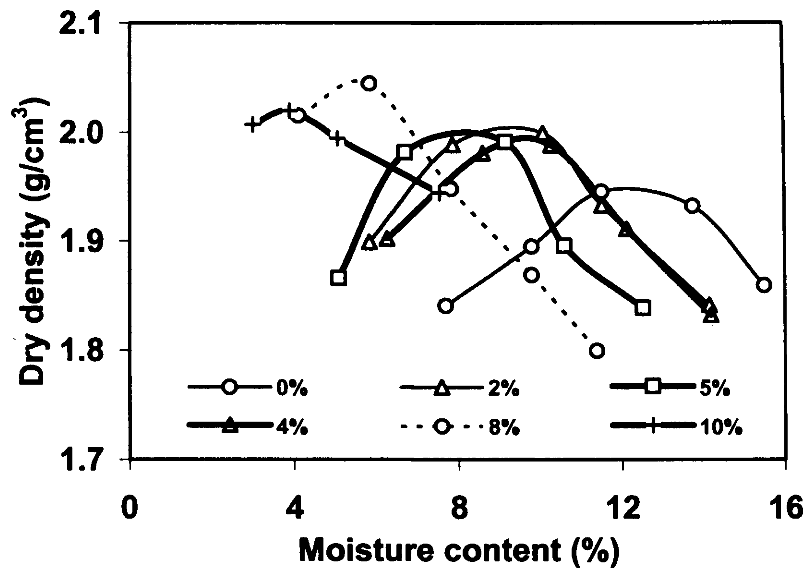

Figure 4.16. Compaction curves for natural and oil mixed Sabkha soils (Soil S_{B-8})

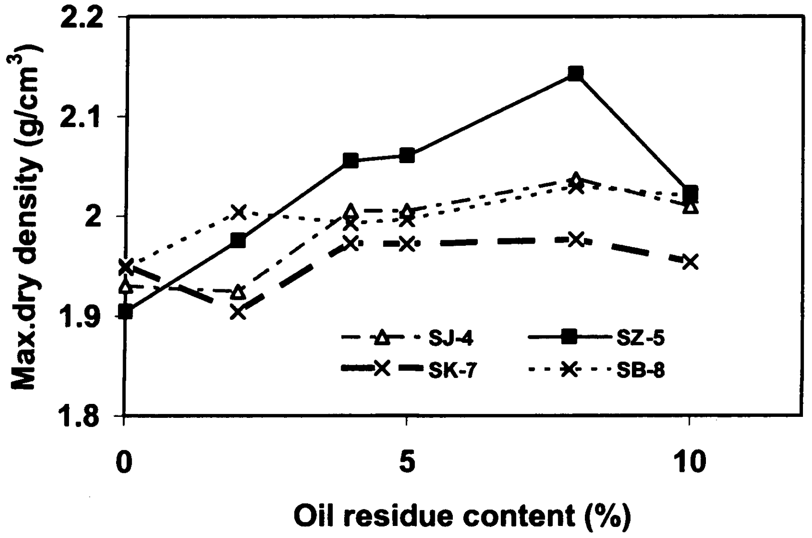

Figure 4.17. Maximum dry density values for natural and oil mixed Sabkha soils from the main locations

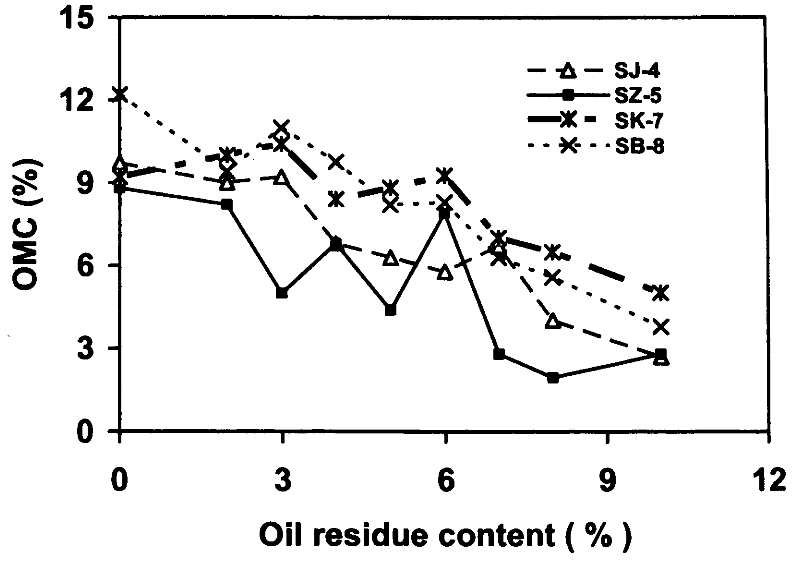

Figure 4.18. Optimum moisture content for natural and oil mixed Sabkha soils from the four main locations

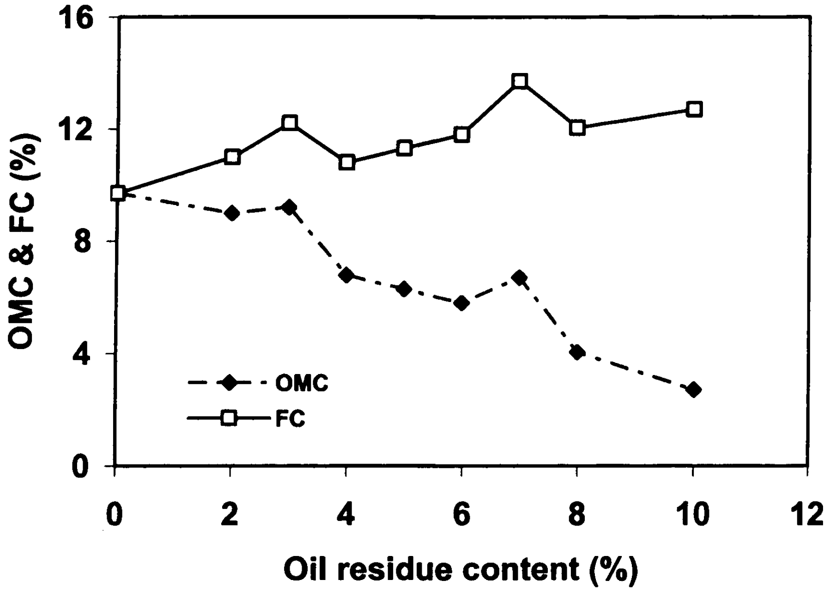

Figure 4.19. Optimum moisture and fluid contents for natural and oil mixed Sabkha soils (S_{J-4})

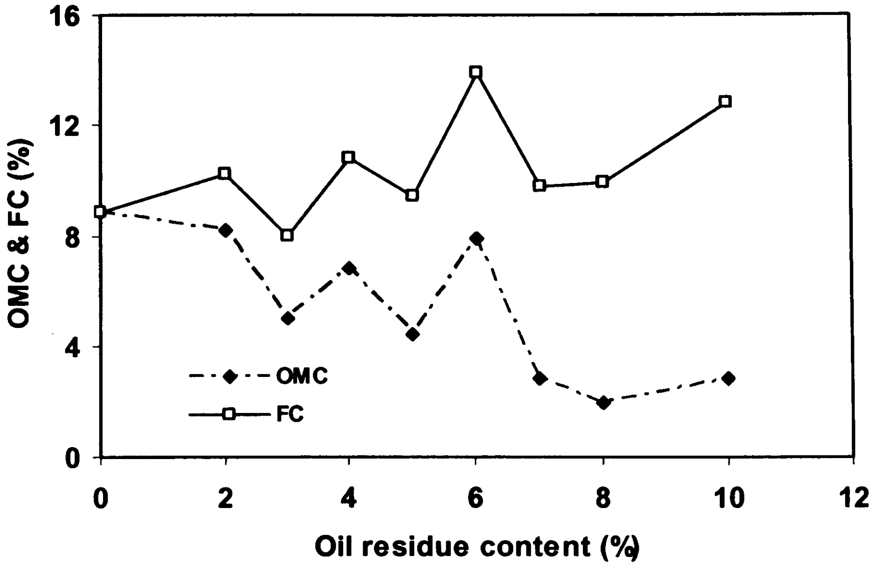

Figure 4.20. Optimum moisture and fluid contents for natural and oil mixed Sabkha soils (S_{Z-5})

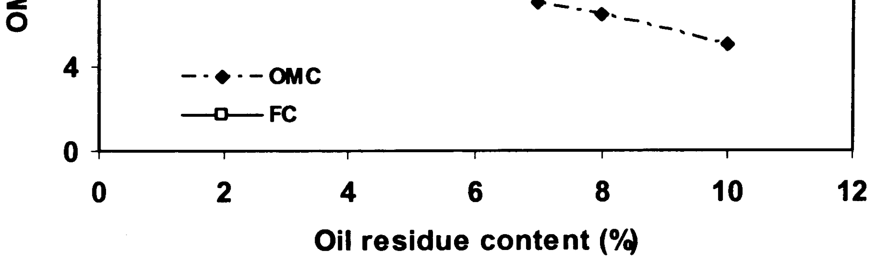

Figure 4.21. Optimum moisture and fluid contents for natural and oil mixed Sabkha soils (S_{K-7})

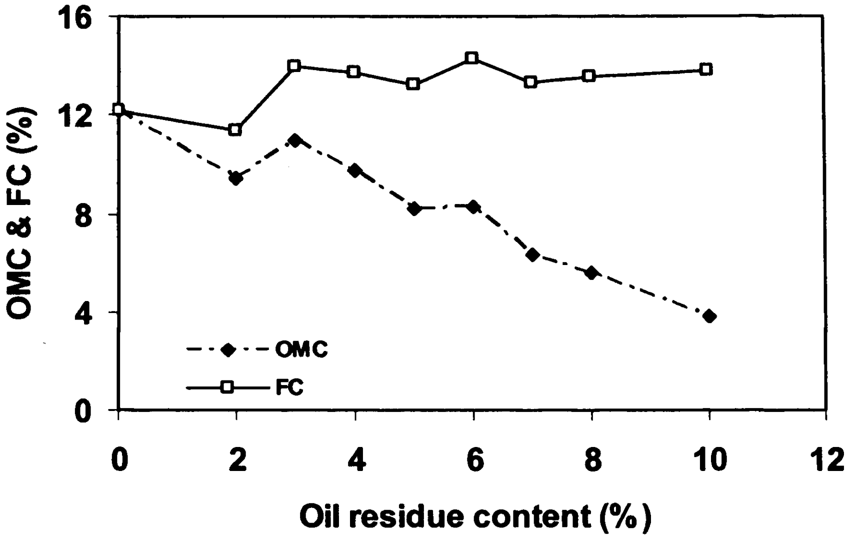

Figure 4.22. Optimum moisture and fluid contents for natural and oil mixed Sabkha soils (S_{B-8})

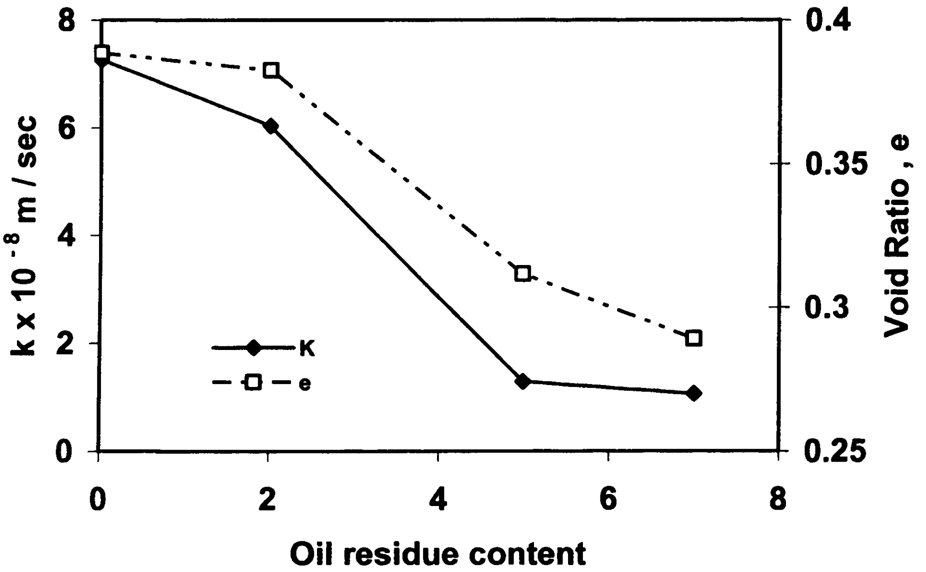

Figure 4.23. Coefficient of permeability and void ratio for natural and oil mixed Sabkha soils (S_{J-4})

Plate 4.1. Soil particle aggregations

Plate 4.2. Rigidity of oil mixed soils

Plate 4.3. Expanded soil samples during compaction

Chapter 5

Strength Aspects of Natural and Oil Mixed Sabkha Soils

5.1 Introduction

Investigation of the physical properties of the oil mixed Sabkha soils described in the previous chapter indicated that the lubrication effect of the oil residue had modified the soils' compaction parameters. However, the density of the Stabilised Sabkha soil can not be used as the only criterion in any stabilisation programme (Al-Amoudi et al., 1995). In addition, the lubrication effect due to the viscosity of the oil residue may have affected the shearing properties of the Sabkha soil. Accordingly, the effects of different oil contents on the unconfined compressive and shear strength of oil mixed Sabkha soil will be explored in this chapter. Strength parameter is one of the major geotechnical properties of soil that can be modified by different types of additives. Based on previous study findings, it is anticipated that the cohesive properties of Sabkha soil will be modified by oil residue addition, an advantage to it.

The strength characteristics of natural and oil mixed Sabkha soils will be investigated through conducting unconfined compression and direct shear tests. The testing programme for the strength aspects and unconfined compression test procedures and results are presented in section 5.2 and 5.3, respectively. Direct shear test procedures and results are explained in section 5.4. A review of main findings and a list of references are provided in sections 5.5 and 5.6, respectively.

5.2 Testing programme

This part of the experimental work covered phase D of the testing programme, as detailed in Figure 5.1. The strength aspects of oil mixed Sabkha soils from the four main locations, namely S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, were investigated in terms of unconfined compression and direct shear tests. Each of these tests was carried out on both natural and oil mixed Sabkha soils with different oil contents ranging from 0% to 10%.

5.3 Unconfined compression test

The main objective of this test was to examine the unconfined compression strength (*UCS*) of natural and oil mixed Sabkha soils at dry and soaked conditions. The unconfined compression test is a rapid means to measure relative changes in strength due to oil residue addition and to verify the usefulness of oil residue in improving Sabkha soil.

Several researchers (Aiban, 1995; Al-Amoudi, 1994; and 2002) have used the unconfined compression test to measure the effectiveness of different techniques for stabilising Sabkha soil. In this test, a cylindrical soil specimen is prepared and subjected to a steadily increasing axial load, without confinement, until failure.

5.3.1 Testing procedures

The unconfined compression test was carried out according to BS1377: 1990. Sabkha soils were mixed with different oil residue percentages. Each mixture was mixed at its optimum moisture content, identified from tests carried out in Section 4.4.5. The method for mixing dry soil with different oil residue percentages at its optimum moisture content is the same as that described in Section 4.3. Using the modified proctor compaction test mould, samples were prepared using the same compaction effort to reach maximum dry densities within narrow limits of variations from the values obtained in Section 4.4.5.

Soil samples for the unconfined compression test were obtained by inserting a 38.0 mm internal diameter tube of 230mm length into the compacted soil as shown in Plate 5.1. The sharp cutting edge of the tube was forced into the centre of the compacted soil sample in the mould to minimise the effect of side friction. The tube containing the soil specimen was removed from the mould without hammering in order to maintain the specimen's integrity. Soil was loosened around the tube to pull it out easily, as shown in Plate 5.2. The tube was placed on the extruder and the cylindrical soil sample was jacked out as shown in Plate 5.3. During extraction of the soil specimen, the upper part of the soil was levelled and small cavities were filled in with the same soil material. Samples were handled carefully to minimise disturbance and distortion. The height and weight of the sample were recorded. The tube was cleaned carefully after every use to minimise side friction that might affect the extrusion of the soil sample.

The extracted cylindrical soil specimens were 38 mm in diameter and an average 76 mm in height, representing a ratio of 1:2 diameter to height. Soil samples were subjected to a strain rate of 0.5 mm / minute, which enabled the test to be completed within 10 to 15 minutes. Load readings and deformations were recorded at regular intervals and stopped at failure. Failure was considered to have occurred when load reading decreased.

5.3.2 Results and discussion

Peak stress in the stress strain relationship is defined as the unconfined compressive strength (UCS) of the soil. The vertical stress at any stage of loading is obtained by dividing the total vertical load by the corrected cross sectional area, since the cross sectional area, A, at any stage of loading increases with the increase in compression.

Results are presented and discussed in terms of the following:

- Stress/strain relationship
- Unconfined compressive strength/oil content

5.3.2.1 Stress- strain relationship

The stress-strain relationships for natural Sabkha soils from the four main locations, which represent the applied compressive stress versus the axial strain, are shown in Figure 5.2. Large strains were noted at the first stage of loading, below 10 kPa, which may be attributed to the rearrangement of soil particles and roughness of the ends of soil sample. Stress-strain curves for Sabkha soils S_{J-4}, S_{K-7} and S_{B-8} reached more or less constant slopes at intermediate stresses, while the strain curves for Sabkha soil S_{Z-5} continued to increase with low applied loads.

The stress-strain curves of natural Sabkha soil exhibited peaks corresponding to strains ranging from 2.8% to 6.5%. These peaks were definite and clear for soils S_{J-4}, S_{K-7} and S_{B-8}, whereas Sabkha soil S_{Z-5} did not show a clear peak. Soil sample S_{K-7} showed peak strength at a higher strain of 6.5%, while soil S_{Z-5} showed peak strength at a lower strain of 2.8%.

Figures 5.3 to 5.6 show the stress-strain curves for Sabkha soils mixed with different oil residue content from the four main locations, S_{J-4}, S_{K-7}, S_{B-8} and S_{Z-5}, respectively. The stress-strain relationships for the natural soil are used as a reference to evaluate the change in soil behaviour due to oil addition. A general look at these figures indicates that their stress-strain responses were generally similar, in that they were markedly affected by oil residue addition.

The stress-strain relationships observed for natural and oil mixed Sabkha soils S_{J-4} are shown in Figure 5.3. A continuous increase in the slope of stress-strain curves is observed at small strains with increasing oil residue addition. At the applied stress value of 10 kPa, the strain decreased from 1.93% for the natural Sabkha soil S_{J-4} to 1.09% for the same Sabkha soil mixed with 8% oil residue, reflecting an increase in soil stiffness due to oil residue addition. A close look at Figure 5.3 shows a distinct axial stress failure was reached at an axial strain of about 4% for natural Sabkha soil. In contrast, oil mixed Sabkha soils exhibited more ductile behaviour, since Sabkha soils with oil residue contents of 5% and 8%, reached a higher axial strain.

Similar trends were noted for soils S_{K-7} and S_{B-8} as shown in Figures 5.5 and 5.6, respectively. Soil S_{Z-5} in its natural condition had the lowest stress-strain curve among the tested soils, which can be attributed to the lower fine content. The oil mixed soil S_{Z-5} showed remarkable results compared to the natural, since the stress-strain curves dramatically changed with continuous oil addition (see Figure 5.4). Oil mixed soil S_{Z-5} exhibited more ductile behaviour. At a 5% oil residue addition, there was a three fold increase in the axial strain of oil mixed soils compared to natural soil samples.

The previous discussion indicates that the stress-strain behaviour of Sabkha soils was affected by oil residue addition. The stress-strain curves were modified following oil addition, possibly due to the formation of cohesive bonds.

5.3.2.2 Unconfined compressive strength

Peak compressive strength in the stress-strain curve was considered to be the unconfined compressive strength (UCS) of the tested soil sample. Figure 5.7 presents UCS results for natural soils and corresponding failure strain. The figure indicates that the UCS for natural Sabkha soils ranged between 2.75 kPa and 53.1 kPa. The coarser-grained Sabkha soil $S_{Z\text{-}5}$ had the lowest unconfined compressive strength of 2.75 kPa, while soil $S_{B\text{-}8}$ had the highest unconfined compressive strength. Such results were expected for natural Sabkha soil since this type of soil possesses generally very low strength in its natural state (Al-Amoudi, 1994).

The low UCS value for soil $S_{Z\text{-}5}$ may be primarily attributed to its coarser gradation and lower fines content, since it was classified as poorly graded sand (SP) compared to the other Sabkha soils.

The increase in the UCS of tested Sabkha soils is due to apparent cohesion resulting mainly from cementation, interlocking of particles, and developed capillary stress in partially saturated soils (Al-Sanad et al., 1990; and Mitchell, 1993). The existence of different types of salts, such as gypsum and calcite, results in an increase in bonds between soil particles, since a small percentage of these salts (less than 2%) provides considerable strength (Al-Sanad et al., 1990). Therefore, the higher percentage of salts content in soils $S_{J\text{-}4}$, $S_{K\text{-}7}$, and $S_{B\text{-}8}$, reported in section 3.8.2, was expected to provide higher apparent cohesion in them than soil $S_{Z\text{-}5}$ with the lowest salt content, and, consequently higher unconfined compressive strength. In general, natural Sabkha soils showed a low unconfined compressive strength resulting from apparent cohesion.

Figures 5-8 to 5-11 show the unconfined compressive strength for Sabkha soils of the four main locations mixed with different oil residue percentages. Superimposed on these Figures are the maximum dry densities at which the specimens were prepared. The

Figures show that the unconfined compressive strength value was markedly affected by oil residue addition. The strength of natural Sabkha soils, which was relatively low, improved considerably with oil residue addition. The Figures also suggest that oil residue amount can significantly affect the UCS of Sabkha soil. Beyond an oil residue content of 5%, a large decrease in soil strength occurred with further oil residue addition.

In order to quantify change, the increase or decrease in unconfined compression strength of different Sabkha soils mixed with different oil residue percentages was calculated. Change in unconfined compressive strength $\Delta\ UCS$ is defined as:

$$\Delta\ UCS = \qquad (UCS_{st} - UCS_{n}) \times 100\ / UCS_{n}$$

where, UCS_{st} , UCS_{n} are the unconfined compressive strengths of oil mixed and natural soils, respectively. The calculated values are presented in Table 5.1, and indicate that the oil residue had contributed to the increase in compressive strength of Sabkha soils $S_{J\text{-}4}$, $S_{Z\text{-}5}$, $S_{K\text{-}7}$, and $S_{B\text{-}8}$ at different rates. Although the coarser Sabkha soil $S_{Z\text{-}5}$ was considered the weakest among the tested soils, a remarkable increase occurred due to oil residue addition. The unconfined compressive strength of soil $S_{Z\text{-}5}$ increased sharply from 2.75 kPa for natural soil to 13.7 kPa and 16.6 kPa at oil residue contents of 4% and 5%, representing a 398% and 504% increase, respectively. The ability of the oil residue to hugely enhance the strength of sandy Sabkha soil, which had low salt contents, is evident from soil sample $S_{Z\text{-}5}$ results. Modification in soil strength was observed during samples' preparation and testing. Experimentally, great care was needed in the sampling process for natural Sabkha soil $S_{Z\text{-}5}$, since any slight disturbance could have broken the sample into pieces. Oil mixed samples from the same soil were more easily handled than the natural soil samples.

For other Sabkha soils, maximum modification in unconfined compressive strength was in range of 34% to 84% for oil mixed Sabkha soils $S_{J\text{-}4}$, $S_{K\text{-}7}$ and $S_{B\text{-}8}$. The unconfined compressive strength of different Sabkha soils tested at different oil residue contents are presented in Figure 5.12. This Figure shows that unconfined compressive strength increased with oil residue addition up to 5%. Beyond this oil content, a large decrease occurred in the UCS.

In general, the strength developed in oil mixed Sabkha soils can be taken as a measure of the cohesive properties developed due to oil residue addition. As mentioned previously, the developed cohesion in natural Sabkha soils was low and attributed mainly to the cementation and interlocking of particles. The adsorbed viscous oil residue due to electrostatic weak bonding on soil surfaces increased the bonding between soil particles and consequently increased cohesion. An increase in the liquid limit of oil mixed Sabkha soils is indicative of increased soil bonding due to oil residue addition. The increase in the *UCS* of Sabkha soils mixed with oil may also be attributed to the increase in density of the compacted soils as shown in Figures 5.8 to 5.11, since their strength depends on density (Livench et al., 1998). Closer packing of the compacted oil mixed Sabkha soils due to higher density increased the shear strength and consequently increased the unconfined compressive strength of soils.

The results in Table 5.1 indicate that oil residue addition beyond 5% had an adverse effect on the behaviour of Sabkha soil, since unconfined compressive strength decreased to lower values for all tested soil samples. This decrease in *UCS* with more oil addition may be attributed to thicker oil residue layers formed around the soil particles, which increased the lubrication effect, and sliding of these particles over each other which consequently reduced the strength. A similar reduction was observed by Mohammed (1995) and Puri et al. (1994) during their investigation of the geotechnical properties of highly crude oil-contaminated sands.

Figures 5.8 to 5.11 also show that although the dry density of oil mixed Sabkha soils continued to increase beyond 5% oil addition, the *UCS* started to decrease with oil addition, supporting the finding of Al-Amuodi et al. (1995) that density cannot be used as the primary indicator of stabilisation.

5.3.2.3 Mode of failure

Observation of the samples during the *UCS* test indicated that the failure of different samples occurred in a number of different ways. The failure planes were visible in most cases. The tested samples failed either by shearing on an inclined plane or by bulging. In natural soils, the presence of salt bonds induced a brittle compressive behaviour, as shown by the sharp drop in the stress-strain curves and at lower strain than the oil mixed soils. On the other hand, in oil mixed Sabkha soils, soil bulging was the predominant mode of failure (see Plate 5.4), attributable to the increase in cohesion between soil particles due to oil residue addition. Bulging appeared at the lower part of some samples, in some cases a network of cracks was created on the cylindrical surface of samples. It is worth mentioning that soil sample S_{Z-5} totally collapsed under low loads in its natural condition, whereas with oil addition the soil specimen became more stable and collapsed in a bulging mode.

5.3.3 Effect of soaking

The effect of soaking on the geotechnical and engineering behaviour of Sabkha soil is considered very critical. The durability of Sabkha soils mixed with oil under soaking conditions was investigated to evaluate the potential effect of oil residue addition on minimisation of the adverse effect of soaking. Natural and oil mixed Sabkha samples were prepared following the same steps described in Section (5.3.1) and soaked for 24 hours in distilled water. Additional tests were carried out on other soil samples directly after preparation without soaking to provide benchmark data for identifying the effect of oil addition on the behaviour of soaked Sabkha soils. Results of soaking tests are presented in Figures 5.13 to 5.16 for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. Figures show that the stress-strain curves of the soaked oil mixed Sabkha soils exhibited peaks corresponding to lower strains than dry oil mixed soils S_{Z-5}, S_{K-7} and S_{B-8}. These peaks were definite and clear for all tested soils.

The unconfined compressive strength for soaked natural Sabkha soils could not be determined as the specimens disintegrated upon soaking. The collapse of natural Sabkha samples occurred immediately upon soaking for S_{Z-5} samples and after a few hours for S_{J-4}, S_{K-7} and S_{B-8} samples. This may be attributed to the reduced capillary effect, a main factor providing apparent cohesion, and to salts' dissolution (Aiban, 1998).

To show the effect of soaking on the unconfined compressive strength of Sabkha soils mixed with oil residue at different percentages, soaked samples' results were plotted together with unsoaked results for soil S_{J-4} in Figure 5.17. This Figure shows that the unconfined compressive strength of oil mixed Sabkha soils decreased due to soaking, but remained high enough compared with the soaked natural soil results. Comparing oil mixed soil results with that of natural soil, oil residue addition evidently provided resistance to the adverse effects of soaking. The unconfined compressive strength for Sabkha soil mixed with 4% oil residue was reduced due to soaking, from 71.7 kPa to 40 kPa, representing a percentage decrease of 44%. With 7% oil residue, it was noted that the unconfined compressive strength decreased by 22%. The higher UCS of soaked oil mixed soils compared to natural soil may be attributed to the resistance of the developed cohesion and bonding between soil particles to the saturation effect. The adsorption process of hydrophobic oil residue formed a coating layer that changed the affinity of the soil for water (Kaiser, 2000). This resulted in decreased salt dissolution due to the waterproofing effect of the adsorbed oil layer. This effect was expected to increase with oil residue addition due to the formation of a coating layer and consequently more water proofing. Figure 5.17 also shows that the difference between dry and soaked UCS decreased with continuous oil addition.

A similar trend was noted for dry and soaked Sabkha soils from other locations as shown in Figure 5.14 for soil $S_{Z\text{-}5}$. The natural Sabkha disintegrated upon soaking in water, while the soaked unconfined compressive strength for the soil sample $S_{Z\text{-}5}$ mixed with 5% oil residue was 9.3 kPa. This represented 56% of the strength of the oil mixed sample tested at dry conditions.

Andrade et al. (2004) in their study on contaminated soils observed the formation of aggregates made up of grains held together by oil and concluded that the hydrophobic characteristics of soil particles coated with oil were higher than those of clean soils, which minimised water adsorption on the soil particles. The waterproofing effect of the oil residue was expected to minimise the dissolution of different types of salts and provide resistance to the soaking effect.

5.4 Direct shear test

The main objective of the direct shear test was to investigate the effect of oil residue on the shear strength of oil mixed Sabkha soil in terms of the angle of shearing resistance (φ_f) and the cohesion intercepts (C).

The effect of oil residue addition to Sabkha soil on shear strength was investigated since the addition of different types of hydrocarbons may cause loss of strength due to the lubrication effect. Main parameters in shear strength are the angle of internal friction and cohesion. In the previous section, it was reported that oil residue addition increased the unconfined compressive strength of oil mixed Sabkha soils, an indication of the developed cohesive property between soil particles. However, friction between soil particles may have been affected by oil residue addition. Accordingly, the effect of oil residue addition on main shear strength parameters was investigated by conducting direct shear tests on natural and oil mixed Sabkha soils.

5.4.1 Testing procedures

The direct shear test was carried out according to BSI, 1990, BS 1377, using a standard Wykeham-Farrance manufactured machine with a mechanical loading system. Tests were carried out on soil specimens of 60 mm square by 20 mm thick under different normal loads. The vertical loads were applied incrementally to give varying vertical stresses of 50, 100, 150 and 200 kPa. In some cases, a vertical stress of 400 kPa was used. Each vertical stress was allowed for a period of time so that full settlement of the specimen occurred. Preliminary test indicated that approximately 45 minutes was required to ensure the settlement of the specimen under applied vertical pressure. The soil specimen was then sheared at a displacement rate of 0.120 mm/min, under drained conditions intercept. Tests were conducted under low shearing speed to ensure total dissipation of pore water pressure. During the shearing process, readings of vertical and shear displacements, and shear force were recorded at convenient time intervals.

Two series of direct shear tests were performed to accomplish the outlined study objectives. The first series was carried out on natural and oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} with different oil residue percentages under optimum moisture conditions. The second series was carried out on samples S_{J-4} and S_{Z-5} prepared in a similar way to that of the first series but soaked in water. Tested soil samples were soaked for 24 hours before carrying out the test.

Other details relating to mixing oil residue with Sabkha soil have been described previously in Section (4.3).

5.4.2 Results and discussion

Results are presented and discussed as follows:

- A plot of shear stress versus horizontal displacement was drawn for each tested soil sample at each applied vertical load. From this, the stress-strain behaviour of the tested soil sample could be studied and the maximum shear stress, considered to be the shear strength, corresponding to the state of failure τ_f, could be read.

- From previous data, the maximum shear stresses, τ_f, were plotted against the corresponding values of normal stresses, σ_n. The subsequent graph generally approximated to a straight line and represented the Mohr-coulomb envelope for each tested soil sample. The inclination of this line to the horizontal axis was equal to the angle of shearing resistance of the soil, φ_f, and its intercept with the vertical axis was the cohesion, C.

Results of the direct shear testing are presented in Figures 5-18 to 5-43 for natural and oil mixed Sabkha soils.

5.4.2.1 Shear stress versus shear displacement - Dry conditions

Figures 5.18, 5.19, 5.20 and 5.21 illustrate the shear stress versus horizontal displacement curves of natural Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, tested under normal pressure, ranging from 50 to 200 kPa, respectively. The stress-strain curves presented in these figures show a general trend of an almost linear initial portion, followed by a non-linear portion to a well-defined peak shear stress. A comparison of the peak shear strength of natural Sabkha soil samples obtained from these figures, reveals that shear stress increased to a peak value of 161 kPa, 130 kPa, 120 kPa and 82 kPa at a vertical stress of 150 kPa and 200 kPa, 180 kPa, 115 kPa, and to 120 kPa at a vertical stress of 200 kPa for soil samples S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}. Once a peak had been reached, softening was observed as indicated by the reduction in shear stress with increased shear deformation. The tested Sabkha soils exhibited a reduction in shear stress of between 20% and 50% compared to peak shear stress values. Peak shear stress values in previous figures correspond to both friction and cohesion. The frictional component resulted from the frictional resistance of the matching surfaces, while the cohesion component was furnished by the strength of the cementing material bonding the two halves of the bedding plane together. A comparison between the aforementioned figures shows that the shear stress of soil sample S_{B-8} at different vertical stresses was the lowest among the tested soil samples. The lower value of the shear stress may be attributed to the lower content of SiO_2, as reported in the chemical analysis detailed in Section (3.8.2). In addition, the mineralogical content of Sabkha soil S_{B-8} revealed the existence of high shale contents, which crushed more easily, thereby reducing the interlocking or bridging effect.

Soil samples S_{J-4} and S_{Z-5} exhibited higher shear stress at different vertical stresses as shown in Figures 5.18 and 5.19. The increase in the shear stress of soil S_{Z-5} under higher vertical pressure can be attributed to the frictional part of the granular particles since quartz composed 72% of the soil constituents, while in soil S_{J-4} the increase in shear stress may be attributed to friction and cohesion.

A brittle failure was observed to occur for the strongly cemented soils S_{K-7}, and S_{J-4}. Curves for natural Sabkha soils S_{J-4} and S_{K-7} using 100 and 200 kPa vertical stresses demonstrated clearly the brittle failure mode, since the degree of brittleness increases sharply with the amount of cement materials (Ismael et al., 1986-b). Peak shear stresses for different Sabkha soils were reached at displacements between 1.57 mm and 5.4 mm, depending on the normal stress applied. The lower strain in these soils may be attributed to weak cementation bonds which break at small strain levels.

Tests were carried out on 2%, 5% and 8% oil mixed Sabkha soils from the four main locations under a normal stress of 50, 100, 150 , 200 kPa and, in some cases, 400 kPa. Samples of shear stress-horizontal displacement curves for tests on 5% oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} at different vertical stresses are shown in Figures 5.22 to 5.25. These figures show that the pre-failure portion of the shear stress versus horizontal displacement curves was slightly more affected by the oil residue addition than the natural curves at the same vertical stresses. The resulting peak shear stresses slightly decreased or increased with oil addition and different applied vertical stresses for Sabkha soils S_{J-4}, S_{K-7} and S_{B-8}. A comparison of the peak shear strength of oil mixed Sabkha soils S_{J-4} (Figure 5.22) shows that peak shear stresses at normal stresses of 100 kPa and 150 kPa were 124.6 kPa and 151 kPa, respectively which are slightly lower than the shear stresses of the natural soil at similar vertical stresses. Once a peak had been reached in oil mixed Sabkha soils, a reduction in shear stresses was observed with increasing strain. Oil mixed soils exhibited a lower reduction in shear stress than natural soil. A similar trend was noted for Sabkha soils $_{SK-7}$ and S_{B-8}.

To highlight the effect of oil addition on peak stress, comparisons are made in Figures 5.26 to 5.29 between peak shear stresses for natural and oil mixed soils with different oil residue contents for the same vertical stresses. One interesting aspect of these figures is the similarity in trend of almost all the tested soil samples. From these figures, a small variation in shear stress with oil addition at different vertical stresses for soils S_{J-4}, S_{K-7}, and S_{B-8} is observed. There are, however, instances of reductions or increases in shear strength with oil residue content. These exceptions to the general trend can be attributed to the in-homogeneity of Sabkha soils and the high concentration of gypsum in them, which led to variability in results (Al-Amoudi et al., 1992).

A close look at stress-strain curves for natural and oil mixed Sabkha soils reveals that oil residue addition had no clear effect on the displacements required to mobilise the peak shear stresses for the tested soil samples. However, in some cases larger displacements were required to mobilise peak shear stresses for oil mixed Sabkha soils than natural Sabkha soils. For example, shear displacement for natural Sabkha soil S_{J-4} was 1 mm and 2.1 mm at vertical stresses of 50 and 100 kPa (Figure 5.18), while shear displacement for the 5% oil mixed sample from the main location was 2.2 mm and 2.6 mm (Figure 5.22) at the same vertical stresses, respectively.

Stress-displacement for natural Sabkha soils' data showed a brittle failure mode due to a significant drop in strength after peak strength was reached. Further, with more oil addition, testing results indicated that the behaviour of Sabkha soils changed to a more ductile one. The failure mechanism of oil mixed Sabkha changed due to the application of oil residue.

5.4.2.2 Peak shear stress/normal stress relationships-Dry conditions

Strength envelopes were plotted using peak stress obtained from experimental stress-strain relationships and the corresponding applied vertical stress. Mohr-Coulomb envelope curves for natural Sabkha soils are shown in Figure 5.30. The inclination of the failure envelope represents the internal angle of friction, φ_f, while the intersection of that line with the y-axis represents the cohesion intercept, C.

Results suggest that the shear strength of Sabkha soil could be primarily attributed to friction and partly to cohesion. The main part of the friction is represented by the high angle of shearing resistance resulting in high shear strength. Values for the friction angle, φ_f, and cohesion intercept, C, for natural Sabkha soils from the four main locations are summarised in Table 5.2. Internal friction angles values were 43.5°, 35°, 28° and 25° for soils S_{J-4}, S_{Z-5}, S_{K-7}, and S_{B-8}, respectively, within the range expected for Sabkha soils in Kuwait and the Gulf region (Al-Amoudi et al.,1992; Ismael, 1993-b). It is worth mentioning that the higher shear strength parameters values for some test results can be attributed to the increasing density of the compacted Sabkha soil, where it is thought that higher shear strength parameters are achieved due to the decrease in the void ratio (Juillie and Sherwood, 1983). The high shear strength of soil sample S_{J-4} is primarily attributed to both frictional and cohesion parts. Chemical testing and XRD analysis showed that soil sample S_{J-4} consisted of more than 54% SiO_2 and high percentages of calcium carbonates and sulphates.

The cohesion intercept values for the tested soils varied from 18 to 23 kPa. The lowest cohesion intercept value was for soil S_{Z-5}, which can be attributed to the low percentage of salt contents, since chemical test results (Section 3.8.2) had shown that sulphate and carbonate contents were very low. Soil S_{B-8} also had a low cohesion intercept value, which may be primarily attributed to the high shale content (Al-Sanad et al., 1990). The cohesion intercept value is typical of cemented sands in Kuwait and is mainly due to the cementation effect of different types of salts. Cementing agents in Kuwait, as reported by Ismael (1993-b), consist mainly of calcium carbonates, calcium sulphates, and chlorides (Ismael and Mollah, 1998). Al-Sanad et al. (1989) concluded that cementation by various salts provides a considerable proportion of the shear strength of many soils in desert regions. In their experimental study, tests showed that only a very small percentage (2%) of salts, such as gypsum and calcite, is necessary to provide a considerable increase in strength above that of uncemented sand at the same packing. In general, the presence of a cohesion intercept in cemented sands in Kuwait of the order of 4 kPa to 24 kPa is due to slight bonding or inter-particles' cementation which exist at some locations in Kuwait (Ismael et al., 1986-b).

Figures 5.31, 5.32, 5.33 and 5.34 show the relationship between maximum shear stress and corresponding vertical stress for natural and oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. A general look at these figures indicates that the slope of the failure envelope for different oil mixed Sabkha soils decreased with more oil addition, indicating a reduction in friction angles and an increase in cohesion. The values of the friction angle (φ_f) and cohesion intercept (C) for natural and oil mixed soils are summarised in Table 5.2. The aforementioned figures and the table show a general trend of reduction in the internal angle of friction with oil residue addition. The reduction rate varies for different soils and with different oil residue contents.

The friction angle value for different oil residue addition and different Sabkha soils is represented graphically in Figure 5.35. It can be observed from this Figure that soils S_{J-4}, S_{K-7} and S_{B-8} display a similar trend of gentle reduction in the internal angle of friction with oil residue addition up to 5%. Beyond 5% the reduction rate is higher. Soil S_{Z-5} exhibited different behaviour, in that the higher reduction in friction angle with oil addition started at 2% oil residue and became even higher after 5%.

Variation in internal friction angles and cohesion intercept, presented as a percentage of the natural Sabkha soil values, is calculated and listed in Table 5.2. Values in the Table show that percentage reductions in the friction angles are 5.75%, 28%, 16% and 16% at an oil residue content of 5% for Sabkha soil samples S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. These percentage reductions increased to 10%, 71%, 46%, and 32%, respectively at 8% oil addition.

Coupling the results with soil grain size distribution results presented in section (3.8.1.1), it can be concluded that the coarser the soil the higher the effect of oil residue addition on the internal friction angle. Grain size distribution results showed that soil S_{Z-5} had the coarsest gradation of the tested Sabkha soils and also the highest rate of reduction in friction angle with oil addition. The coarser the gradation, the smaller the surface area and the higher the lubrication effect. This explains the higher reduction in friction angle for soil S_{Z-5}.

Figures 5.31 to 5.34 also show that the inclination of the failure envelopes reduced with increased oil residue content, resulting in an increase in cohesion values. Cohesion intercept values for different Sabkha soils with oil residue addition are presented graphically in Figure 5.36. The Figure shows that variation in cohesion intercept values did not follow a uniform trend. It increased at different rates up to 5% oil residue addition and then beyond this oil content sharply decreased for S_{Z-5} while continuing to increase with oil residue addition for other Sabkha soils S_{J-4}, S_{K-7}, and S_{B-8}.

Variation in the cohesion intercept for different soils, presented as a percentage of the natural soil value, is detailed in Table 5.2, which shows increases in the cohesion intercept were 45%, 150%, 52%, and 136% for Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively, at an oil residue content of 5%.

In general, it would seem that oil residue addition affected the Sabkha soils in two simultaneous contrasting ways. Oil residue addition reduced the angle of internal friction and increased the cohesion intercept. The reduction in the friction angles with oil addition is mainly attributed to the lubrication effect of the oil residue. The adsorbed oil residue on the soil surfaces form a layer on the surfaces of mineral surfaces, filling the surface roughness and giving a smooth texture (Karimi and Gray,2000) which reduces the friction between these particles and facilitates their sliding on each other, which will result in reducing the friction mechanism in the oil mixed soils.

The larger the molecular size and the higher the boiling point and viscosity of the oil residue (section 3.9), the larger the bonding between the oil and soil surfaces (Semer and Ready, 1998). Major bonding mechanisms between oil residue and Sabkha soils, although weak, participate in increasing the interparticle bondings of the oil-soil-water system. This increase in overall bonding will increase soil cohesion. Up to an oil residue content of 5%, the reduction in the internal angle of friction ranged from 3% to 28%. The lowest reduction was in soil S_{J-4}, while the highest was in soil S_{Z-5}. The reduction in friction was more pronounced in the coarser soil, S_{Z-5}, which may be attributed to the lubrication effect of the viscous oil, which facilitated sliding of soil particles over each other. These results are in good agreement with findings reported by Al-Sanad et al. (1995), who observed significant reduction in the internal angle of friction with oil addition to different soils. However, Al-Sanad and Ismael (1997), in a follow-up study on the same contaminated sand, noted an increase in the friction angle with ageing effect and attributed this primarily to the evaporation of volatile compounds. Aiban (1998) attributed a reduction in the internal friction angle (φ_f) of contaminated sand to the lubrication effect of the oil at grain contact. Srivastava and Pandey (1998) found both friction angle and cohesion intercept decreased with oil addition for alluvial soil mixed with oil, while for sandy soil mixed with oil residue there was an increase in both friction angle and cohesion intercept up to 3% oil addition, followed by a reduction with more oil addition.

Results in this study indicated that up to an oil addition of 5%, the increase in soil cohesion intercept ranged from 45% to 150%. The trend of increase in cohesion with oil addition was in good agreement with Carrigy (1967) and Ola (1991) who reported that naturally deposited tar sands had a lower strength than comparable clean sands with the possible presence of cohesion intercept. Generally, it is thought oil addition of up to 5% increased the Sabkha soil cohesion intercept without affecting soil particles' contact and salt bonding between them.

The large reduction in the internal friction beyond oil residue addition of 5% may be attributed to the formation of a thicker oil film around soil particles (Shin et al.,1999), and excess oil residue in the voids between the soil particles in the stabilised soil system, preventing soil particles' contact (Kedzi,1974).

Vertical dilation of the tested soils during the shearing test was used to indicate the amount of oil residue in soil voids, since high oil residue in pore voids was expected to create pressure during shearing and increase the vertical dilation of the sheared soil sample. Figures 5.37, 5.38 and 5.39 show the corresponding vertical displacement against horizontal displacement curves for soils S_{J-4}, S_{Z-5} and S_{K-7} at different vertical stresses. Figure 5.37 shows that dilation of the tested soils increased with oil residue addition. At the same vertical stress, dilation was higher at an oil residue content of 8%, suggesting an excess of oil residue in the soil pores with high oil addition. This behaviour also explains the large reduction in the friction angle of tested Sabkha soils with oil addition beyond 5%. The higher dilation at oil content of 8% indicated that more oil residue was available in the pore voids, leading to greater lubrication effect and higher reduction in friction angle. Similar findings were reported by Mohammed (1995) in his investigation of Bahrain soils. Based on the calculation of surface coverage area, he found that 4% of oil was initially sufficient to cover the entire surface of the tested soil. In the present study, during soil testing oil bleeding was observed in high oil content soils, confirming that increased oil residue existed as free oil in the soil voids. In addition, soil dilatations results were supported by the observations during compaction tests previously discussed in section 4.4.5. At high oil content, part of the oil mixed Sabkha soil extended out side the compaction mould.

The general trend shown previously in Figures 5.26 to 5.29 is that peak shear stress increased slightly with oil addition up to 5%, after which it started to decrease slightly. However, there were some exceptions to this trend for some soils at some vertical stresses. This can be attributed to the contrasting effect of the increase in cohesion and the reduction in the friction angle with oil addition.

For soil sample $S_{Z\text{-}5}$, the general trend of slight variation (increase or decrease) with oil residue addition applied for up to 5% oil residue content. Beyond this percentage, the shear stress decreased sharply at all applied vertical stresses. Variability in the behaviour of soil $S_{Z\text{-}5}$ may be attributed to its coarse gradation and low fine contents which affected the main component of shear strength in this soil, the frictional component, and facilitated the sliding of soil particles, resulting in a sharp decrease in peak shear stresses with more oil addition.

5.4.2.3 Effect of soaking

Due to the high salt content in Sabkha soils, as identified in the chemical characterisation presented in section (3.8.2), their shear strength may drop to low values upon inundation with water. This reduction due to soaking is caused by the destruction of the cementation bonds between soil particles, which, in turn, causes a decrease in structural strength.

Accordingly, it was felt necessary to investigate the behaviour of natural and oil mixed Sabkha soils under soaked conditions to evaluate the effect of oil residue on shear strength parameters.

Results presented in the previous section revealed that soil S_{Z-5} differed in its shear strength behaviour from other Sabkha soils, and soils S_{J-4}, S_{K-7} and S_{B-8} showed similar shear strength behaviour. It was therefore decided to investigate the soaking effect on direct shear using soils S_{J-4} and S_{Z-5} only.

Samples for soaked direct shear tests were prepared using the same sample preparation procedures previously described in section (5.4.1). After applying the vertical load and allowing the expected consolidation, the direct shear box was filled with distilled water and left for 24 hours. After this period, the soil specimen was sheared following the same steps mentioned in section (5.4.1).

5.4.2.3.1 Shear stress-horizontal displacement - Soaked conditions

The effect of saturation on the stress-strain relationship for natural and oil mixed Sabkha soils is illustrated in Figures 5.40 and 5.41. These figures show the stress-strain curves for dry and soaked conditions and 5% oil mixed Sabkha soils S_{J-4}, and S_{Z-5}, respectively at the same vertical stress of 100 kPa. Figure 5.40 shows that the shear stress for the natural Sabkha soil S_{J-4} reduced from 110 kPa to 31 kPa upon soaking, a 70% reduction. On the other hand, the peak shear stress for the 5% oil mixed soil reduced from 92 kPa to 73 kPa, a 21% reduction. Both natural and oil mixed Sabkha soils were affected by saturation; however, the reduction in peak shear stress value was lower in the oil mixed Sabkha soil than in the natural. A similar trend is noted in Figure 5.41 for soil S_{Z-5}, in that the reduction in peak shear stress due to saturation was much lower for oil mixed Sabkha soil.

5.4.2.3.2 Peak shear stress/ normal stress relationships-Soaked conditions

Figures 5.42 and 5.43 show the relationship between maximum shear stress and vertical stress for natural and 5% oil mixed Sabkha soils S_{J-4} and S_{Z-5} , respectively. These figures show that the slope of the failure envelope for the soaked natural and the 5% oil mixed Sabkha soils was lower than that for the dry, indicating a reduction in friction angle due to soaking. The friction angle (φ_f) reduced from 42° and 40° for natural and 5% oil mixed Sabkha soils to 28° and 30° due to soaking, representing a reduction percentage of 33% and 25% for natural and oil mixed soil, respectively. Similarly the cohesion intercept (C) reduced from 15kPa and 33kPa to 2kPa and 18kPa for the natural and oil mixed soil due to soaking, representing a reduction of 86% and 45%. Figure 5.43 shows that the reduction in friction angle and cohesion intercept of oil mixed Sabkha soil $S_{Z\text{-}5}$ was lower than that of natural soil. These results suggest that oil residue addition reduced the effect of soaking on the shear stress parameter and shear strength, further implying that shear stress loss in oil mixed soils was lower than that in natural soil. This may be attributed to the waterproofing effect of the oil residue that prevented the dissolution of salts and reduction in cementation.

In summary, test results indicated that oil residue addition prevented shear strength loss of compacted Sabkha soils upon soaking. The reduction in the friction angle and cohesion intercept of natural soil upon soaking may be attributed to internal fabric attenuations, such as destruction of bonds, weakening of cementation, and breakdown of soil packets (Alawaji, 2001) since salt-cemented soils owe much of their shear strength to their cementation (Al-Sanad, 1986). Tests on natural and artificially cemented sands suggest that considerable loss of strength may result for such soils upon soaking (Al-Sanad et al., 1989; 1990; and Alawaji, 2001). Similar findings have been reported by Ismael et al. (1986-b) based on soaked and unsoaked direct shear tests undertaken on natural Sabkha soils. They observed that the angle of internal friction of calcareous desert sands reduced from 40° to 35.5° due to saturation.

5.5 Conclusion

An experimental programme was undertaken to investigate the effects of oil residue on the strength aspects of oil mixed Sabkha soils. A series of unconfined compression and direct shear tests were conducted on natural and oil mixed Sabkha soils with different oil residue contents. Sabkha soil samples were tested in both dry and soaked conditions. Samples were considered dry (D) when they were prepared and tested at their OMC. Soaked samples (S) were those prepared at OMC, soaked in water for 24 hours and then tested. Experiments were conducted on soils $S_{J\text{-}4}$, $S_{Z\text{-}5}$, $S_{K\text{-}7}$ and $S_{B\text{-}8}$ at different oil residue contents. The following conclusions are drawn from this part of the experimental work:

- Natural Sabkha soil possessed low *UCS* and direct shear strength. Unconfined compressive strength ranged from 2.75 kPa to 53.10 kPa for the different Sabkha soil samples, and the friction angle and cohesion intercept ranged from 25° to 43.5° and 18 kPa to 23 kPa, respectively.
- The *UCS* of the Sabkha soil improved with oil addition. An increase in the *UCS* in the range of 34% to 504% was observed upon the addition of up to 5% of oil residue to the Sabkha soil.
- Modification of the *UCS* was much greater for coarser Sabkha soil with oil addition of up to 5% than natural soil.
- Oil residue addition to Sabkha soil prevented complete loss of its strength upon soaking and reduced the effect of soaking on the UCS. Natural Sabkha soils disintegrated upon soaking, while the UCS of 5% oil mixed Sabkha soils was reduced in the range of 42% to 60% from the dry oil mixed values.
- The brittle failure in Sabkha soil changed to more ductile failure with more oil addition to Sabkha samples.
- Beyond 5% oil content, the *UCS* was reduced in all Sabkha soils at dry and soaked conditions.
- Shear strength parameters were affected by oil addition. Friction angles decreased in the range of 5% to 28% and cohesion intercept values increased in the range of 45% to 150% upon oil addition of 5%.
- Due to increased cohesion and reduction of the friction angle with oil addition to soil, the general effect of oil addition on shear strength could be considered negligible.
- Oil residue addition prevented total shear loss of soaked soils. The reduction in shear strength parameters was lower in 5% oil mixed Sabkha than natural Sabkha soils.

5.6 References

Aiban, S.A., 1995. Strength and Compressibility of Abqaiq Marl, Saudi Arabia. *Engineering Geology*, 39(3-4): 203-215.

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Al-Amoudi, O.S.B., 1994. Chemical Stabilisation of Sabkha Soils at High-Moisture Contents. *Engineering Geology*, 36(3-4): 279-291.

Al-Amoudi, O.S.B., 2002. Characterisation and Chemical Stabilisation of Al-Qurayyah Sabkha Soil. *Journal of Materials in Civil Engineering*, 14(6): 478-484.

Al-Amoudi, O.S.B., Abduljauwad, S.N., El-Naggar, Z.R. and Rasheeduzzafar, 1992. Response of Sabkha to Laboratory Tests - A Case-Study. *Engineering Geology*, 33(2): 111-125.

Al-Amoudi, O.S.B., Asi, I.M. and El-Naggar, Z.R., 1995. Stabilisation of an Arid, Saline Sabkha Soil Using Additives. *Quarterly Journal of Engineering Geology*, 28: 369-379.

Al-Awaji, H.A., 2001. Settlement and Bearing Capacity of Geogrid-Reinforced Sand Over Collapsible soil. *Geotextiles and Geo-membranes*, 19(2): 75-88.

Al-Sanad, H.A., 1986. Characterisation of Salt-Bearing Soils (Sabkha) for Pavement Design Purposes in the State of Kuwait. Journal of the University of Kuwait-Science, 13(1): 29-41.

Al-Sanad, H.A., Eid, W.K. and Ismael, N.F., 1995. Geotechnical Properties of Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical Engineering*-ASCE, 121(5): 407-412.

Al-Sanad, H.A. and Ismael, N.F., 1997. Aging Effects on Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3): 290-293.

Al-Sanad, H.A., Shaqour, F.M., Hencher, S.R. and Lumsden, A.C., 1989. The Shear Strength of Salt-Cemented Sand from Kuwait, Proceedings of the first Regional Conf. Civil Engineering, Bahrain.

Al-Sanad, H.A., Shaqour, F.M., Hencher, S.R. and Lumsden, A.C., 1990. The Influence of Changing Groundwater Levels on the Geotechnical Behaviour of Desert Sands. *Quarterly Journal of Engineering Geology*, 23(4): 357-364.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North-Western Spain). *Journal of Environmental Quality*, 33: 2103-2110.

BSI, 1990. British Standard 1377 (1990): Methods of Test for Soils for Civil Engineering Purposes, British Standards Institution, London.

Carrigy, M.A., 1967. The Physical and Chemical Nature of A Typical Tar Sand: Bulk Properties and Behaviour, Proceedings of the 7th International World Petroleum Congress, (1): 573-581.

Ismael, N.F., 1993-b. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035. Washington, D. C.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Ismael, N.F., Mollah, M.A. and Al-Khaldi, O., 1986-b. Geotechnical Properties of Cemented Soils in Kuwait. Australian Road Research, 16(2): 94-104.

Juillie, Y. and Sherwood, D.E., 1983. Improvement of Sabkha Soils of the Arabian Gulf Coast, Improvement of Ground. Proc.8th European conference on Soil Mechanic and Foundation Engineering, pp.781-788.

Kaisar, K., Haumaier, L. and Zeck, W., 2000. The Sorption of Organic Matter in Soils as Affected by the Nature of Soil Carbon. *Soil Science*, 165(277-304).

Karimi-Lotfabad, S. and Gray, M.R., 2000. Characterisation of Contaminated Soils Using Confocal Laser Scanning Microscopy and Cryogenic-Scanning Electron Microscopy. *Environmental Science & Technology*, 34(16): 3408-3414.

Kedzi, A., 1974. Handbook of Soil Mechanics. Soil Physics, 1. Elsevier Scientific Publishing Company, Amsterdam, p.249.

Livneh, M., Livneh, N.A. and Hayati, G., 1998. Site Investigation of Sub-Soil with Gypsum Lenses for Runway Construction in an Arid Zone in Southern Israel. *Engineering Geology*, 51(2): 131-145.

Mitchell, J.K., 1993. Fundamentals of Soil Behavior. 2nd edition, John Wiley and Sons Inc., New York, p.437.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and Its Geoenvironmental Implications. PhD Thesis, McGill University, Montreal, Canada.

Ola, S.A., 1991. Geotechnical Properties and Behaviour of Nigerian Tar Sand. *Engineering Geology*, 30(3-4): 325-336.

Puri, V.K., Das, B.M., Cook, E.C. and Shin, E.C., 1994. Geotechnical Properties of Crude Oil-Contaminated Sand. In: A. Tracey and B.H. Keith (Editors), Analysis of Soils Contaminated with Petroleum Constituents. ASTM STP1221, Philadelphia, USA, pp. 75-88.

Semer, R. and Reddy, K.R., 1998. Mechanisms Controlling Tolune Removal from Saturated Soils During In Situ Air Sparging. Journal of Hazardous Materials, 57: 209-230.

Shin, E.C., Lee, J.B. and Das, B.M., 1999. Bearing Capacity of a Model Scale Footing on Crude Oil-Contaminated Sand. *Geotechnical and Geological Engineering*, 17: 123-132.

Srivastava, R.K. and Pandey, V.D., 1998. Geotechnical Evaluation of Oil Contaminated Soil. In Contaminated and Derelict Land, Material Properties and Measurement, Thomas Telford (Editor), pp. 204-209.

Table 5.1. *UCS* for natural and oil mixed Sabkha soils

Soil	**Oil (%)**	**Dry *UCS* (kPa)**	**Soaked *UCS* (kPa)**	**Variation due to oil addition- Dry (%)**	**Variation due to Soaking. (%)**
S_{J-4}	0	44.3	disintegrate	–	–
	4	71.7	40.0	62.0	-44.0
	5	81.5	47.0	84.0	-42.0
	6	46.5	36.0	5.00	-23.0
	7	44.6	35.0	1.00	-22.0
	8	57.3	35.0	29.0	-39.0
	10	39	27.0	-12.0	-30.0
S_{Z-5}	0	2.75	disintegrate	–	–
	4	13.7	–	398	–
	5	16.6	9.30	504	-44.0
	6	14.2	–	416	–
	8	9.66	–	250	–
S_{K-7}	0	37.9	disintegrate	–	–
	4	52.8	–	39.0	–
	5	57.0	23.0	50.0	-60.0
	6	50.7	–	34.0	–
	8	44.2	–	16.0	–
S_{B-8}	0	53.1	disintegrate	–	–
	4	60.3	–	14.00	–
	5	71.0	41.0	34.0	-42.0
	6	44.7	–	-16.0	–
	8	54.2	–	2.00	–

Table 5.2.Shear strength parameters for natural and oil mixed Sabkha soils

Soil	Oil (%)	Φf (Degree)	C (kPa)	Δ % φf (%)	Δ C (%)
S_{J-4}	0	43.5	22.0	–	–
	2	42.0	24.0	-3.45	9.09
	5	41.0	32.0	-5.75	45.4
	8	39.0	47.0	-10.30	113.6
S_{Z-5}	0	35.0	18.0	–	–
	2	33.6	42.0	-4.00	133.3
	5	25.0	45.0	-28.6	150.0
	8	10.0	22.0	-71.4	22.22
S_{K-7}	0	28.0	23.0	–	–
	2	26.0	25.0	-7.14	8.695
	5	23.5	35.0	-16.1	52.170
	8	15.0	55.0	-46.4	139.13
S_{B-8}	0	25.0	19.0	–	–
	2	23.0	40.0	-8.0	110.5
	5	21.0	45.0	-16.0	136.8
	8	17.0	52.0	-32.0	173.0

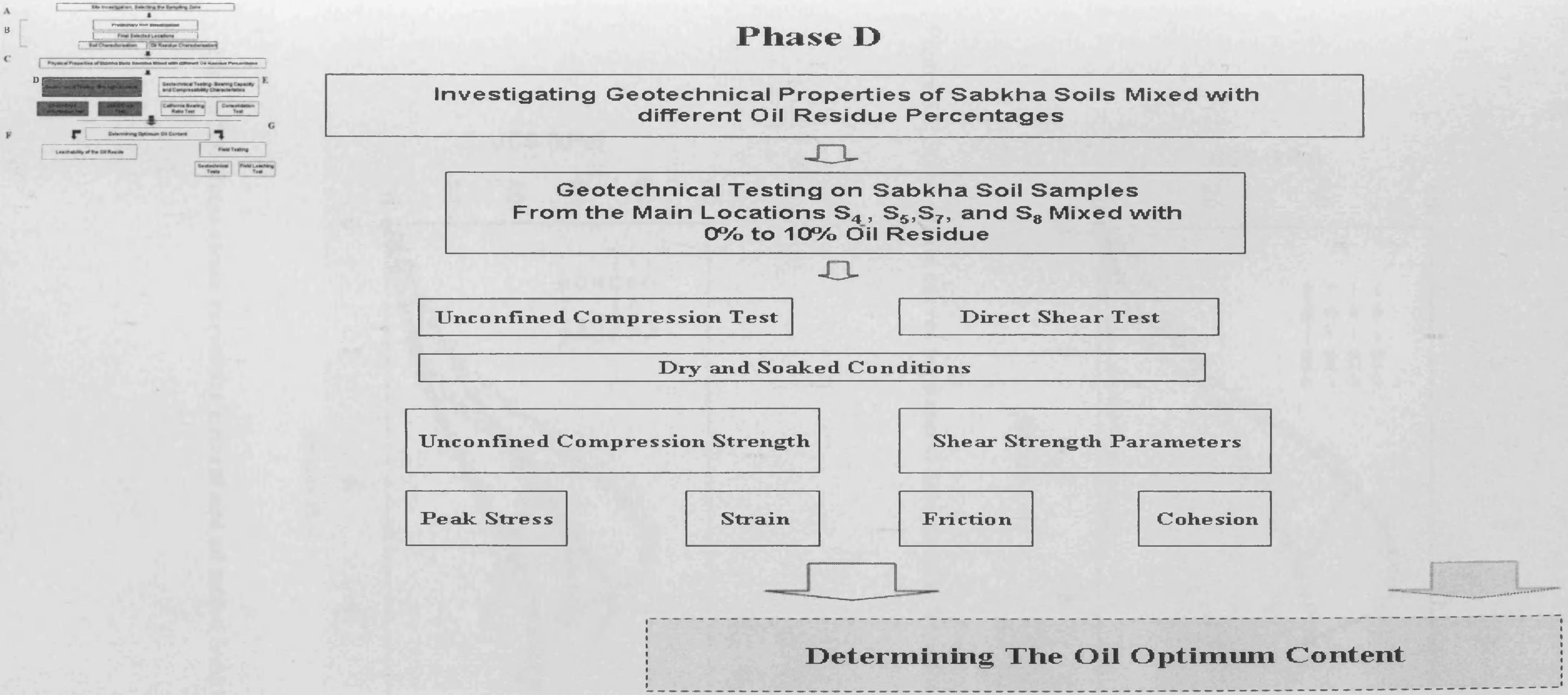

Figure 5.1. Phase D of the experimental programme

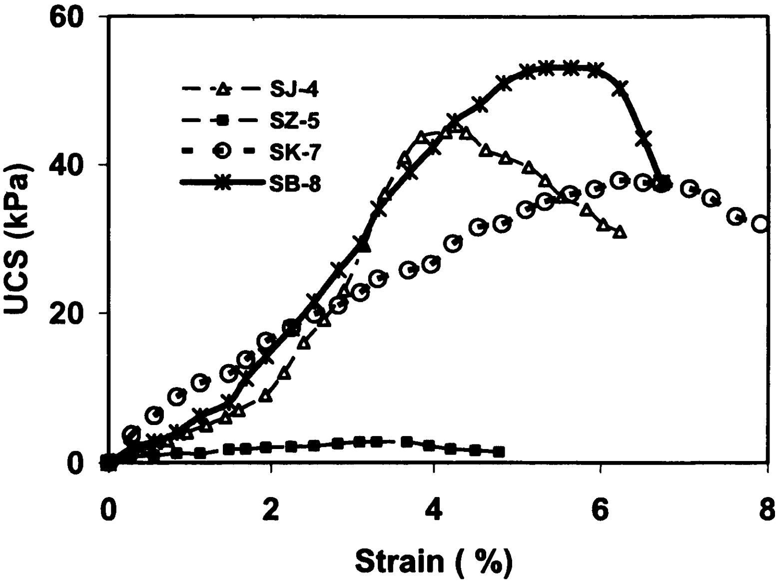

Figure 5.2. Stress-strain curves for natural Sabkha soils from the main locations

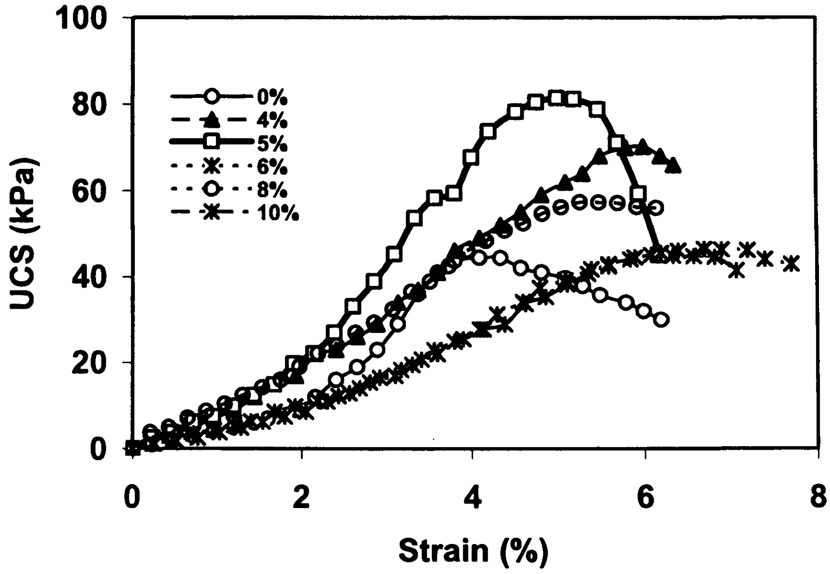

Figure 5.3. Stress-strain curves for natural and oil mixed Sabkha soils (S_{J-4})

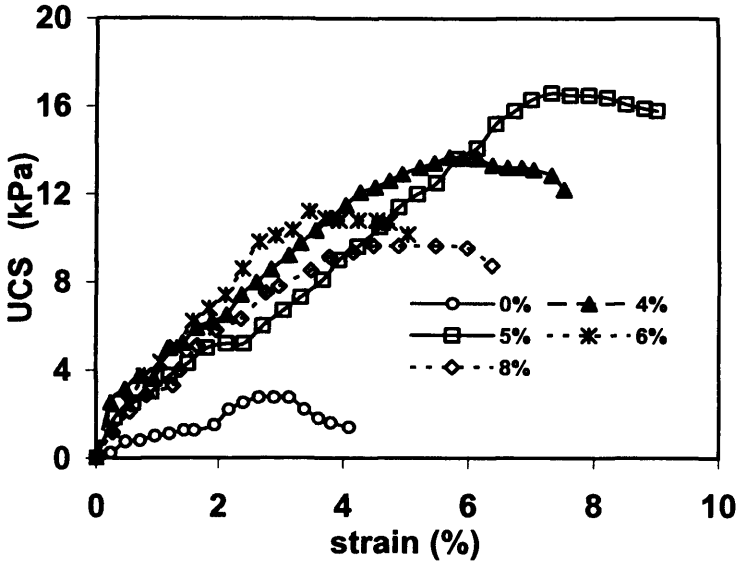

Figure 5.4. Stress-strain curves for natural and oil mixed Sabkha soils (S_{Z-5})

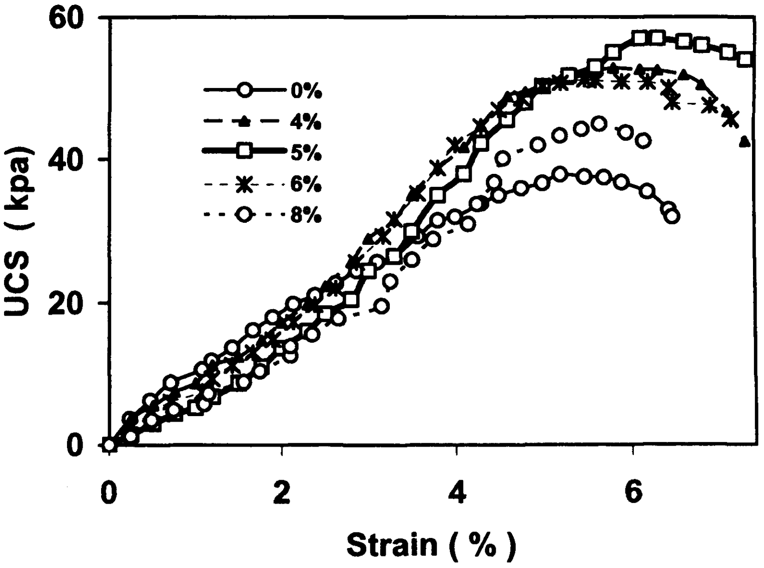

Figure 5.5. Stress-strain curves for natural and oil mixed Sabkha soils (S_{K-7})

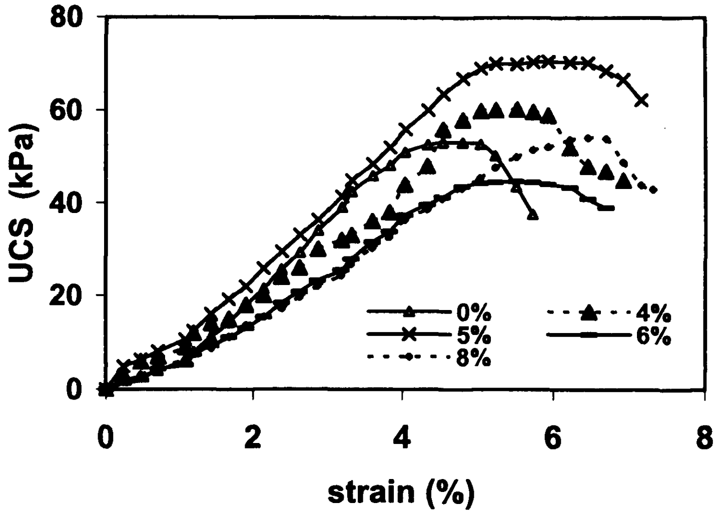

Figure 5.6. Stress-strain curves for natural and oil mixed Sabkha soils (S_{B-8})

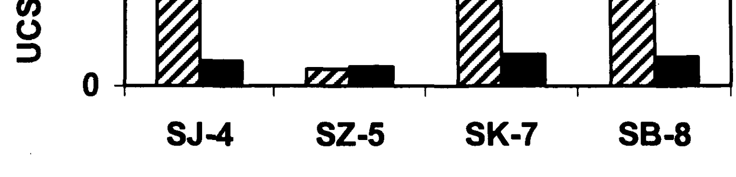

Figure 5.7. *UCS* and corresponding failure strain for natural Sabkha soils

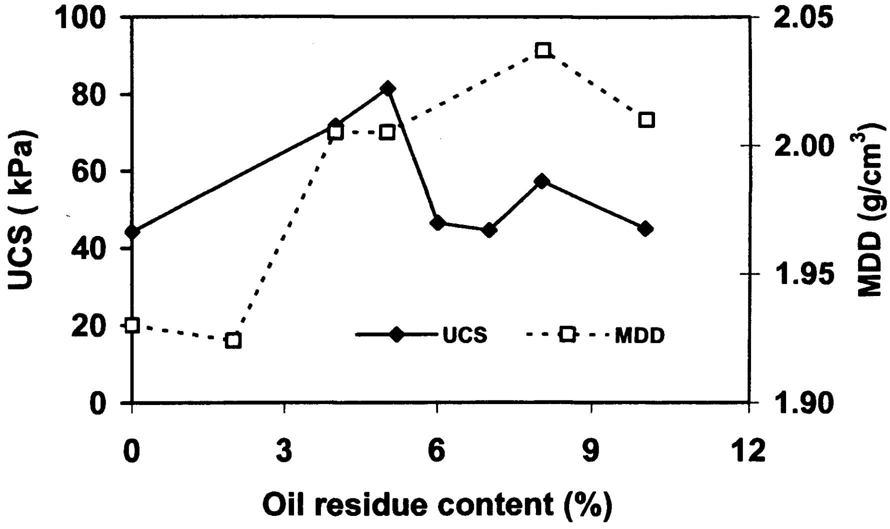

Figure 5.8. *UCS* and maximum dry densities for natural and oil mixed Sabkha soils ($S_{J\text{-}4}$)

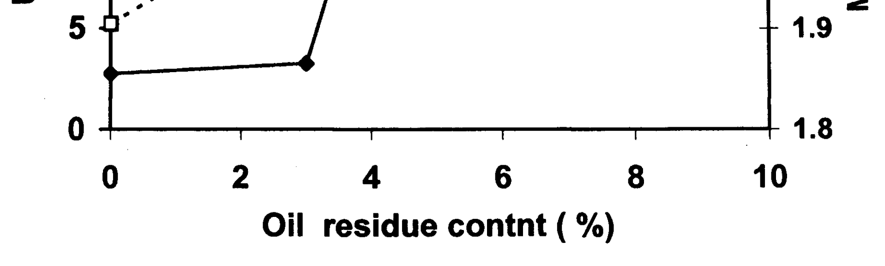

Figure 5.9. *UCS* and maximum dry densities for natural and oil mixed Sabkha soils ($S_{Z\text{-}5}$)

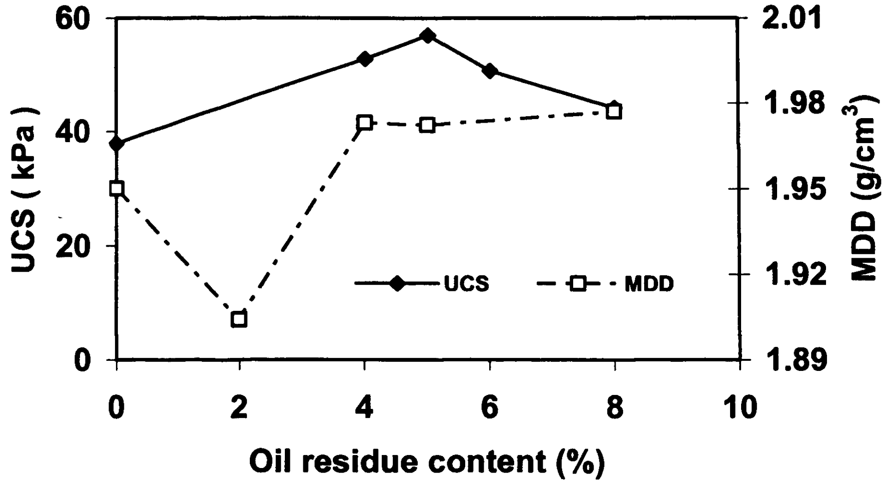

Figure 5.10. *UCS* and maximum dry densities for natural and oil mixed Sabkha soils (S_{K-7})

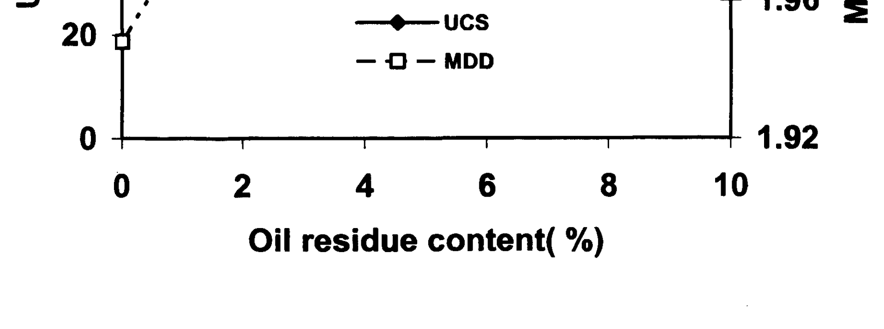

Figure 5.11. *UCS* and maximum dry densities for natural and oil mixed Sabkha soil (S_{B-8})

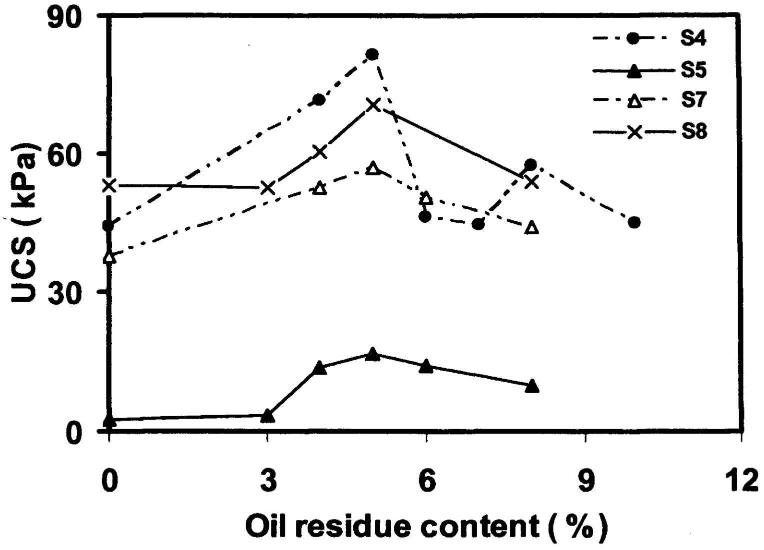

Figure 5.12. *UCS* for natural and oil mixed Sabkha soils (S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8})

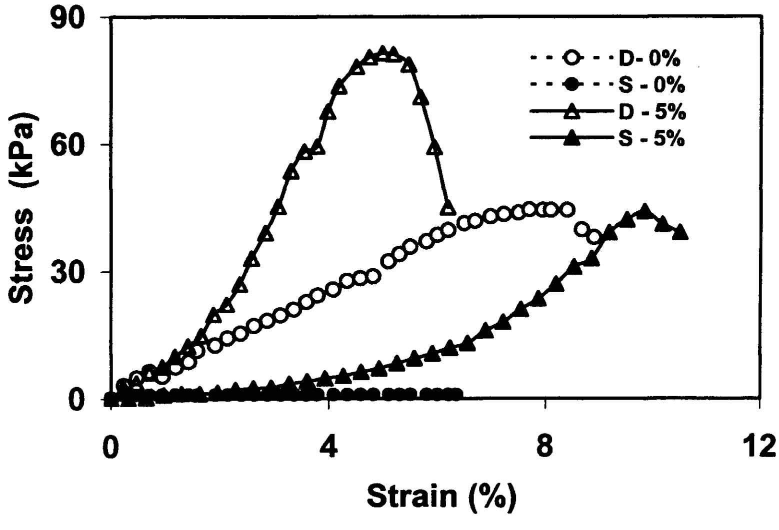

Figure 5.13. Stress-strain curves for natural and 5% oil mixed Sabkha soils (S_{J-4}) at dry and soaked conditions

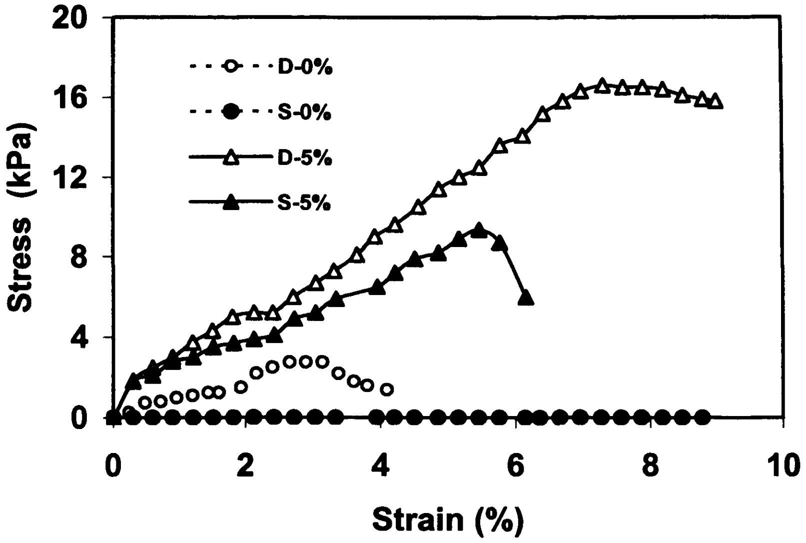

Figure 5.14. Stress-strain curves for natural and 5% oil mixed Sabkha soils (S_{Z-5}) at dry and soaked conditions

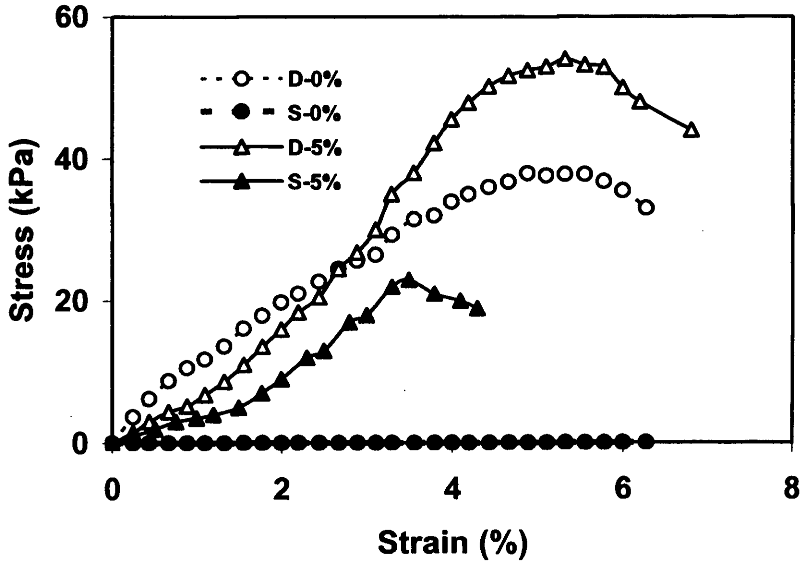

Figure 5.15. Stress-strain curves for natural and 5% oil mixed Sabkha soils (S_{K-7}) at dry and soaked conditions

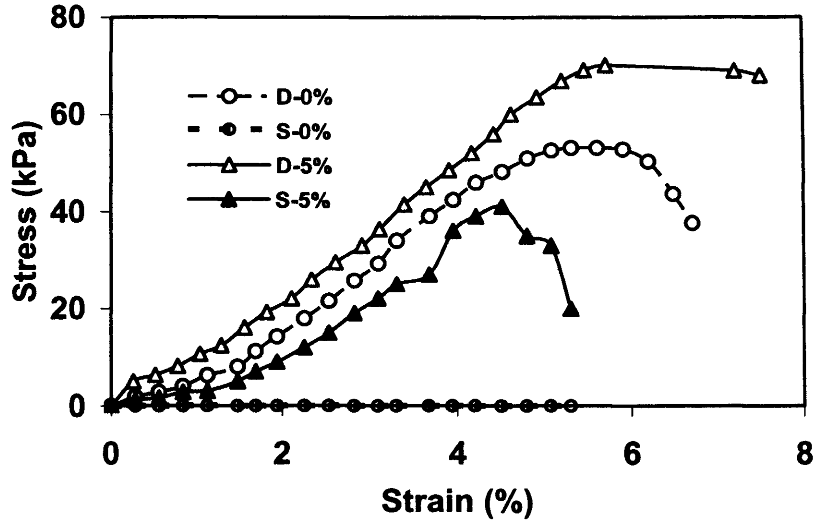

Figure 5.16. Stress-strain curves for natural and 5% oil mixed Sabkha soils (S_{B-8}) at dry and soaked conditions

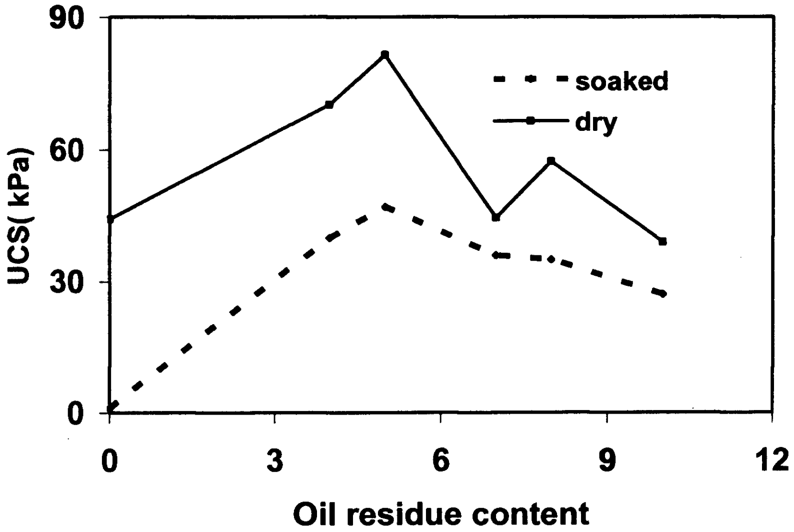

Figure 5.17. Effect of oil residue content on the UCS of Sabkha soil (S_{J-4})

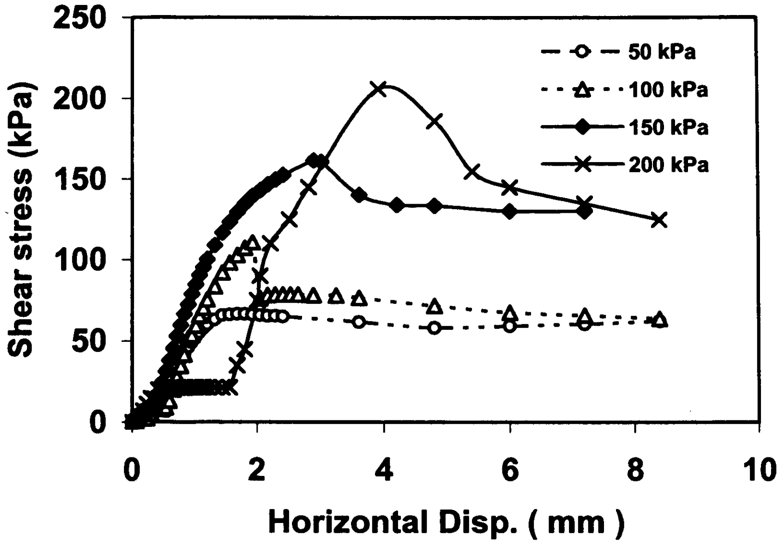

Figure 5.18. Shear stress-strain curves for natural Sabkha soil S_{J-4} at different normal stresses

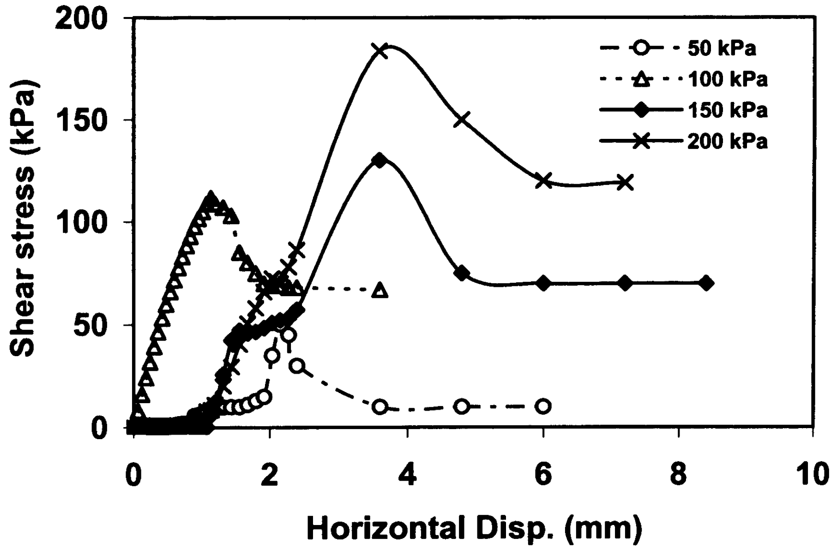

Figure 5.19. Shear stress-strain curves for natural Sabkha soil S_{Z-5} at different normal stresses

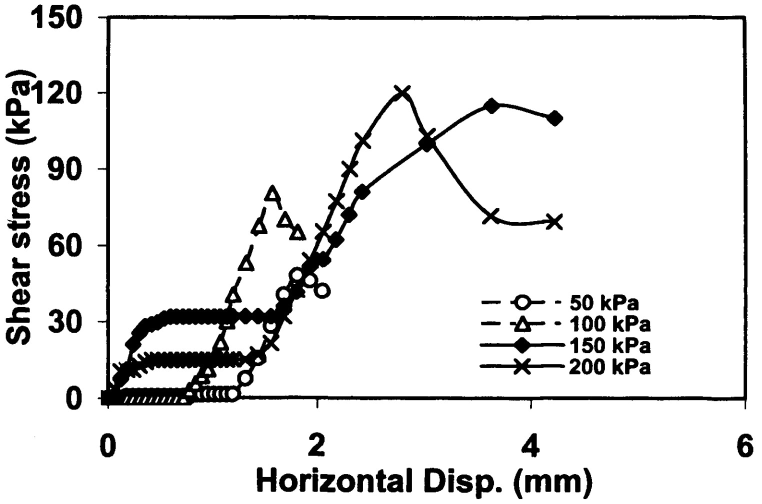

Figure 5.20. Shear stress-strain curves for natural Sabkha soil S_{K-7} at different normal stresses

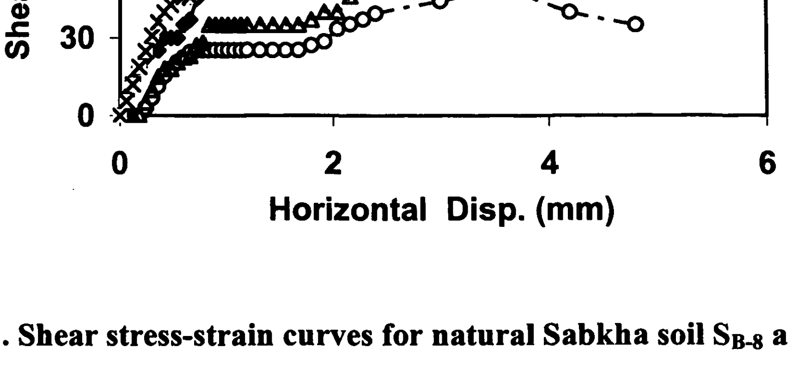

Figure 5.21. Shear stress-strain curves for natural Sabkha soil S_{B-8} at different normal stresses

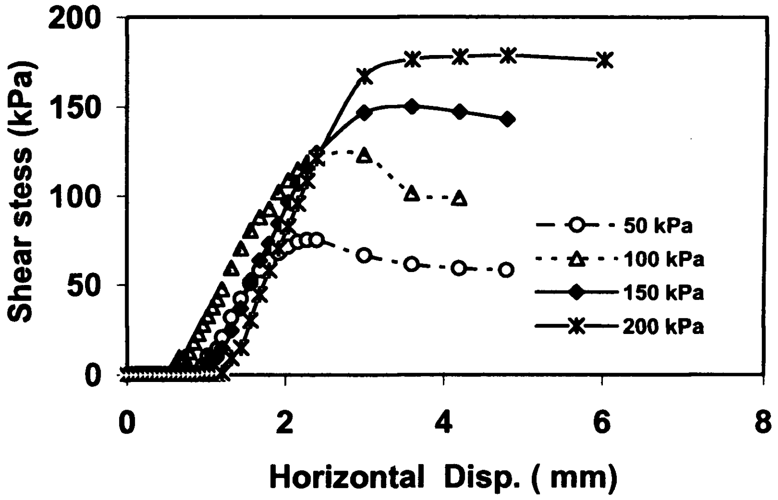

Figure 5.22. Shear stress-strain curves for 5% oil mixed Sabkha soil (S_{J-4}) at different vertical stresses

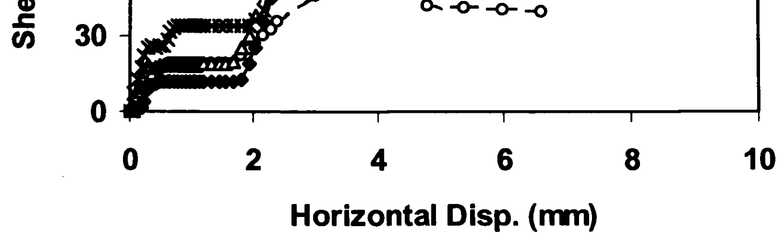

Figure 5.23. Shear stress-strain curves for 5% oil mixed Sabkha soil (S_{Z-5}) at different vertical stresses

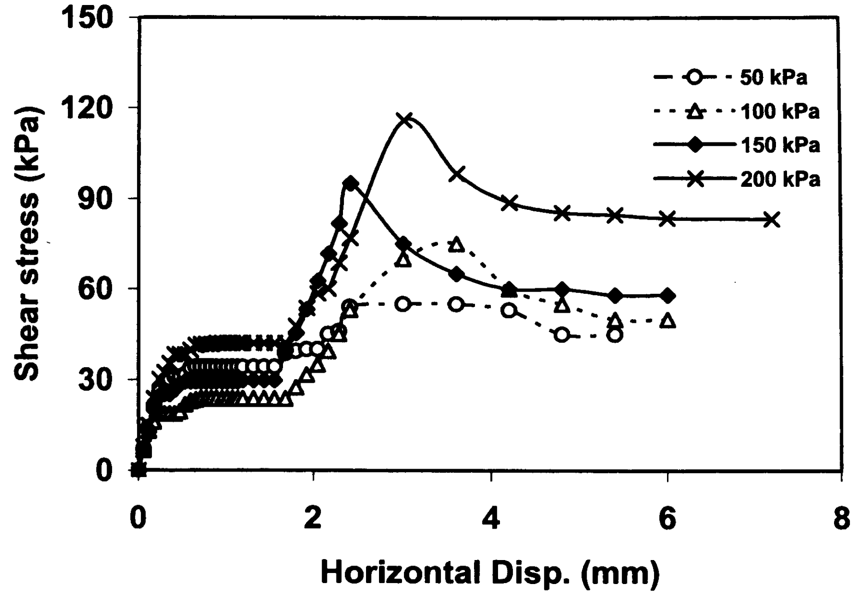

Figure 5.24. Shear stress-strain curves for 5% oil mixed Sabkha soil (S_{K-7}) at different vertical stresses

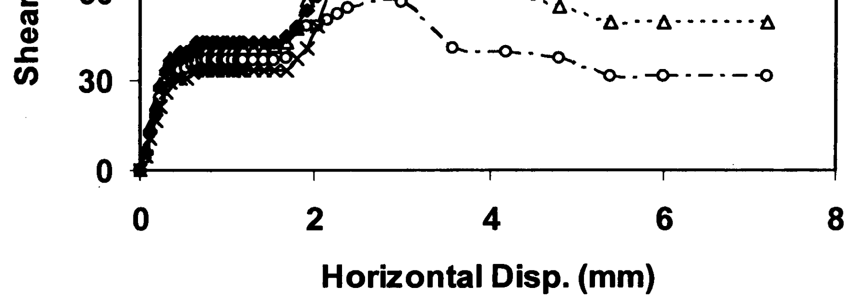

Figure 5.25. Shear Stress-strain curves for 5% oil mixed Sabkha soil (S_{B-8}) at different vertical stresses

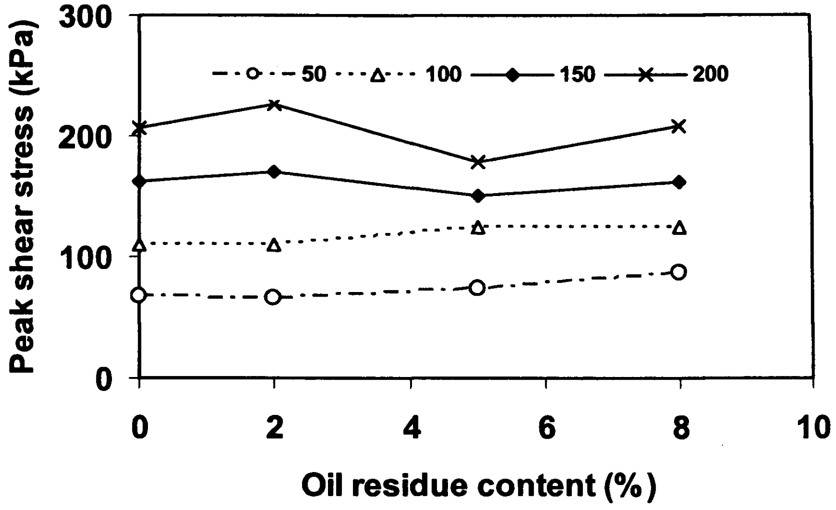

Figure 5.26. Effect of oil residue on peak shear stress at different vertical stresses

(S_{J-4})

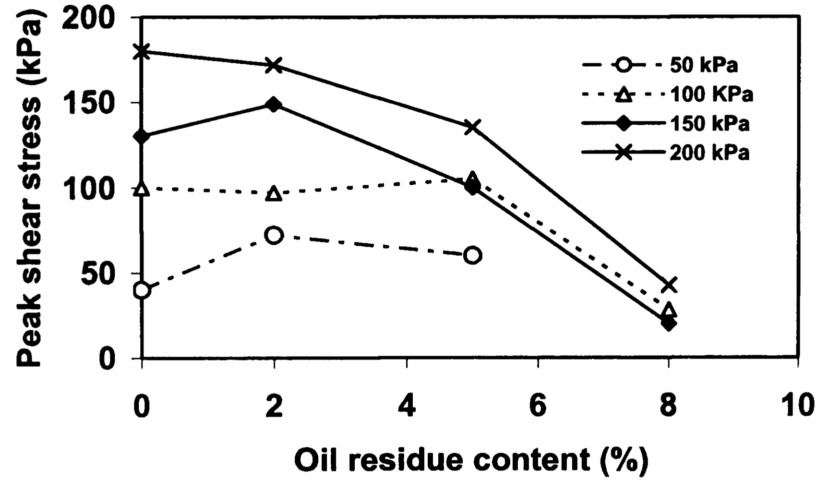

Figure 5.27. Effect of oil residue on peak shear stress at different vertical stresses

(S_{Z-5})

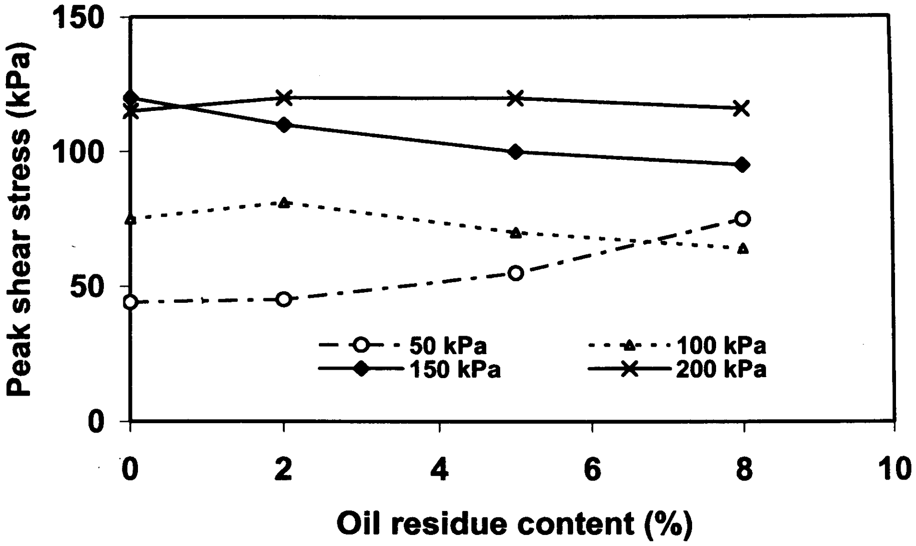

Figure 5.28. Effect of oil residue on peak shear stress at different vertical stresses (S_{K-7})

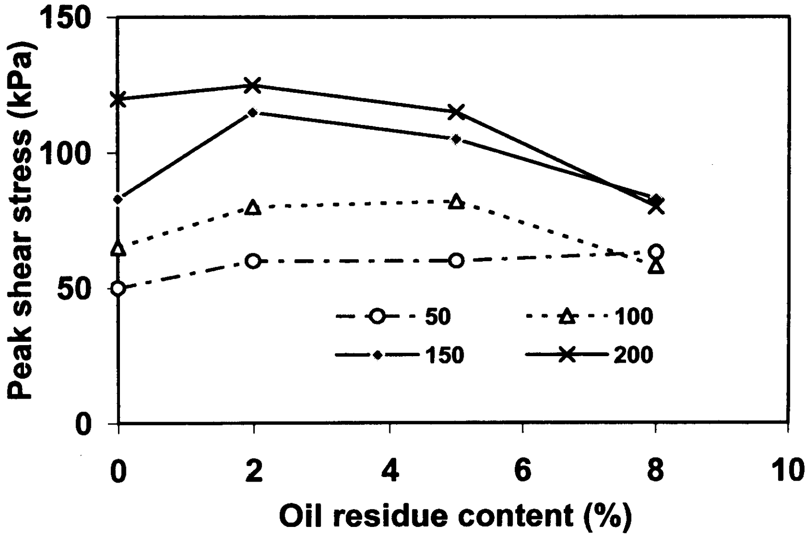

Figure 5.29. Effect of oil residue on peak shear stress at different vertical stresses (S_{B-8})

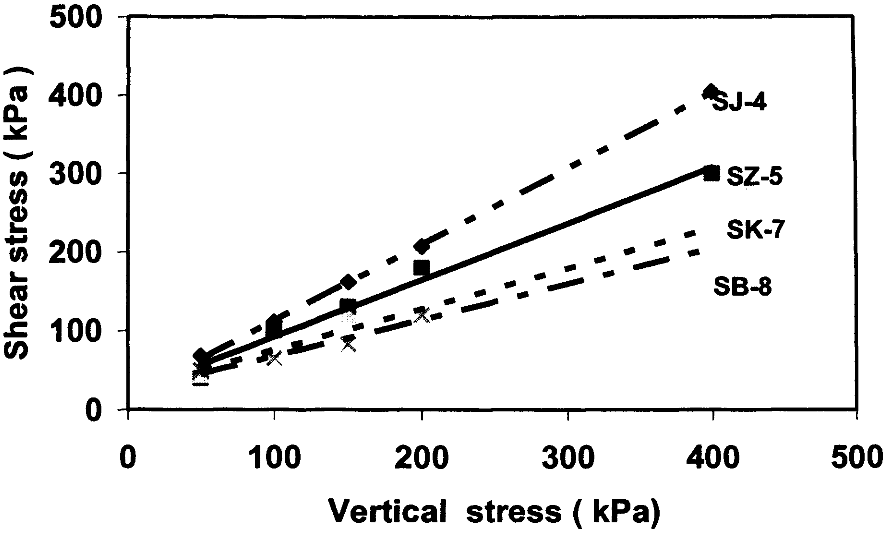

Figure 5.30. Failure envelopes for natural Sabkha soils from the four main locations

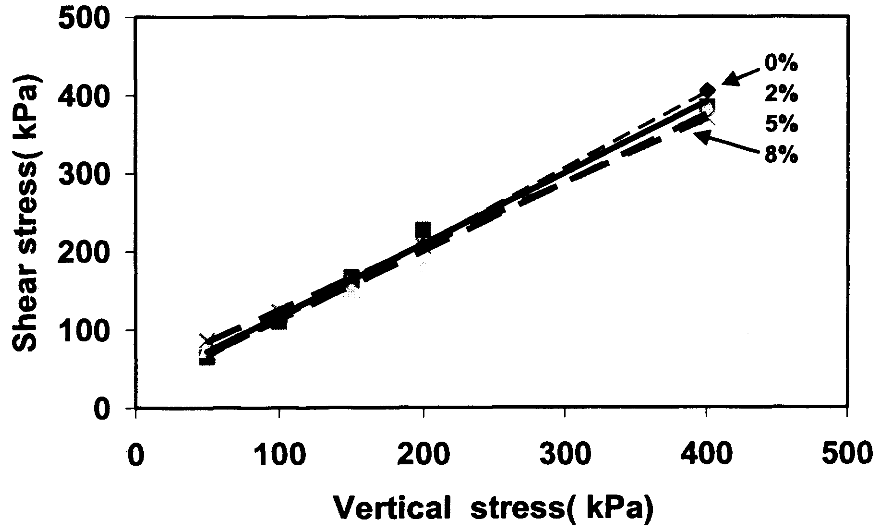

Figure 5.31. Failure envelopes for oil mixed Sabkha soil (S_{J-4})

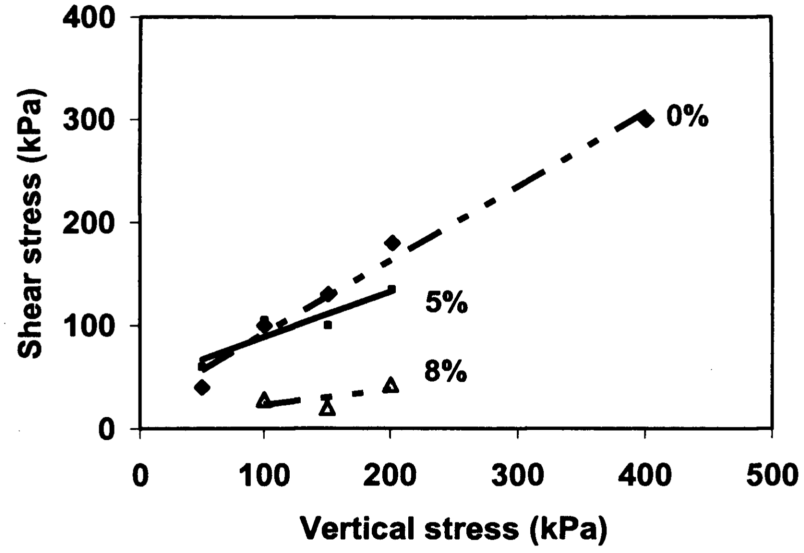

Figure 5.32. Failure envelopes for oil mixed Sabkha soil (S_{Z-5})

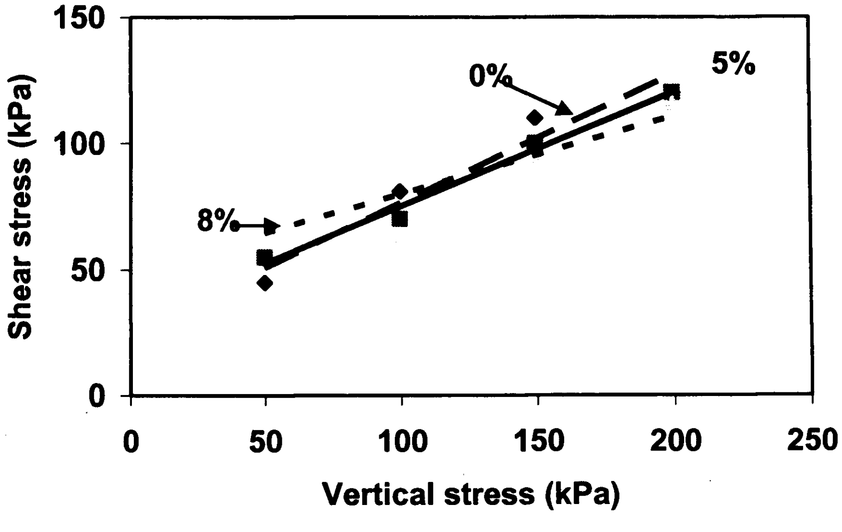

Figure 5.33. Failure envelopes for oil mixed Sabkha soil (S_{K-7})

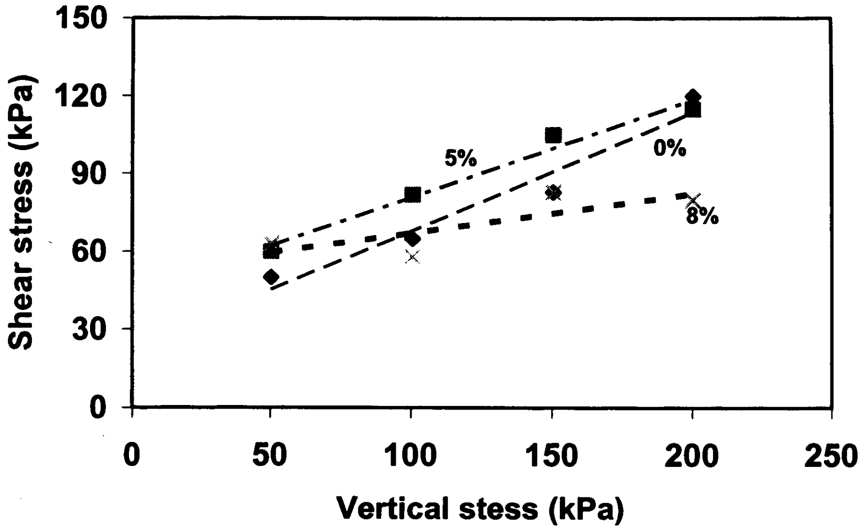

Figure 5.34. Failure envelopes for oil mixed Sabkha soil (S_{B-8})

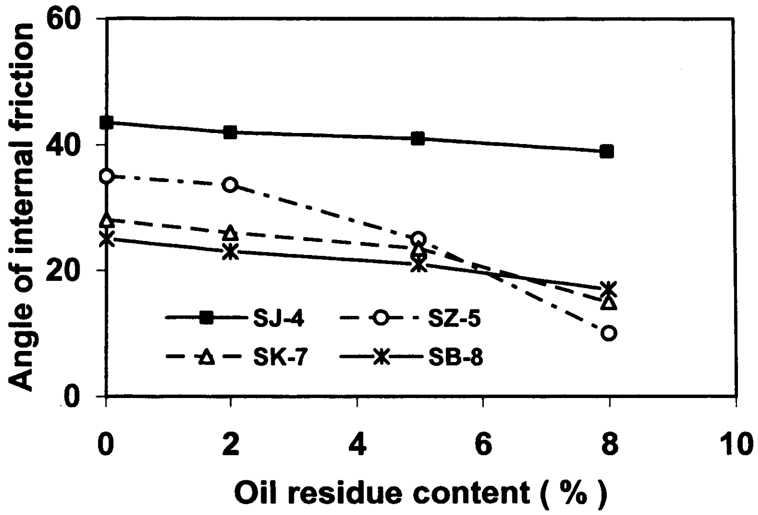

Figure 5.35. Friction angle variation with oil residue addition to Sabkha soils from main locations

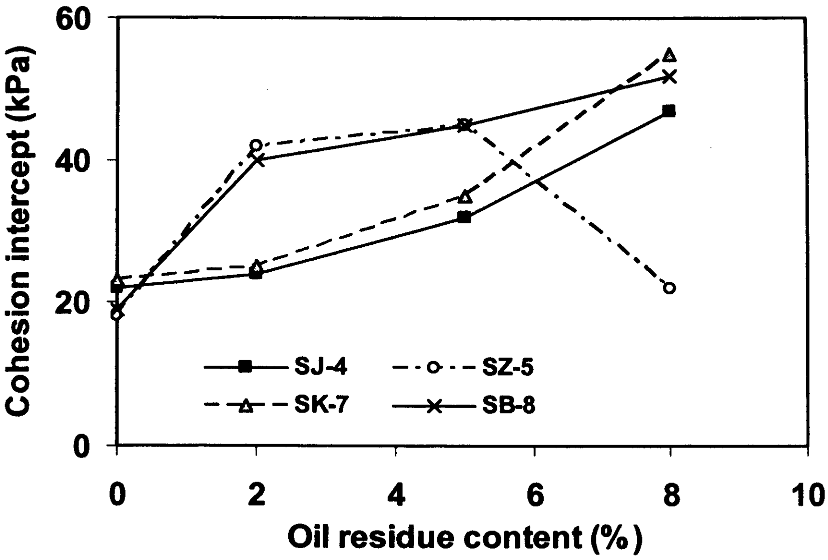

Figure 5.36. Cohesion intercepts variation with oil residue addition to Sabkha soils from main locations

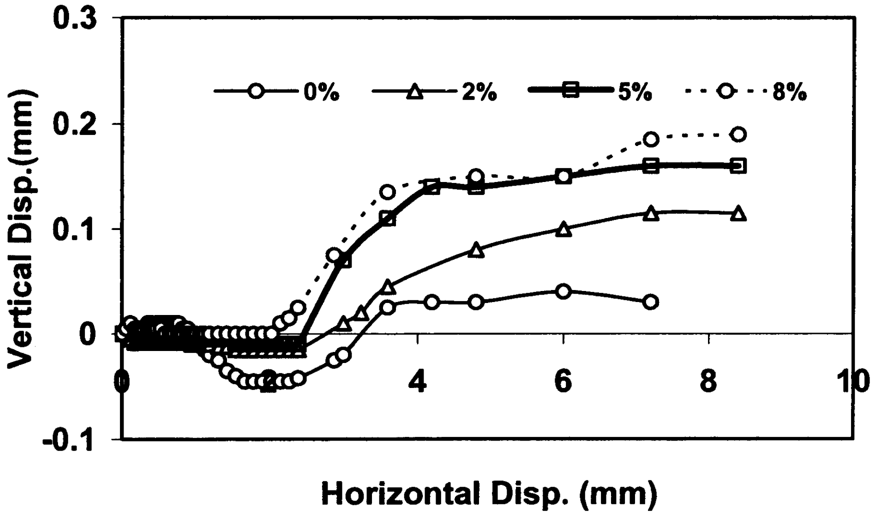

Figure 5.37. Vertical dilation versus horizontal displacement for natural and oil mixed Sabkha soils (S_{J-4}) at vertical stress of 150 kPa

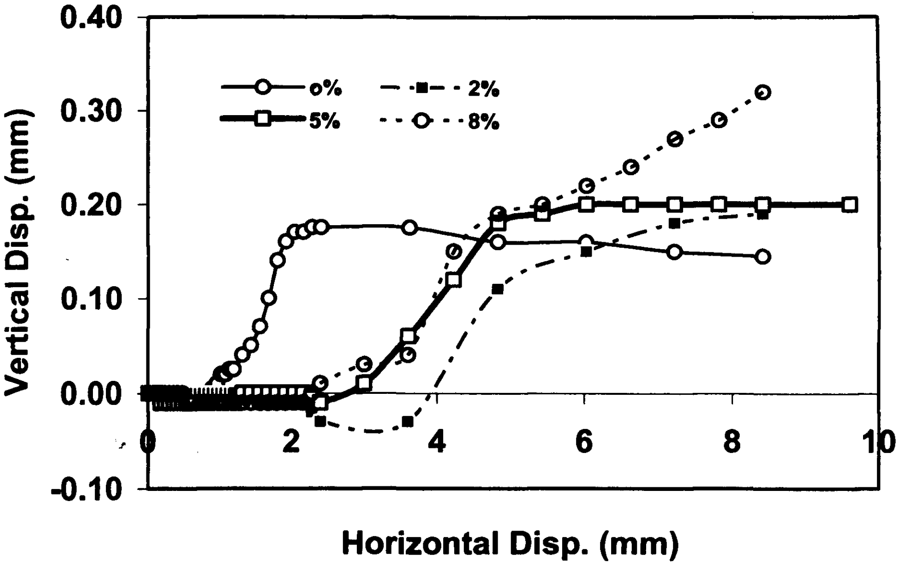

Figure 5.38. Vertical dilation versus horizontal displacement for natural and oil mixed Sabkha soils (S_{Z-5}) at vertical stress of 100 kPa

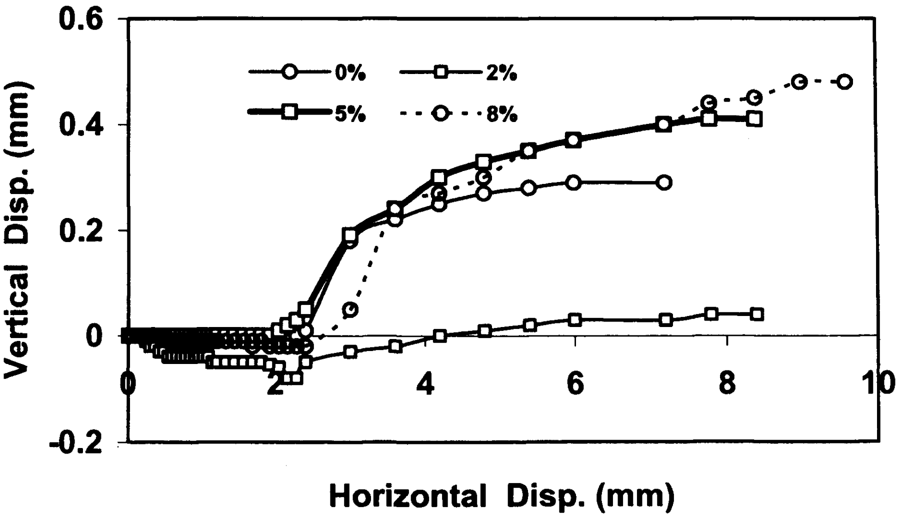

Figure 5.39. Vertical dilation versus horizontal displacement for natural and oil mixed Sabkha soils (S_{K-7}) at vertical stress of 150 kPa

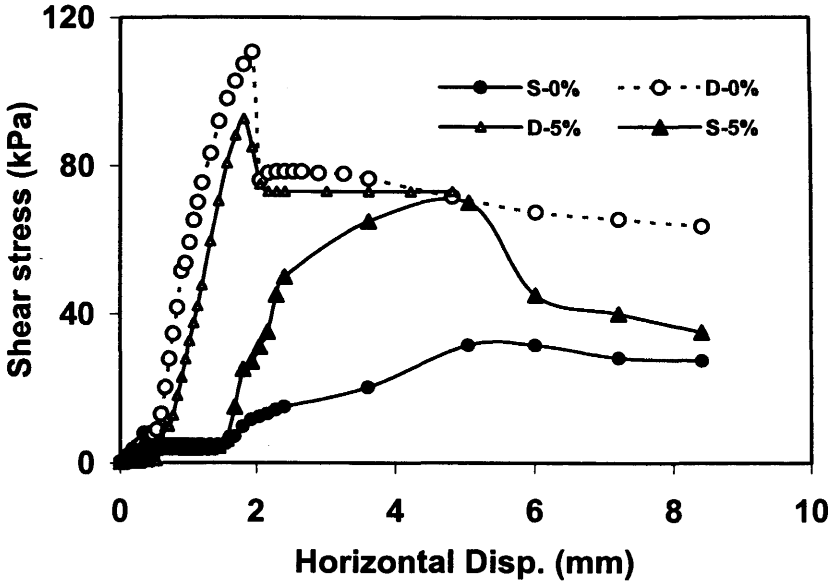

Figure 5.40. Effect of saturation on stress-strain relationship for natural and oil mixed Sabkha soils (S_{J-4}) at vertical stress of 100 kPa

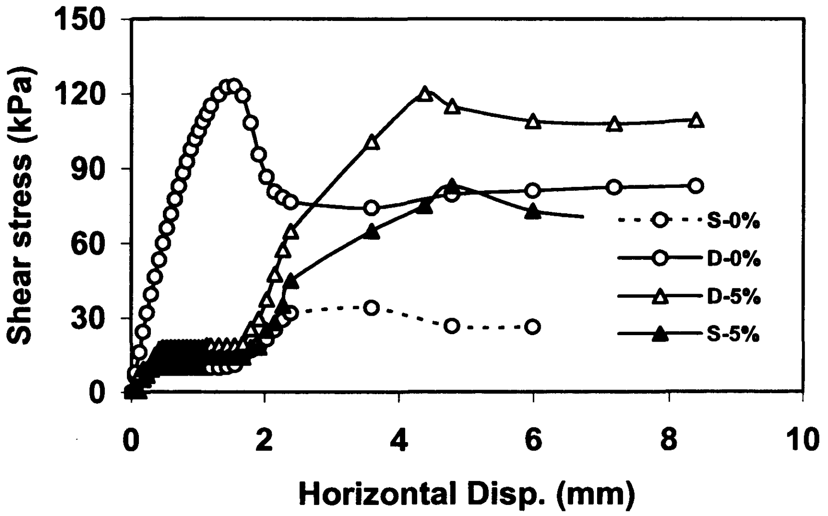

Figure 5.41. Effect of saturation on stress-strain relationship for natural and oil mixed Sabkha soils (S_{Z-5}) at vertical stress of 100 kPa

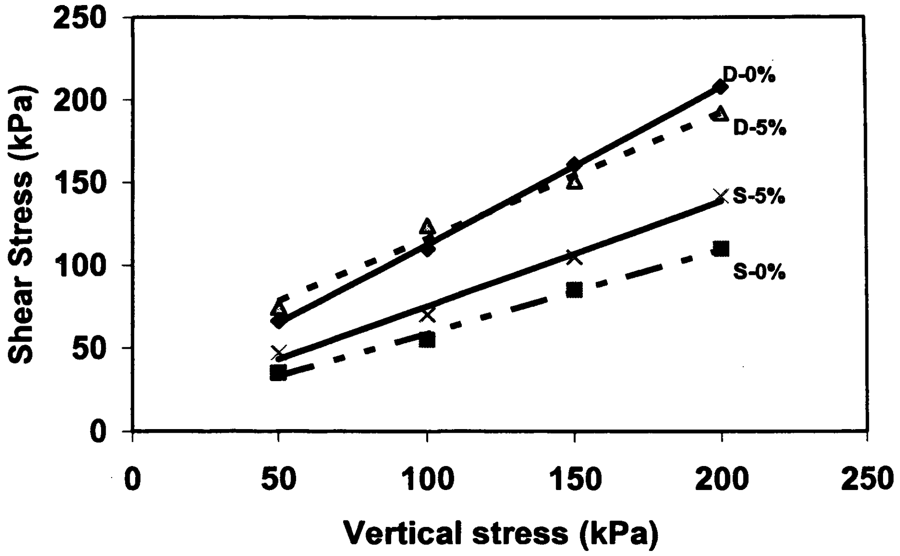

Figure 5.42. Failure envelopes for natural and oil mixed Sabkha soils (S_{J-4}) at dry and soaked conditions

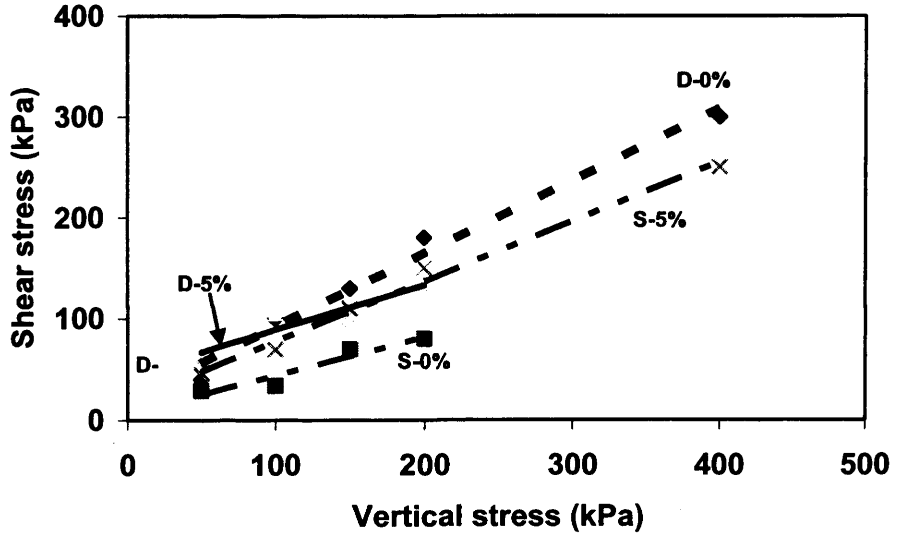

Figure 5.43. Failure envelopes for natural and oil mixed Sabkha soils (S_{Z-5}) at dry and soaked conditions

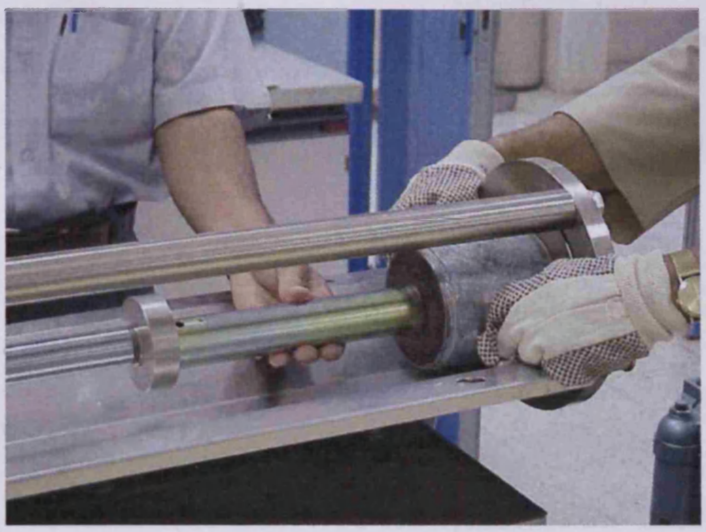

Plate 5.1. Inserting the mould into the compacted soil.

Plate 5.2. Removing the tube containing the soil from the mould

Plate 5.3. Extracting and levelling the soil specimen

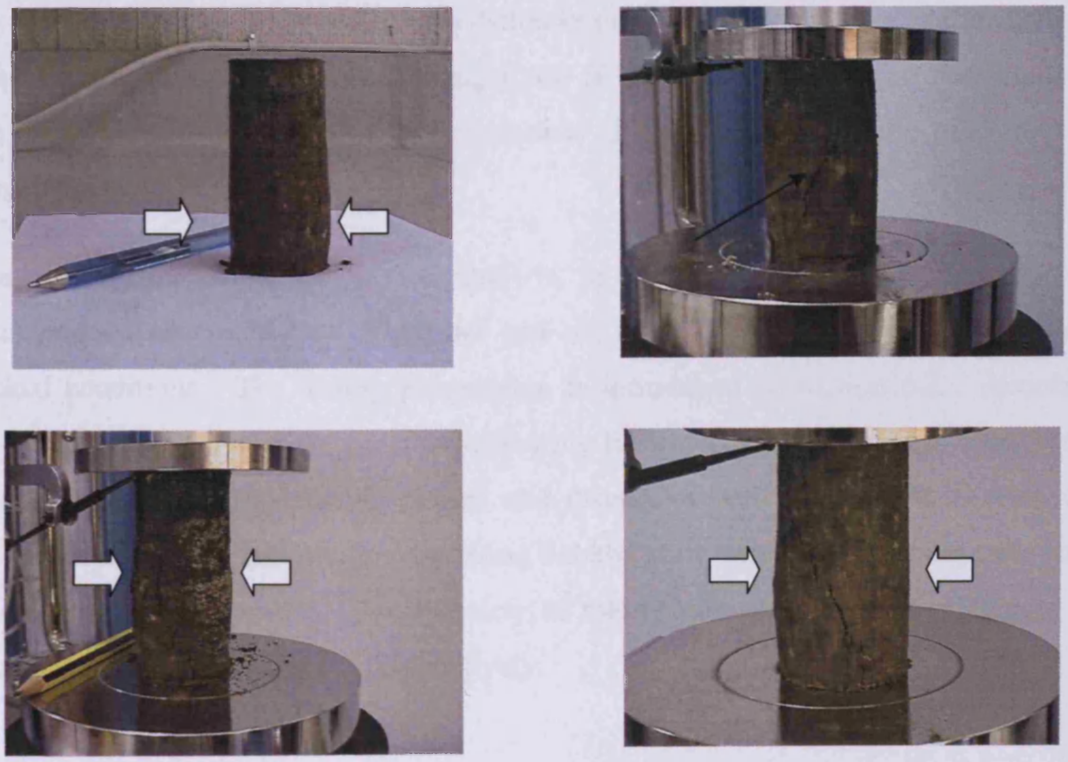

Plate 5.4. Mode of failure of tested soil samples

Chapter 6

Bearing Capacity and Consolidation Characteristics of Natural and Oil Mixed Sabkha Soils

6.1 Introduction:

The possibility of using stabilised Sabkha soils in road construction as subgrade or other backfilling material necessitates thorough knowledge of their geotechnical behaviour. To accomplish this, Sabkha soils with different oil contents were subjected to CBR and consolidation tests. California Bearing Ratio (CBR) and consolidation characteristics are major properties that need to be assessed if the material is to be used for road construction.

The primary objective of this chapter is to evaluate the bearing capacity and consolidation characteristics of natural and oil mixed Sabkha soils in both dry and soaked conditions. The testing programme is introduced in section 6.2. Procedure, results and discussion of the California Bearing Ratio test are presented in Section 6.3. Consolidation tests Procedures, results and discussion are presented in Section 6.4. Optimum oil residue content for stabilising Sabkha soils based on foregoing test results is discussed in section 6.5. An overview of main findings and list of references are provided in section 6.6 and 6.7, respectively.

6.2 Testing programme

This part of the experimental work covered phase E of the testing programme shown in Figure 6.1. The bearing capacity of oil mixed Sabkha soil was investigated utilising the

California Bearing Ratio test (CBR), and compressibility characteristics were investigated applying the consolidation test.

6.3 California Bearing Ratio test (CBR)

The main objective of this test was to examine the effect of oil residue on CBR value of dry and soaked oil mixed Sabkha soil samples. The California Bearing Ratio test is extensively used in the evaluation of materials' suitability for pavement construction. Several investigations have used the CBR test as a major parameter in evaluating the strength properties of stabilised soils (Al-Amoudi et al., 1992; and Al-Sanad et al., 1995).

The California Bearing Ratio test is an empirical test used to determine the strength and stiffness of subgrade soil. The test is used for evaluating the suitability of subgrade and materials used as subbase and base course for road construction. CBR results have been correlated with the thickness of various materials required for flexible pavement layer design. In general, high CBR materials are considered stiffer and superior for road construction.

In the CBR test, the force required to push a standard plunger into soil at a constant rate is measured at suitable time intervals. The CBR is defined as the ratio of the force required to drive a circular piston into soil in a special container to that required for similar penetration into a standard sample of compacted crushed rock. The ratio is determined at penetrations of 2.5 and 5.0 mm and is expressed as a percentage of the standard load. The highest calculated CBR value corresponding to 2.5 mm and 5mm penetration is rounded off and reported in a percentage value as the CBR of the material.

6.3.1 Testing procedures

Due to the large amount of Sabkha soil and oil residue to be used in the CBR test, it was decided to carry out this test in Kuwait using the same Sabkha soil source kept in the Ministry of Defence Laboratory. CBR tests were carried out according to AASHTO Designation: T 193-81 (1990). Similar steps described in section 4.3 were followed to prepare of oil mixed samples. Samples were prepared with different oil residue content, at their optimum moisture content values obtained in section (4.4.5).

The CBR test apparatus consisted of a load frame load measuring device, cylindrical loading plunger, and dial gauges. A cylindrical plunger with a cross sectional area of 1935 mm^2 (3.0 in^2) was pushed at a fixed rate of 1.0 mm/min into the soil specimen. As penetration proceeded, load ring dials were read at every 0.25 mm interval of penetration.

The maximum CBR value was expected for soil compacted to its maximum dry density (Aiban, 1995). Preliminary experimental trials were undertaken to determine dry density corresponding to compaction effort in the CBR mould at different oil contents. Density values were found to vary with compaction effort and were not well correlated with the compacting effort. To obtain the maximum dry density value for oil mixed Sabkha soils the AASHTO procedure was followed (AASHTO, 1990). Three specimens of oil mixed Sabkha from each mix were prepared using different compaction efforts. Their compacted densities ranged from 90 % (or lower) to 100 % (or higher) of the maximum dry density. 10, 30 and 65 blows per layer were used to compact the soil. The CBR/dry density curve was plotted, and the CBR value corresponding to the maximum dry density was determined as shown in Figure 6.2.

Dry samples (D) were those samples prepared at their OMC and tested directly, while soaked samples (S) were prepared at their OMC, soaked for 4 days and then allowed to drain for 15 minutes before testing.

6.3.2 Results and discussion

CBR test results for natural and oil mixed Sabkha soil samples for dry and soaked conditions are presented in this section.

Results are presented and discussed in terms of the following:

- Load (kN) /penetration curve (mm)
- CBR values/oil content

6.3.2.1 Dry conditions

Load-penetration curves for natural Sabkha soils at dry condition are shown in Figures 6.3. The flatter load/penetration curve for S_{Z-5} indicates higher penetration of this soil under lower load than other Sabkha soils. The calculated CBR from the previous figure for natural Sabkha soils at dry condition is listed in Table 6.1. CBR values ranged from 30 for soil sample S_{Z-5} to 50 for soil sample S_{K-7}. Soil samples S_{J-4} and S_{B-8} had CBR values of 42 and 40. Higher CBR values for soils S_{K-7}, S_{J-4} and S_{B-8} could be attributed to their higher salt content as revealed in soil chemical characterisation (section 3.8.2). Due to the existence of different types of salts in them, the CBR of compacted Sabkha soils was higher than that of lower cemented soil since stronger bonding of particles occurred. Lower penetration as shown in Figure 6.3 was an indication of high CBR values for soils S_{J-4} and S_{K-7}. Similar findings were reported by Al-Sanad et al. (1990) in their work on cemented sand.

Test results were in the range of CBR values of soils in Kuwait reported by Ismael and Mollah (1998), since such soils are generally calcareous in nature and contain different types of salts. It is worth noting that CBR values for the soil samples in this study were slightly higher than those reported by Al-Sanad (1986) for the same region, possibly due to the variation in Sabkha flats. Moreover, CBR values obtained in this study were for soil samples prepared at their maximum dry densities, while Al-Sanad's CBR values were obtained from samples bored in the field with their natural moisture content.

Load-penetration curves for 0%, 2% and 5% oil mixed Sabkha soils tested at dry condition are presented in Figures 6.4 to 6.7 for soil samples S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. These curves indicate that soil penetration increased at lower applied loads with oil residue addition. Inclinations of the load-penetration curves became flatter with oil addition. For example, in Figure 6.6, the recorded penetration readings for an applied load of 2 kN, were 0.6 mm, 1.2 mm and 2.0 mm for Sabkha soil S_{K-7} with an oil residue content of 0%, 2% and 5%, respectively.

Calculated CBR values for oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} at 0% to 8% oil content tested at their optimum moisture content are presented in Table 6.1 and shown in Figure 6.8. Comparison of CBR test values revealed a reduction in CBR value with oil addition at different rates. The percentage reduction in CBR values for oil mixed Sabkha S_{J-4}, S_{K-7} and S_{B-8} was 16.6%, 48% and 25% at 5% oil residue addition, respectively. Beyond this oil residue percentage, a sharp decrease was observed in CBR value, since the reduction percentage value was 85.7%, 58% and 80% for soil samples S_{J-4}, S_{K-7} and S_{B-8} respectively, at 6% oil residue content. The trend for soil S_{Z-5} differed, in that a slight increase of 6.6% was noted in the CBR value at oil residue addition up to 5%. Beyond 5% oil content, the CBR value reduced by 30% and 86.6% at oil residue content of 6% and 8%, respectively. Visual inspection during experimental work indicated that the oil residue mixed Sabkha soil samples became softer at high oil residue content (Plate 6.1).

The reduction in CBR value with oil addition may be attributed to the lubrication effect of the oil residue. It was reported in section 5.4.2.2 that the reduction in friction angle for 5% oil mixed Sabkha soils ranged from 5.75% to 28%. The reduction in friction was due to the adsorbed viscous oil layer lubricating and facilitating the sliding of soil particles resulting in an increase in the penetration of the plunger piston.

With increasing oil addition and due to weak adsorption, most of the oil residue will possibly exist as free oil in the soil voids (section 5.4.2.2). The thickly formed oil layer around soil particles and in the voids may have prevented the particles interlocking and increased the lubrication effect which caused a sharp decrease in the CBR value. It was observed during soil testing that with oil addition the mixture became stickier and softer. Similar findings were reported by Mohammed (1995) who attributed the behaviour to an increase in fluid content of the stabilised soil. A reduction in CBR values of oil contaminated soil was also reported by Hassan et al. (2005) in their study on the use of petroleum-contaminated soil in construction applications.

6.3.2.2 Soaked conditions

Load-penetration curves for natural Sabkha soils from the four main locations at dry and soaked conditions are shown in Figure 6.3. This figure shows penetration was higher with lower loads in soaked samples. Load penetration curves for soaked soil samples are almost all in the lower part of the figure and parallel to the x-axis, indicating more penetration with an applied lower load. The recorded load for 10 mm penetration in dry Sabkha soil sample S_{K-7} was 12 kN. Due to soaking effect, the same penetration was reached with an applied load of 1.2 kN.

Calculated CBR values for dry and soaked natural Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} are shown in Figure 6.9 and listed in Table 6.1. The Figure indicates that CBR values decreased due to soaking. For example, the CBR value for natural Sabkha soil sample S_{K-7} dropped from 50 to 9 upon soaking, a reduction of 82%. Similarly, the CBR value for soil sample S_{B-8} dropped from 40 to 11, a reduction of 72.5%. Table 6.1 shows that CBR values dropped within the range 53% to 82% upon soaking. The drop in CBR value was very high in soil samples S_{K-7} and S_{B-8} where the CBR value decreased by more than 70%. This may be attributed to the dissolution of the cementing materials upon soaking as argued by Aiban (1995) and Al-Amoudi and Abduljauwad (1995-b). Soaking may have resulted in the destruction of bonds, weakening of cementation, and breakdown of soil packets (Alawaji, 2001).

Similar results were also reported by Al-Amoudi et al. (1992) and Al-Amoudi and Abduljauwad (1995-b), whose experimental studies indicated that Sabkha soil, which possesses low strength in its natural condition, is highly susceptible to collapse upon exposure to water, and the CBR value upon flooding decreased by 50%. Kuwait soils are generally calcareous in nature and contain different types of salts, particularly gypsum, chloride, and carbonates (Ismael, 1993-b). These soils provide adequate strength, which drops considerably under soaked conditions. With long term saturation, soil loses all or most of the cementation components of strength (Ismael et al., 1986-b) and the aggregated carbonate lumps are weakened, thereby dissolving some of the cements and reducing the strength (Aiban, 1998).

Load-penetration curves for oil mixed Sabkha soils at dry and soaked conditions are shown in Figures 6.4, 6.5, 6.6 and 6.7 for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. It can be observed that load-penetration curves for oil mixed soils at soaked conditions are in the upper part of figures compared with the curves for natural soaked Sabkha soils.

CBR values for soaked oil mixed Sabkha soils are listed in Table 6.1 and shown in Figures 6.10, 6.11, 6.12 and 6.13 for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. These figures show that the significant difference between dry and soaked CBR values diminishes with oil addition. Comparison of CBR results indicates that CBR values for soaked oil mixed Sabkha soils are lower than at dry conditions. However, the difference decreases with oil residue addition. For example, the CBR value for natural Sabkha soil sample S_{J-4} dropped from 42 to 19 upon soaking, a percentage reduction of 55%. At an oil percentage of 2%, the CBR value dropped from 35 for the dry sample to 20 for the soaked sample, a percentage reduction of 43%. The percentage reduction decreased continuously with oil addition, until it reached 14% at oil content of 5%. The significant difference between dry and soaked CBR values for oil mixed Sabkha soils reduced continuously with oil addition up to the higher tested oil percentage.

Effect of oil addition on CBR values of soils from the four main locations under soaked conditions is shown in Figure 6.14. This figure indicates that upon soaking, the CBR values for oil mixed Sabkha soils increased with oil residue addition of up to 5%, while with more oil addition CBR values decreased rapidly. CBR values increased by about 1.5 to 2 fold of the natural soaked CBR as oil content increased to 5% for all tested Sabkha soil samples. Beyond an oil residue content of 5%, a dramatic decrease in soil strength occurred.

The increase in CBR values for soaked oil mixed Sabkha soils may be attributed to the reduction in water absorption of fine constituents of the soil due to the waterproofing effect of the oil, while in the natural condition Sabkha soil samples are highly susceptible to collapse upon saturation (Al-Amoudi and Abduljauwad, 1995-b). The adsorbed hydrophobic oil residue on the soil particles formed a coating layer that changed the affinity of oil mixed soils to water (Kaiser et al., 2000). This layer, which covered the cemented soil lumps, reduced the salt dissolution and consequently reduced the different between the dry and soaked CBR values. The reduction in the variation of CBR values between dry and soaked soils is indicative of a reduction in the dissolution of different types of salts due to the developed waterproofing. Similarly, Andrade et al. (2004) concluded in their study on contaminated soils that the higher hydrophobic characteristic of soil particles coated with oil is the main cause of the developed waterproofing effect (Al-Sarawi et al., 1998), which minimises water adsorption and dissolution of the cementing materials. With more oil addition, the sharp reduction in CBR values for the soaked samples can be attributed to the formation of a thicker oil layer around soil particles, which increased lubrication effect and prevented particles interlocking.

Similar results were reported by Al-Sanad et al. (1995) during their investigation of clean and contaminated sand. Their analysis showed that CBR values improved with the presence of oil up to 4% (by weight). Asi et al. (2002) concluded during their experimental study using foamed asphalt in stabilising dune sands, that foam asphalt film covering soil particles is less sensitive to moisture damage, leading to higher values of soaked stability since the water proofing effect of bituminous materials is one of the main functions of the stabilisation.

6.4 Consolidation characterisation

Evaluation of the effect of oil residue addition on the compressibility and swelling behaviour of oil mixed Sabkha soil is important, since lubrication effect of the oil residue may cause excessive settlements and lead to serious consequences. Lack of information about the behaviour of oil mixed Sabkha soils made it important to investigate these properties.

Tow series of consolidation tests were carried out on Sabkha soils. The first series was carried out to investigate compressibility and swelling and the second undertaken to investigate the collapse potential. Oil residue contents used in these tests were 2% to 10% for Sabkha soil S_{J-4}, and 3% and 5% for soils S_{Z-5}, S_{K-7} and S_{B-8}.

6.4.1 Consolidation test

The main objective of this part of the experimental programme was to investigate the effect of oil addition on the consolidation characteristics of oil mixed Sabkha soils. One-dimensional loading and unloading oedometer consolidation tests were carried out on natural and oil mixed Sabkha soils in soaked conditions according to BS1377: 1990. Tests were performed using a Wykeham Farrance WF 24001 equipment.

6.4.1.1 Procedures

Oil mixed Sabkha soils were mixed with their corresponding optimum moisture contents determined in section 4.4.5. Sabkha soil samples were mixed with oil residue and prepared using the method outlined in section 4.3.

A soil specimen was placed and compacted in a stainless-steel ring, 70 mm in diameter and 20 mm in height. The inside of the ring was lubricated with silicon gel to minimise side friction between the ring and the soil specimen.

The compacted sample in the stainless-steel ring was placed between two porous stones. The porous stones were kept in distilled water for 24 hours to reach saturation and to prevent absorption of water from the sample. The specimen was placed in the consolidation cell under a pressure of 0.1 kPa. The compacted specimen in the consolidation cell was inundated with distilled water from the bottom, and then pressures were raised incrementally to a maximum of 936 kPa.

Each load increment was kept for a period of 24 hours. Although the soil samples were classified as silty to poorly graded sand, it was felt necessary to keep the samples under 24 hours loading due to the low permeability of oil mixed Sabkha soils (section 4.4.6), and to obtain results at similar loading durations as those carried out by other investigators on soils in Kuwait. Vertical displacements were measured by calibrated dial gauges. Strain readings were taken at the end of this period and before the application of new load increment. Dial readings for the height of the specimen were taken in each stage of loading and unloading at the end of 24 hours.

6.4.1.2 Results and discussion

In the analysis of consolidation results, it is necessary to determine variation in the void ratio during load application and to present the load-void ratio relationship. The Pressure-void ratio relationship is plotted with log pressure as the abscissa and void ratio as the ordinate for natural and oil mixed Sabkha soils and is shown in Figures 6.15 to 6.18 for soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. Results are discussed under the following headings:

- Void ratio variation.
- Yield stress.
- Compression index.
- Swelling index.

6.4.1.2.1 Void Ratio variation

The effect of oil residue addition on the compressibility characteristics of Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} is shown in Figures 6.15, 6.16, 6.17 and 6.18, respectively. These figures reveal that the void ratio was lower in the oil mixed Sabkha soil than in the natural Sabkha soil, and the reduction in void ratio increased with oil content. Variations in the void ratio with oil residue content for Sabkha soil S_{J-4} tested at pressures of 25 kPa, 130 kPa, 208 kPa and 936 kPa are shown in Figure 6.19. This figure shows that the void ratio decreased with oil addition for the same soil at the same applied stress. At an applied pressure of 936 kPa the void ratio decreased from 0.455 for natural Sabkha soil to 0.355, 0.3688 and 0.255 for 3%, 5% and 10% oil mixed Sabkha soils. The decrease may be attributed to oil addition that filled the voids between the soil particles and reduced the void ratio. This facilitated the entry of oil coated fine particles into larger pores and channels and caused a reduction in porosity and permeability (Andrade et al., 2004). Similarly, Singh et al. (2006) observed that the void ratio of sandy soil reduced from 0.5 to 0.44 and o.43 for 3% and 9% gasoline addition, respectively.

6.4.1.2.2 Yield Pressure

Yield stress values can be used to evaluate the effect of oil residue addition on the consolidation properties and strength of the cementation bonds of Sabkha soils

(Vaughan, 1988). An examination of e-log p curves showed that, in general, the void ratio decreased at different rates throughout the loading stage. The void ratio decreased at a slow constant rate with pressure until a point, considered the yield pressure, beyond which the reduction rate began to increase with pressure.

Yield pressures were determined from their e-log p curves following the same steps used to estimate the maximum past pressure by the graphical procedure proposed by Casagrande (1936) and detailed by Arora (1997). Yield pressure results are tabulated in Table 6.2 and presented graphically as a function of oil residue content for different soil samples from the four main locations in Figure 6.20. It is interesting to observe from the figure that the yield pressure for Sabkha soils increased with oil residue addition of up to 5% and decreased beyond that percentage. The increases in yield pressure due to oil residue addition ranged from 20% to 60% for different Sabkha soils.

The increase in yield pressure may be attributed to the lubrication effect of the oil residue which reduced the frictional resistance between soil particles (section 5.4.2.2) and increased the dry density of the compacted soil (section 4.4.5) which in turn increased the stability and bearing capacity of the soil. The increase could also be attributed to the cohesion effect developed due to oil residue, which strongly bound the soil particles. The adsorbed oil residue on the soil particles induced an interparticle adhesive force described previously in section (5.4.2.2). The increase may also be attributed to the waterproofing effect of the oil residue, which reduced the dissolution of salts and the cementing bonding between soil particles, as was suggested previously in chapter 4.

The high reduction in the yield stress with more oil addition beyond 5% could be attributed to the formation of thick oil layer around soil particles which reduced the friction angle and increased the lubrication effects as explained in section 5.4.2.2.

6.4.1.2.3 Compression index (Cc)

The compression index, which is a parameter for expressing the relative compressibility of the soil, can be determined from the relationship of void ratio with vertical pressure (e-log p). Figures 6.15 to 6.18 present the one-dimensional compression behaviour of oil mixed Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. Figure 6.15 reveals different curves have different slopes for the straight-line portions of the loading curves beyond the yield pressure. The compression index is represented by the slope of the steep straight line portion of the loading curve beyond the yield pressure. The value of this parameter is negligible below the yield pressure. The C_c values are tabulated in Table 6.2.

Compression index values, Cc, calculated from Figures 6.15 to 6.18, were 0.0443, 0.033, 0.0413 and 0.055 for natural Sabkha soils S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. These values indicate that Sabkha soil S_{B-8} had the highest compression index, while soil S_{Z-5} had the lowest value among the tested Sabkha soils. The crushing mechanism, after some initial rearrangement as grains successively carry strong contact forces (Bolton and Cheng, 2001), was expected to be a major factor, even at intermediate stresses in Sabkha soil, due to the existence of low strength minerals, such as calcium carbonates, gypsum and shells. The high compressibility of Sabkha soil S_{B-8} was expected because of the high gypsum content, revealed previously in the XRD test, since saturation softens non soluble salts and increases compressibility (Ismael and Mollah, 1998). In addition, the low quartz content in soil S_{B-8} (34.86%) was also a factor expected to increase the compressibility of this soil. The lower compression index for soil sample S_{Z-5} may be attributed to its chemical composition characterised by low gypsum content and high quartz content. In general, the abundance of sulphates caused soaked soil to become softer and more compressible.

Calculated compression indices, C_c, for oil mixed Sabkha soils derived from Figures 6.15 to 6.18 are also tabulated in Table 6.2. To evaluate the oil residue effect, variations in compression index values with oil content are presented graphically in Figure 6.21. In general, C_c of oil mixed Sabkha soils followed a similar trend as oil residue content increased. Noticeably, the compression index for natural soil S_{J-4} increased at an oil residue content of 2% to 0.0534 from 0.0443, suggesting a substantial increase in C_c at low oil residue content. The same behaviour was observed for soils S_{K-7} and S_{B-8}, where the compression index increased from 0.0413 and 0.055 for natural sabkha soils to 0.055 and 0.075 for 3% oil mixed Sabkha soils, respectively. A reduction in the compression index was noted beyond 3% oil residue percentage. The compression indices for tested Sabkha soils reduced to lower values with more oil addition, to reach the lowest value at 5% oil residue. The compression index values for S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8} dropped to 0.045, 0.029, 0.041 and 0.051, respectively, lower than the C_c values of the natural soil.

The various mechanisms probably responsible for the variation in compressibility of oil mixed Sabkha soils can be explained as follows. Oil residue which covers the surface of aggregates and fills the pores of the soils facilitates their entry and permanence in the larger pores and channels of the soil, resulting in a gluing together of larger particles. This aggregation increases soil adhesion and the binding of soil grains which, in turn, reduces their compressibility. Due to the hydrophobic characteristics of sabkha soils (Al-Sarawi et al., 1998; Andrade et al., 2004 and Karimi and Gray, 2000), the coating oil inhibits the interaction of soil with water, thereby increasing the waterproofing effect and resulting in a considerable reduction in C_c and an increase in yield stress. Increase in the soil dry density is another factor that might reduce the compression index of the oil mixed soil.

Al-Sanad et al. (1995) and Meegoda and Ratnaweera (1994) reported a slight increase in the compressibility of oil contaminated sand and clay compared to natural clean soil. The authors attributed this to the lubrication effect of the oil addition, which facilitated sliding between particles. It should be noted that in their studies, soils were not compacted to maximum dry densities, which may be the reason for the increase in compressibility. In addition, the viscosity of the oil used in their studies may have been a main factor contributing to the increase in compression indices. However, Al-Sanad et al. (1995) and Al-Sanad and Ismael (1997) in their experimental studies on contaminated sand from Kuwait, reported a reduction in the compression indices of tested soil samples. They attributed this reduction to the ageing effect that had led to a reduction in oil content due to the evaporation of volatile compounds. In the present study, the oil residue was characterised by high viscosity which was expected to increase the cohesive bonding between soil particles and reduce the compression index, since pore fluid viscosity influences the compressibility of contaminated soils (Meegoda and Ratnaweera, 1994).

6.4.1.2.4 Swelling index

During the consolidation test, unloading was carried out after reaching maximum yield pressure. Unloading was undertaken in two stages. Swelling index, C_s, was calculated from the slope of the unloading straight portion of the e-log pressure curve. The calculated swelling index value for natural and oil mixed Sabkha soil samples at different oil residue contents is tabulated in Table 6.2.

The swelling index values for natural Sabkha soil samples ranged from 0.009 for Sabkha soil $S_{j\text{-}4}$ to 0.011 for soil $S_{z\text{-}5}$. The effect of oil residue addition on C_s of Sabkha soils is presented in Figure 6.22. The swelling indices for oil mixed Sabkha soils with 5% oil residue are slightly lower than those of natural Sabkha soils $S_{K\text{-}7}$ and $S_{J\text{-}4}$, and slightly higher for soil $S_{B\text{-}8}$. The swelling index increased greatly with oil residue addition of 8%. Comparing natural and oil mixed Sabkha soils' results presented in Figure 6.22 indicates variation in swelling indices with oil content addition is very low within the 0%-5% range.

In general, variations in the swelling index with oil residue addition up to 5% were insignificant. However, oil residue addition slightly improved the compression characteristics of oil mixed Sabkha soils in terms of yield pressure.

6.4.2 Collapse potential test

The main objective of this test was to investigate the effect of oil addition on the collapse potential of oil mixed Sabkha soils. The potential for collapse upon inundation with water is determined, for a given value of normal stress, using an oedometer test (Jenning and Knight 1975). This test was carried out according to the procedure described by Ismael et al. (1986-b) and proposed by Knight (1963).

6.4.2.1 Procedures

A compacted soil specimen at its optimum moisture content was loaded in the consolidation apparatus, as described in section 6.4.1.1, until a pressure of 200 kPa was reached. The sample was not soaked with water at this stage. The specimen was covered with a wet towel to maintain its optimum moisture content. The load was kept for 24 hours and at the end of this period the sample was saturated by flooding it with distilled water. Twenty-four hours after the beginning of saturation, a settlement reading was taken and then the test was continued by increasing the load to its maximum limit.

6.4.2.2 Collapse potential test results

Collapse potential, C_P. is defined as the additional volumetric strain due to wetting under a constant normal pressure expressed as a percentage: it was determined by measuring the change in settlement upon wetting.

Figure 6.23 shows the e-log p relationship for a collapse test conducted on natural Sabkha soils from the four main locations under a normal pressure of 200kPa. The sudden compression observed upon submersion appears as a vertical line on the 200 kPa loading mark. The longer this vertical line the more collapsible is the soil. From test results the collapse potential for natural Sabkha soils was calculated to be 0.19%, 0.12%, 0.31% and 0.14% for S_{J-4}, S_{Z-5}, S_{K-7} and S_{B-8}, respectively. According to the severity rating suggested by Jennings and Knight (1975), all tested Sabkha soils were considered to have no problem with collapse.

Soil S_{K-7} was observed to have the highest collapse potential, while soil S_{Z-5} had the lowest. The higher collapse potential value for soils S_{K-7} and S_{J-4} compared to soil S_{Z-5} was mainly related to their chemical and mineral composition. Soil S_{Z-5} had a more competent and stable matrix, due to soil composition characterised by low fine content. In general, the presence of moisture in soils S_{J-4} and S_{K-7} may have weakened the cementation provided by the salts, thus reducing the strength and increasing the compressibility of the soils.

Figure 6.24 shows the e-log p relationships for collapse tests conducted on natural, 5% and 10% oil mixed Sabkha soils under a normal pressure of 200 kPa for soil S_{J-4}. It can be observed from the Figure that the vertical line on the 200 kPa reading mark is shorter for the 10% oil mixed Sabkha soil than for the natural.

Table 6.2 contains the collapse potential of natural and oil mixed Sabkha soils. The table shows that the collapsibility of oil mixed Sabkha soils reduced with oil residue addition. With 5% oil addition, the collapse potential for soil S_{J-4} reduced from 0.19% for the natural soil to 0.17%, representing a percentage reduction of 5.5%. For soils S_{K-7} and S_{B-8}, the reduction percentages were 65%, 35% and 14% respectively for 5% oil addition. It should be noted that the collapse potential values of natural and oil mixed Sabkha soils were within the acceptable limits set by Jennings and Knight (1975). With more oil addition of 8% and 10% the collapse potential for soil S_{J-4}, shown in Figure 6.25, reduced to 0.073% and 0.025%, representing reduction percentages of 62% and 87%, respectively.

Mechanisms responsible for the collapse that occurred after saturation of both natural and oil mixed Sabkha soils were probably the reduction in capillary tension and dissolution of salt bonding. It was observed during testing that collapse settlement did not develop instantaneously after saturation. On the contrary, collapse settlement developed over a few hours. The slow collapse was an indication of chemical cementing bonding since the collapse occurred due to the dissolution or softening of the bonding agents (Ismael and Mollah, 1998). Collapse is traditionally envisioned as being the result of strength loss in the binding agent, following grain re-arrangement in the coarse fraction (Jennings and Knight 1975).

As was shown experimentally during the investigation of the physical properties of oil mixed Sabkha soils, oil addition reduced the hydraulic conductivity of the oil mixed soil (Section 4.4.6). The non-aqueous phase liquid (NAPL) appeared as a film surrounding the micro-aggregates and filling in the interior pores (Karimi and Gray, 2000). The hydrophobic characteristics of the oil mixed Sabkha soil (Andrade et al., 2004) minimised water percolation and the danger of salt dissolution in the soil matrix.

This author suggests that due to crushing of the soil particles after some initial rearrangement, as the grains successively carried strong contact forces, possibly more dissolution occurred in natural Sabkha soil, whereas newly exposed areas were continuously covered with oil residue in oil mixed Sabkha soils.

The collapse potential of the Sabkha soil S_{J-4} reduced to a very low value at oil residue content of 10%, at which the oil residue began to fill most of the pore spaces and to form a coating around the skeleton of grains leading to the formation of a waterproofing layer that minimised the dissolution of salts resulting in a dense and stable structure. Al-Houty et al. (1993) and Al-Sarawi et al. (1998) concluded, from their studies on contaminated soil in Kuwait, that oil rendered the contaminated soil layer completely hydrophobic. The author proposes the same conclusion for oil mixed Sabkha soil.

6.5 Optimum oil residue content

The optimum oil residue content required to modify Sabkha soil samples was expected to be lower than 8%, based on the investigated physical properties in Chapter 4. The main physical parameter, the dry density, continued to increase with oil addition up to 8% and to decrease beyond this. However, the density of the stabilised Sabkha cannot be used as the only criterion in any stabilisation programme (Al-Amodi et al., 1995). Geotechnical investigations concentrating on strength aspects, revealed that unconfined compressive and shear strength were both affected at different rates by oil residue addition. Due to modification of the cohesive soil property, the unconfined compressive strength of the oil mixed soil increased with oil addition up to 5%. Beyond that percentage, the strength started to decrease. On the other hand, the shear strength components, namely, friction angle and cohesion, were affected in contrasting ways simultaneously. The friction component decreased with oil residue addition and the reduction rate was higher beyond an oil content of 5%, while the cohesive component increased with oil residue addition.

At 5% oil residue addition, CBR values were slightly affected at dry conditions, while at soaked conditions the CBR value increased more due to waterproofing effect. The compressibility characteristics were slightly modified at this oil percentage.

The above results and analysis suggest that 5% oil residue addition is the optimum oil residue content for the stabilisation of the tested Sabkha soils.

6.6 Conclusion

A laboratory testing programme was carried out to investigate the soaked and unsoaked CBR values and compressibility characteristics of natural and oil mixed Sabkha soil from the four site locations. Strength characteristics were determined in the laboratory by means of the California Bearing Ratio test and consolidation characteristics by means of a standard oedometer tests. Based on the experimental investigations, the following findings were observed:

- Natural Sabkha soils showed low CBR values and were highly susceptible to collapse upon soaking.
- Sabkha soils showed a decrease in the range of 16% to 48% of dry CBR values with oil addition up to 5%.
- Oil mixed Sabkha soils showed appreciable increase in soaked CBR values by about 1.5 to 2 folds of the natural soaked values with oil residue addition up to 5%, and a large reduction beyond this percentage.
- Unsoaked CBR values of oil mixed Sabkha soils were higher than the soaked values, however, the difference diminished with oil addition.
- Yield pressures for Sabkha soils from the four locations increased with oil residue addition up to 5%.
- The compression index (C_c) for natural Sabkha soils increased with the increase in salts' content.
- Both compression and swelling indices decreased with oil residue addition up to 5% due to the waterproofing effect which reduced dissolution and softening effect in tested samples upon saturation.
- The collapse potential decreased at different rates with oil residue addition and was negligible at 10% oil addition.

- The addition of oil residue at 5% to Sabkha soil was effective in reducing the compression and swelling indices and collapsibility characteristics of the stabilised Sabkha soil samples.

- Oil residue addition of 5% to the tested Sabkha soils from the four main locations can be considered the optimum oil residue content. Compaction parameters, strength, compressibility and collapse potential of Sabkha soils noticeably improved due to 5% oil addition, more significantly under soaked conditions.

6.7 References

AASHTO, 1990. American Association of State Highway and Transportation Officials (AASHTO), Standard Method of Test for the California Bearing Ratio, AASHTO Designation: T 193-81.

Aiban, S.A., 1995. Strength and Compressibility of Abqaiq Marl, Saudi-Arabia. *Engineering Geology*, 39(3-4): 203-215.

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-b. Strength Characteristics of Sabkha Soils. *Geotechnical Engineering*, 26(1): 73-92.

Al-Amoudi, O.S.B., Abduljauwad, S.N., El-Naggar, Z.R. and Rasheeduzzafar, 1992. Response of Sabkha to Laboratory Tests - A Case Study. *Engineering Geology*, 33(2): 111-125.

Al-Amoudi, O.S.B., Asi, I.M. and El-Naggar, Z.R., 1995. Stabilisation of an Arid, Saline Sabkha Soil Using Additives. *Quarterly Journal of Engineering Geology, 28: 369-379.*

Al-Awaji, H.A., 2001. Settlement and Bearing Capacity of Geogrid-Reinforced Sand over Collapsible Soil. *Geotextiles and Geomembranes*, 19(2): 75-88.

Al-Houty, W., Abdal, M. and Zaman, S., 1993. Preliminary Assessment of the Gulf War on Kuwait Desert Ecosystem. *Environmental Science and Health.*, A28(8): 1705-1726.

Al-Sanad, H.A., 1986. Characterisation of Salt-Bearing Soils (Sabkha) for Pavement Design Purposes in the State of Kuwait. *Journal of the University of Kuwait*-Science, 13(1): 29-41.

Al-Sanad, H.A. and Al-Bader, B., 1990. Laboratory Study on Leaching of Calcareous Soil from Kuwait. *Journal of Geotechnical Engineering*, 116(12): 1797-1809.

Al-Sanad, H.A., Eid, W.K. and Ismael, N.F., 1995. Geotechnical Properties of Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical Engineering-ASCE*, 121(5): 407-412.

Al-Sanad, H.A. and Ismael, N.F., 1997. Aging Effects on Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3): 290-293.

Al-Sanad, H.A., Shaqour, F.M., Hencher, S.R. and Lumsden, A. C., 1990. The Influence of Changing Groundwater Levels on the Geotechnical Behaviour of Desert Sands. *Quarterly Journal of Engineering Geology*, 23(4): 357-364.

Al-Sarawi, M., Massoud, M.S. and Wahba, S.A., 1998. Physical Properties As Indicators of Oil Penetration in Soils Contaminated with Oil Lakes in the Greater Burgan Oil Fields, Kuwait. *Water, Air and Soil Pollution*, 102(1-2): 1-15.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North-Western Spain). *Journal of Environmental Quality*, 33: 2103-2110.

Arora, 1997. Soil Mechanics and Foundation Engineering. Standard Publishers Distributors, Delhi, p.852.

Asi, I.M., Al-Abdul Wahhab, H.I., Al-Amoudi, O.S.B., Khan, M.I. and Siddiqi, Z., 2002. Stabilisation of Dune Sand Using Foamed Asphalt. *Geotechnical Testing Journal*, 25(2): 168-176.

Bolton, M.D. and Cheng, Y.P., 2001. Micro-geomechanics, Proceedings of the Workshop on Constitutive and Centrifuge Modelling: Two Extremes, Monte Verita, Switzerland, Balkema: 59-74.

BSI, 1990. British Standard 1377: Methods of Test for Soils for Civil Engineering Purposes, British Standards Institution, London.

Casagrande, A., 1936. The Determination of the Pre-Consolidation Load and its Practical Significance. 3: 60-64.

Hassan, H., Taha, R., Al-Rawas, A., Al-Shandoudi, B., Al-Gheithi and Barami, A., 2005. Potential Uses of Petroleum-Contaminated Soil in Highway Construction. *Construction and Building Materials*, 19(8): 646-652.

Head, K.H., 1982. Manual of Soil Laboratory Testing, 2. Pentech Press, London, pp.335-746.

Ismael, N.F., 1993-b. Geotechnical Characteristics of Salt Bearing Soils in Kuwait, Transportation Research Board 72nd Annual Meeting, Paper No. 930035. Washington, D. C.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Ismael, N.F., Mollah, M.A. and AL-Khaldi, O., 1986-b. Geotechnical Properties of Cemented Soils in Kuwait. Australian Road Research, 16(2): 94-104.

Jennings, J.R. and Knight, K., 1975. A guide to Construction on or with Materials Exhibiting Additional Settlement Due to Collapse of Grain Structure. Proceedings, of the Sixth Regional Conference for Africa on soil Mechanics and Foundation Engineering, Johannesburg, pp. 99-105.

Kaisar, K., Haumaier, L. and Zeck, W., 2000. The Sorption of Organic Matter in Soils as Affected by the Nature of Soil Carbon. *Soil Science*, 165(277-304).

Karimi-Lotfabad, S. and Gray, M.R., 2000. Characterisation of Contaminated Soils Using Confocal Laser Scanning Microscopy and Cryogenic-Scanning Electron Microscopy. *Environmental Science & Technology*, 34(16): 3408-3414.

Knight, K., 1963. The Origin and Occurrence of Collapsing Soils, Proceedings of the Third Regional Conference for Africa on Soil Mechanics and Foundation Engineering, pp. 127-130.

Meegoda, N.J. and Ratnaweera, P., 1994. Compressibility of Contaminated Fine-Grained Soils. *Geotechnical Testing Journal*, 17(1): 101-112.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and its Geoenvironmental Implications. PhD Thesis, McGill University, Montreal, Canada.

Singh, S.K., Srivastava, R.K. and John, S., 2006. Assessment and Remediation of Soils Contaminated with Gasoline. In: H.R. Thomas (Editor), 5th ICEG Environmental Geotechnics. Thomas Telford, Geoenvironmental Research Centre, Cardiff University, Cardiff, UK, pp. 294-301.

Vaughan, P.R., 1988. Characterising the Mechanical Properties of In-Situ Residual Soil, Proceedings of the second International Conference on Geomechanics in Tropical Soils, Singapore, pp. 469-487.

Table 6.1. CBR for natural and oil mixed Sabkha soils at dry and soaked conditions

Soil sample	Oil (%)	CBR_D (%)	CBR_S (%)	Variation in CBR due to oil addition (%)	Variation in CBR due to soaking (%)
S_{J-4}	0	42.00	19.00	_	-55.00
	2	35.00	20.00	-16.60	-43.00
	5	35.00	30.00	-16.60	-14.29
	6	6.000	5.000	-85.70	-16.67
	8	4.000	3.000	-90.50	-25.00
S_{Z-5}	0	30.00	14.00	_	-53.30
	2	28.00	23.00	-6.600	-17.86
	5	32.00	29.00	6.600	-9.380
	6	21.00	17.00	-30.00	-19.05
	8	4.000	3.000	-86.60	-25.00
S_{K-7}	0	50.00	9.000	_	-82.00
	2	33.00	23.00	-34.00	-30.30
	5	26.00	24.00	-48.00	-7.690
	6	21.00	19.00	-58.00	-7.700
	8	11.00	9.000	-78.00	18.20
S_{B-8}	0	40.00	11.00	_	-72.50
	2	36.00	14.00	-10.00	-61.10
	5	30.00	21.00	-25.00	-30.00
	6	8.000	6.000	-80.00	-25.00
	6	8.000	NM	NM	NM

Table 6.2. Compression and swelling indices for natural and oil mixed Sabkha soils

Soil	Oil Content (%)	Yield Stress (kPa)	Compression Index	Swelling Index	Collapse Potential (%)
S_{J-4}	0	50	0.0443	0.0090	0.190
	2	50	0.0530	0.0070	NM
	3	57	0.0420	0.0075	NM
	5	62	0.0450	0.0076	0.170
	8	52	0.0590	0.024	0.073
	10	NM	0.0410	0.0080	0.025
S_{Z-5}	0	50	0.033	0.011	0.120
	3	51	0.0288	NM	NM
	5	60	0.029	0.009	0.042
S_{K-7}	0	40	0.0413	0.0070	0.310
	3	55	0.0550	0.0045	0.200
	5	63	0.0410	0.007	0.200
S_{B-8}	0	46	0.0550	0.0079	0.140
	3	67	0.0750	0.0080	NM
	5	70	0.0510	0.0100	0.120

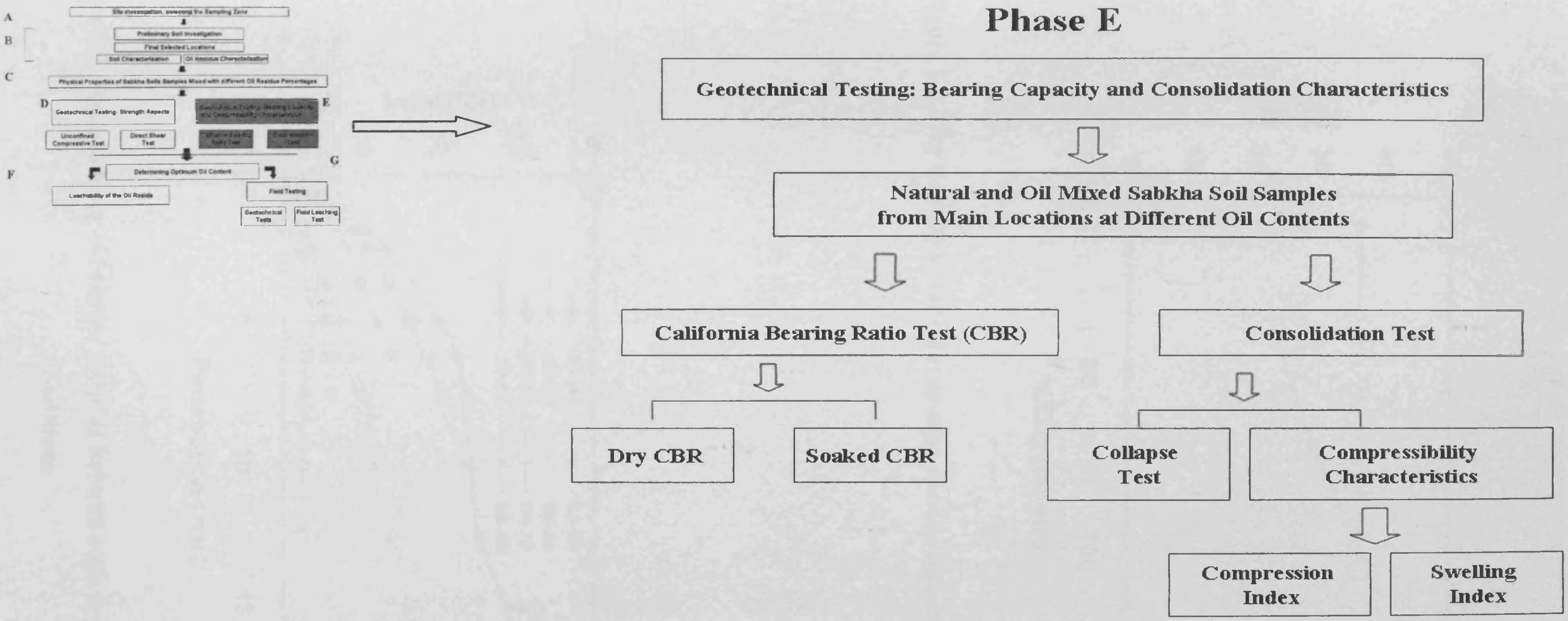

Figure 6.1. Phase E of the experimental programme

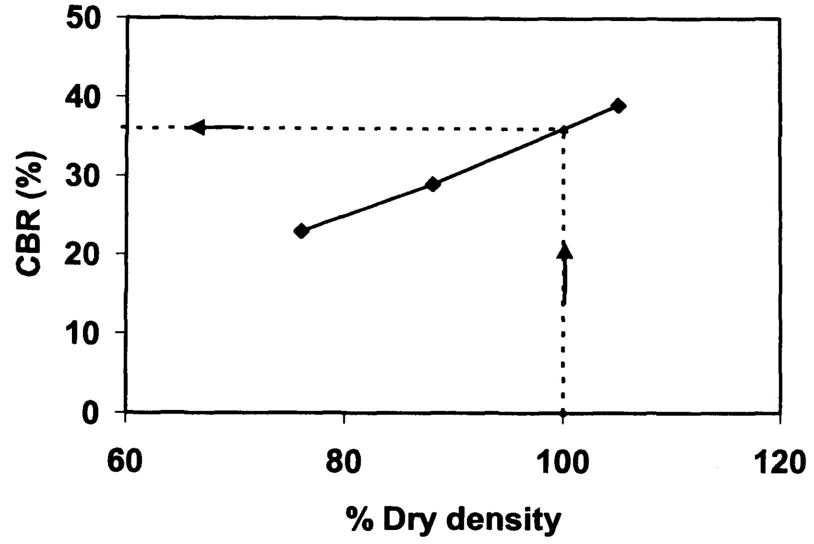

Figure 6.2. Dry density/CBR relationship used to obtain CBR value at MDD

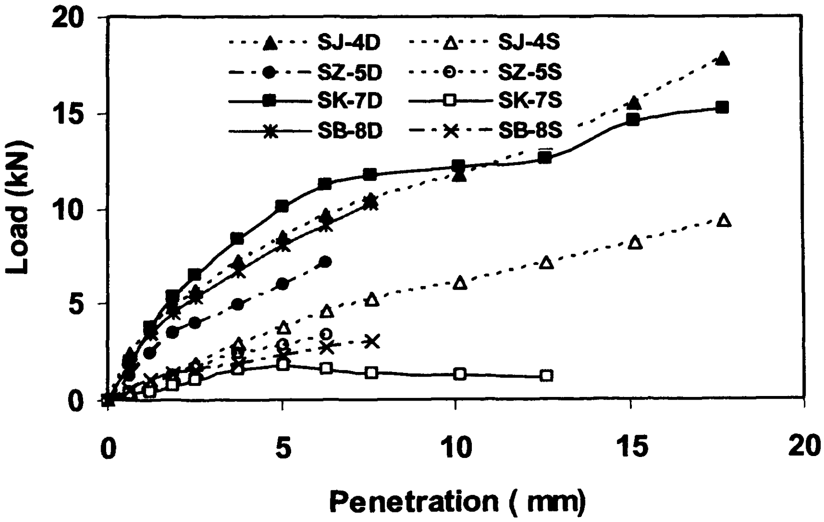

Figure 6.3. Stress-strain curves for natural Sabkha soils at dry (D) and soaked (S) conditions

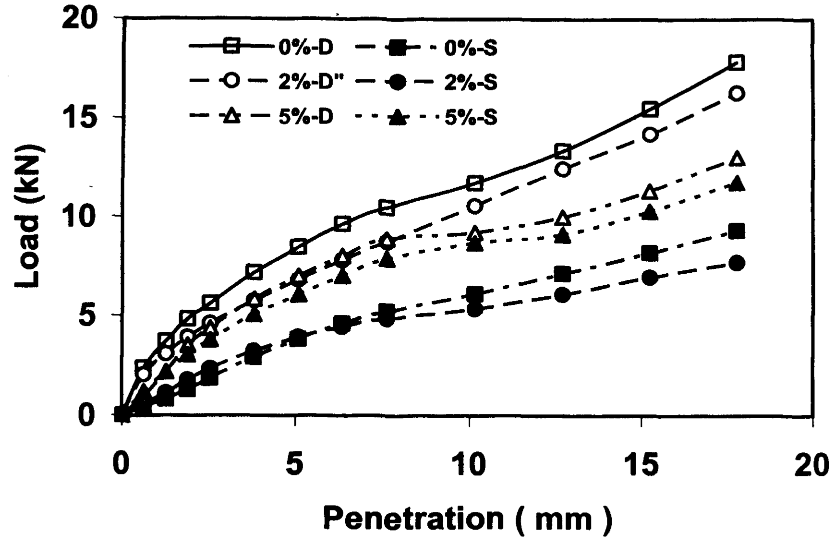

Figure 6.4. Stress-strain curves for natural and oil mixed Sabkha soils (S_{J-4}) at dry (D) and soaked (S) conditions

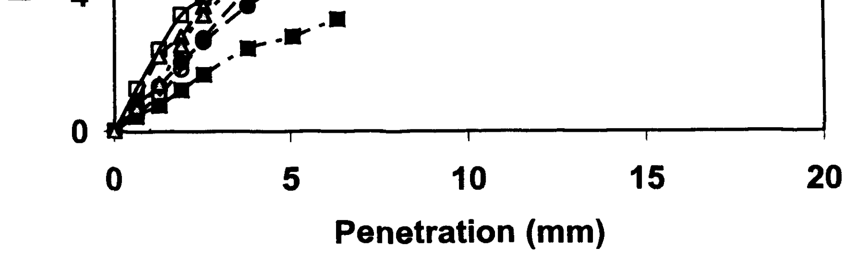

Figure 6.5. Stress-strain curves for natural and oil mixed Sabkha soils (S_{Z-5}) at dry (D) and soaked (S) conditions

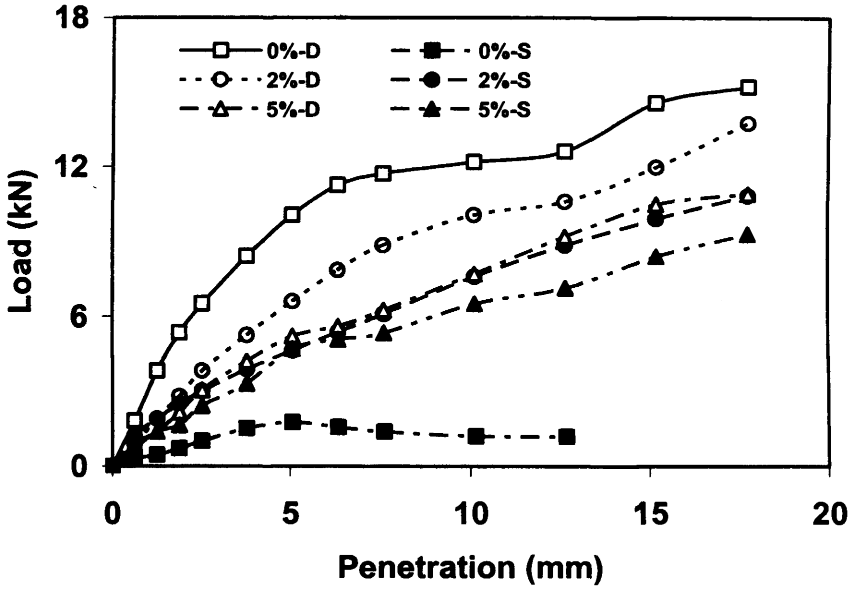

Figure 6.6. Stress-strain curves for natural and oil mixed Sabkha soils (S_{K-7}) at dry (D) and soaked (S) conditions

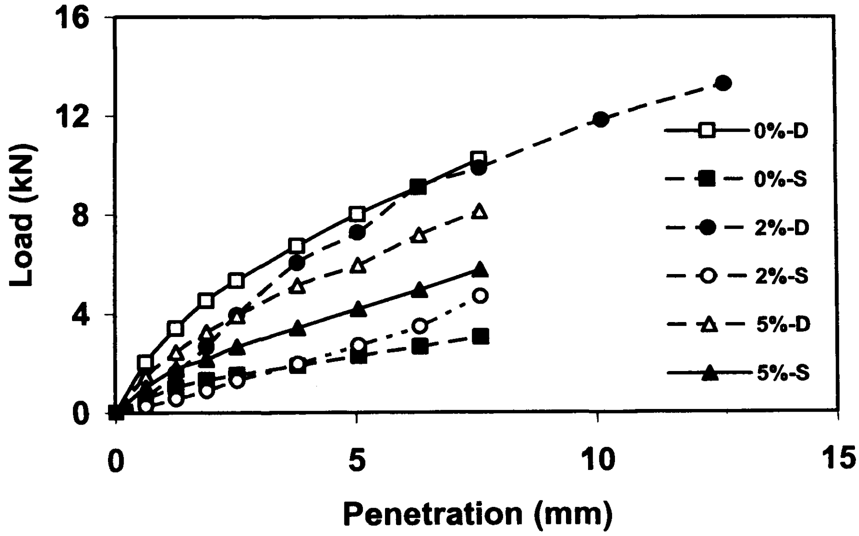

Figure 6.7. Stress-strain curves for natural and oil mixed Sabkha soils (S_{B-8}) at dry (D) and soaked (S) conditions

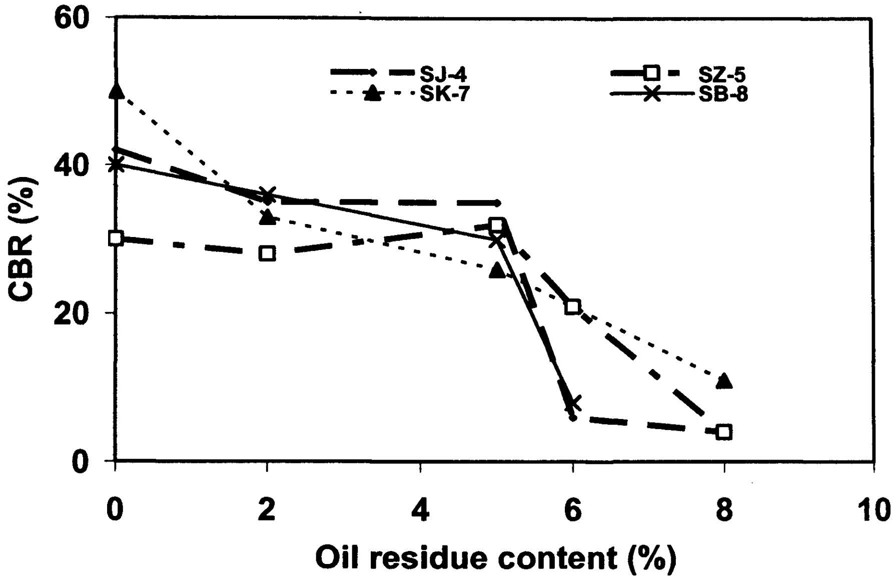

Figure 6.8. Variation in CBR values with oil content for Sabkha soil at dry conditions

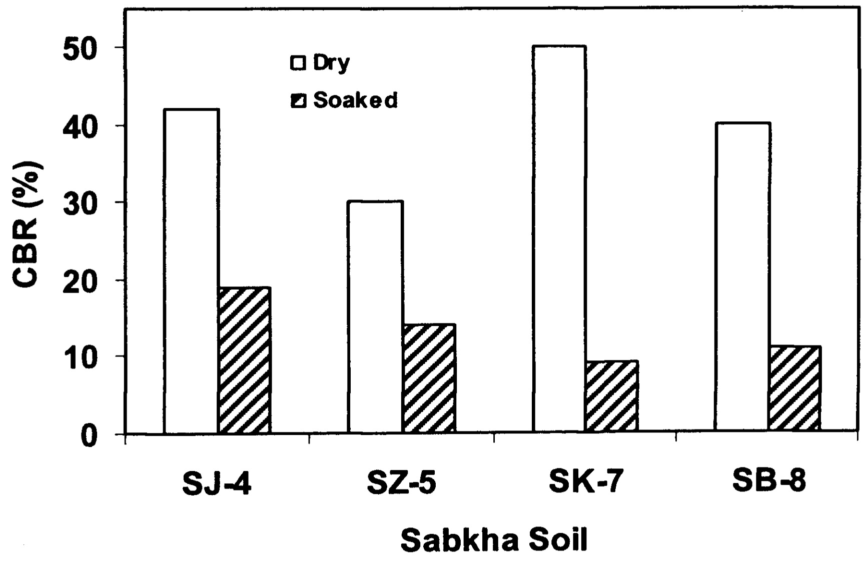

Figure 6.9. CBR for natural Sabkha soil at dry (D) and soaked (S) conditions

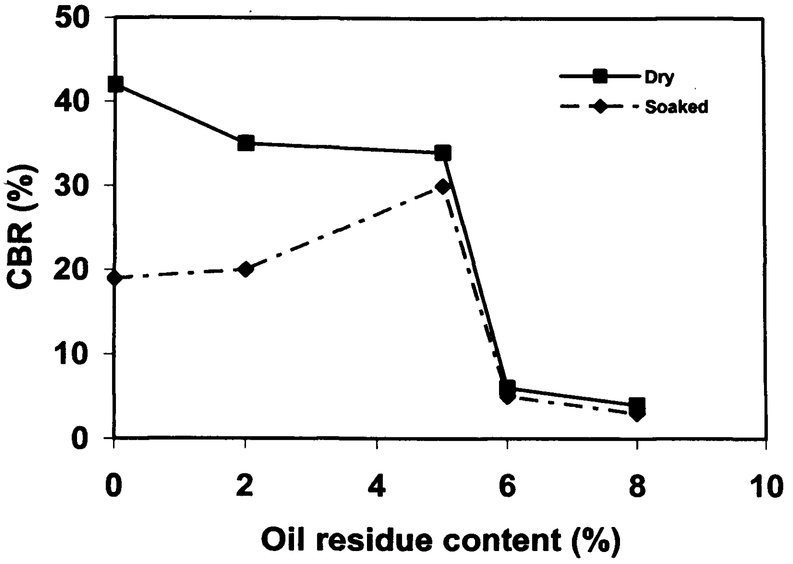

Figure 6.10. CBR for natural and oil mixed Sabkha soils (S_{J-4}) at dry (D) and soaked (S) conditions

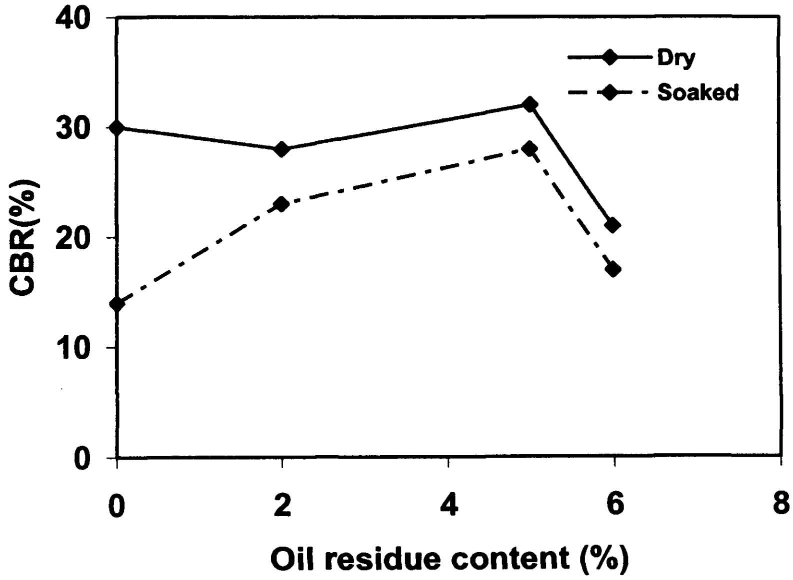

Figure 6.11. CBR for natural and oil mixed Sabkha soils (S_{Z-5}) at dry (D) and soaked (S) conditions

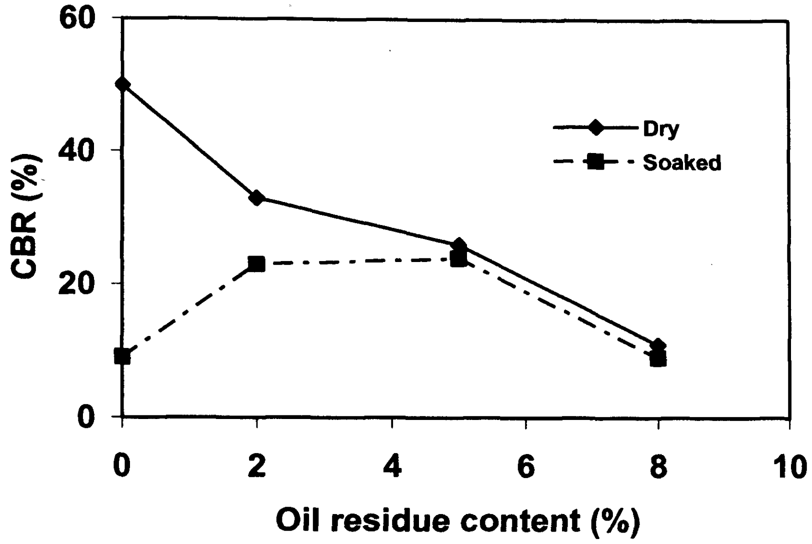

Figure 6.12. CBR for natural and oil mixed Sabkha soils (S_{k-7}) at dry (D) and soaked (S) conditions

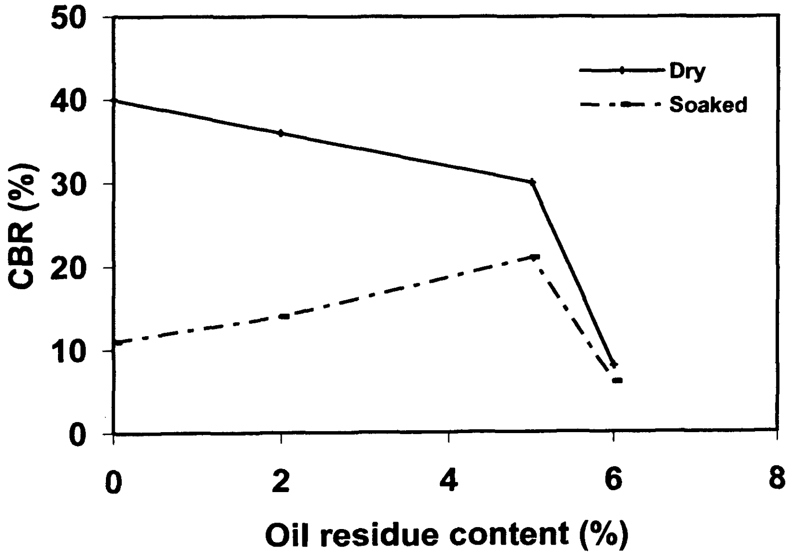

Figure 6.13. CBR for natural and oil mixed Sabkha soils (S_{B-8}) at dry (D) and soaked (S) conditions

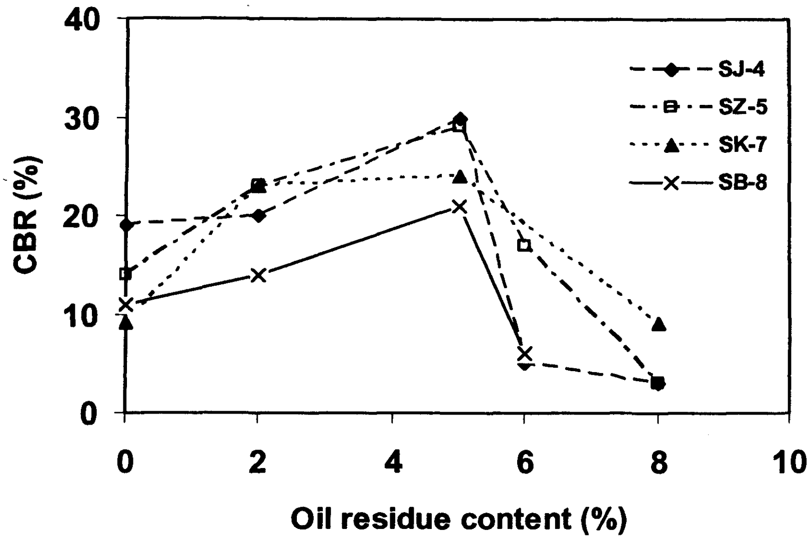

Figure 6.14. Variation in CBR values with oil content for sabbkha soils at soaked conditions

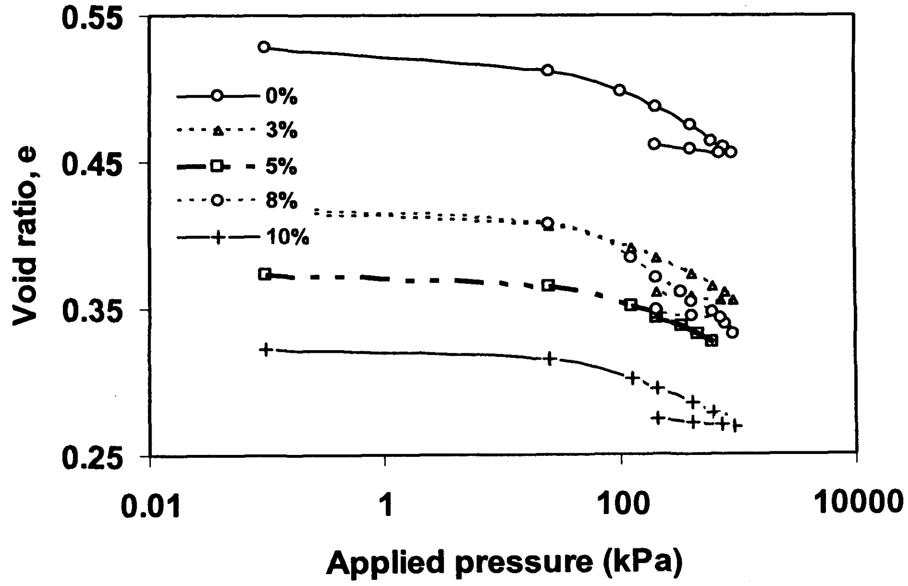

Figure 6.15. Void ratio-log P curves for natural and oil mixed Sabkha soils (S_{J-4})

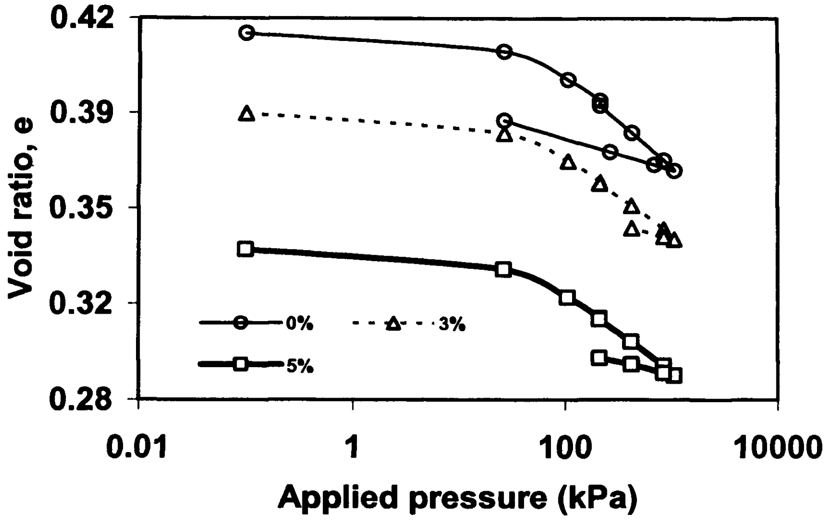

Figure 6.16. Void ratio-log P curves for natural and oil mixed Sabkha soils (S_{Z-5})

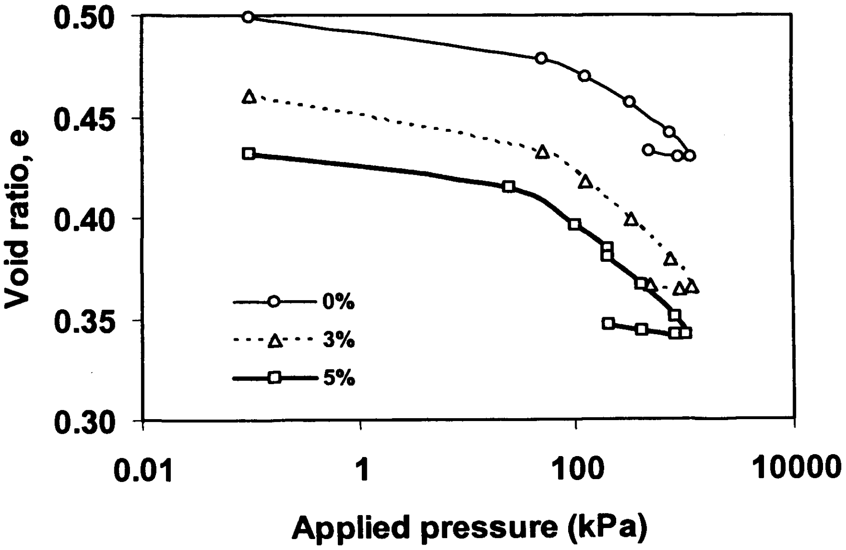

Figure 6.17. Void ratio-log P curves for natural and oil mixed Sabkha soils (S_{K-7})

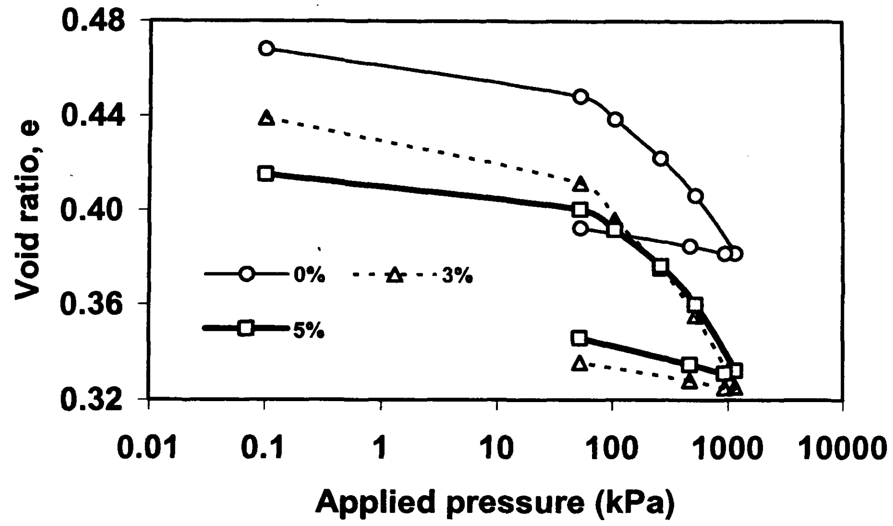

Figure 6.18. Void ratio-log P curves for natural and oil mixed Sabkha soils (S_{B-8})

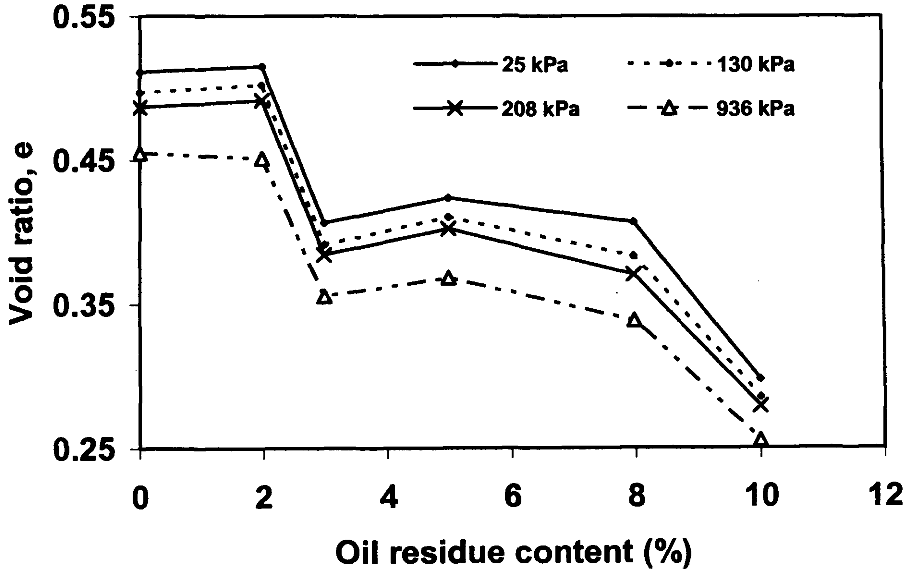

Figure 6.19. Variation in void ratio with oil residue content at different applied pressures for Sabkha soil (S_{J-4})

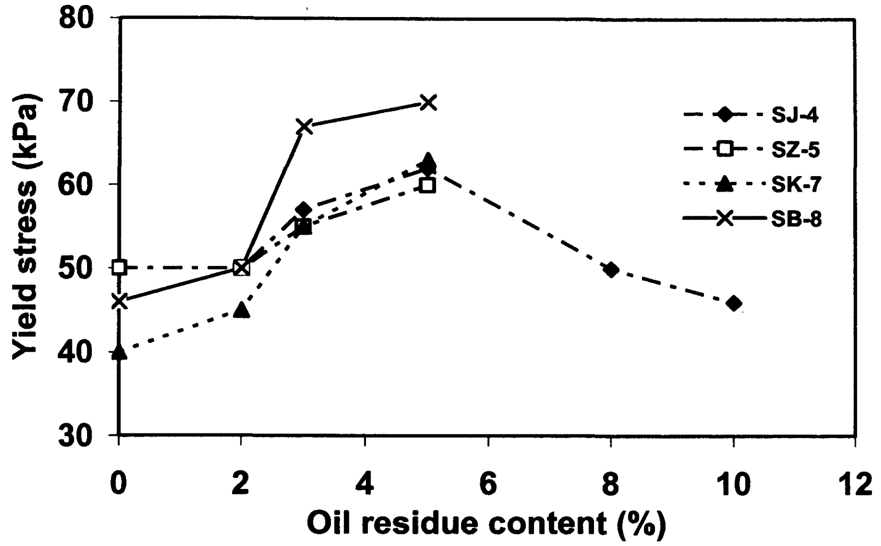

Figure 6.20. Variation in yield stress with oil residue content for Sabkha soils from main locations

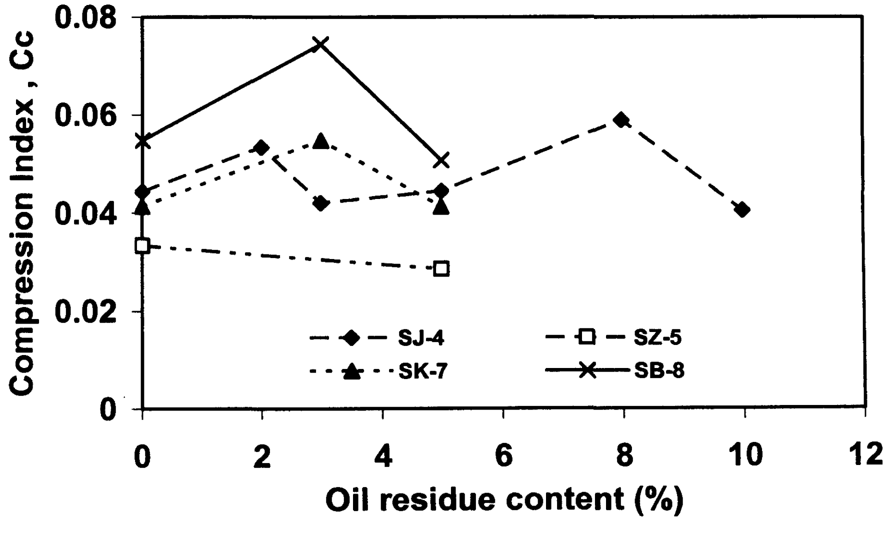

Figure 6.21. Variation in compression index with oil residue content for Sabkha soils from main locations

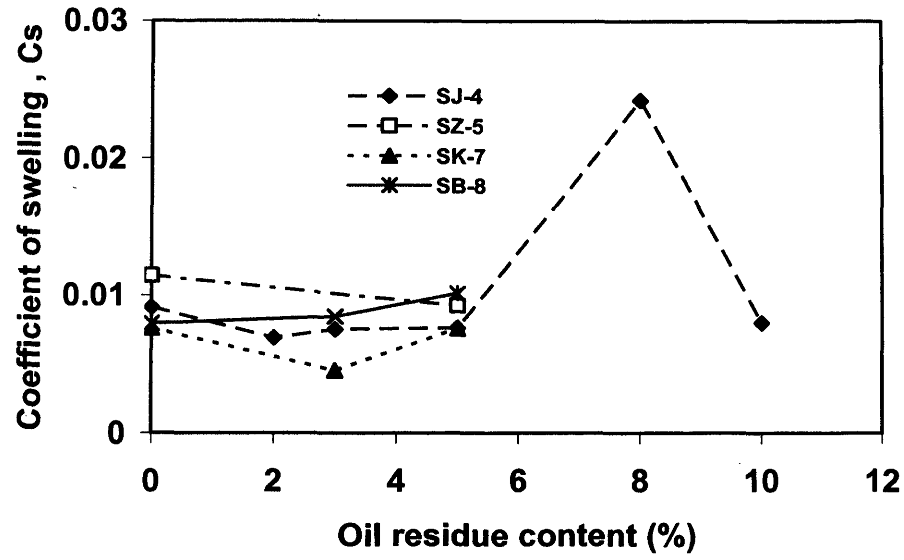

Figure 6.22. Variation of swelling index with oil residue content for Sabkha soils from main locations

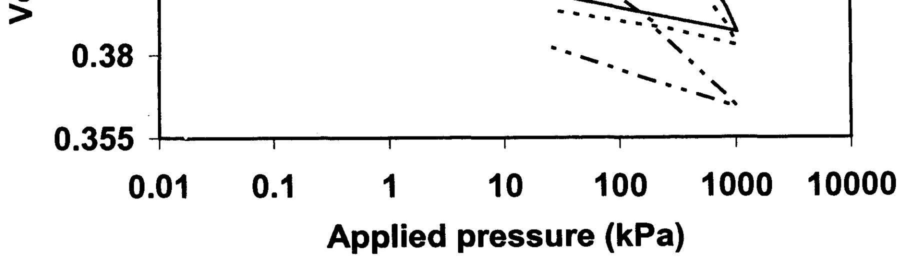

Figure 6.23. Collapse test results for natural Sabkha soils from main locations

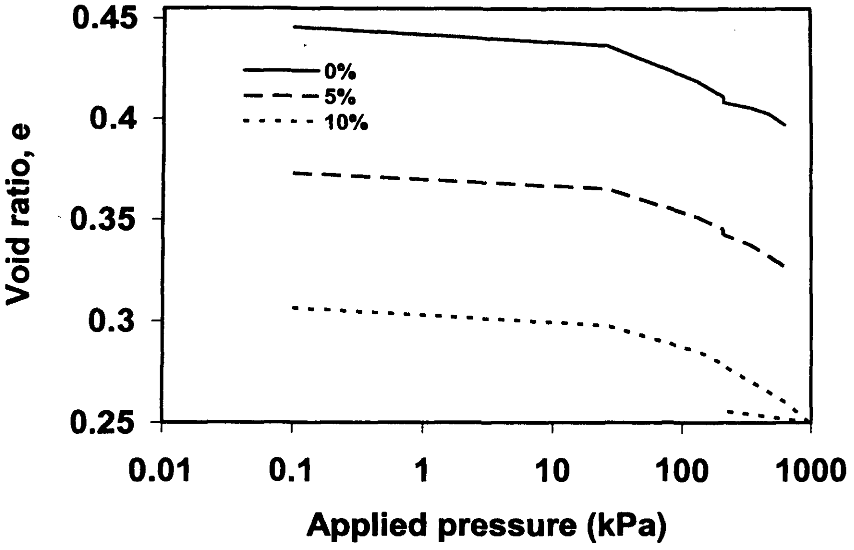

Figure 6.24. Collapse test results for natural and oil mixed Sabkha soils (S_{J-4})

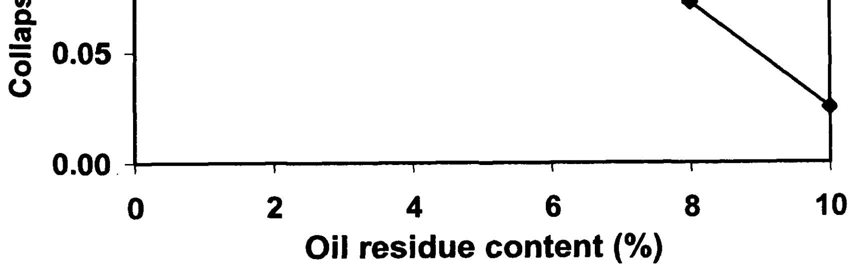

Figure 6.25. Variation in collapse potential with oil content for Sabkha soil (S_J-4)

Plate 6.1. Effect of high oil content on a Sabkha soil sample in CBR testing

Chapter 7

Leachability and Waterproofing Effect of Oil Residue

7.1 *Introduction*

Previous chapters have revealed unconfined compressive, direct shear, CBR, and consolidation characteristics for oil mixed Sabkha soils are modified by oil addition up to 5%. Moreover, modification of these properties is more pronounced under soaked conditions. In general, the stabilisation process is expected to improve some of the unfavourable characteristics of Sabkha soil, which include dissolution of salts, reduction in strength upon wetting, and collapse potential. The potential use of oil mixed Sabkha as a backfilling material or subgrade in road construction necessitates further investigation of its environment impact through leachability. Although oil mixed Sabkha soil will be covered by the surface layers of the road, rainwater and groundwater may come into contact with the stabilised interfacial, leading to leaching or release of components from the stabilised soil layer into the ground.

Accordingly, the leachability characteristics of natural and oil mixed Sabkha soils need to be investigated. To ensure that any leachate will have no adverse impact on environment, the constituents of oil are objectively quantified by running leaching column tests which are conducted to investigate the waterproofing effect of the oil residue and the long-term effect of leaching on the coefficient of permeability of natural and stabilised Sabkha soils.

The testing program is introduced in section 7.2 while Section 7.3 explains the testing procedures and section 7.4 presents an analysis and discussion of results. An overview of main findings and a list of references are provided in Sections 7.5 and 7.6, respectively.

7.2 Testing programme

This part of the experimental work covered phase F of the testing programme, as detailed in Figure 7.1. Two series of tests were carried out on different Sabkha soils. The first series was carried out on 5% stabilised Sabkha soils S_{J-4} and S_{Z-5} in order to investigate oil residue leachability from the oil mixed layer. The second series was carried out on natural and 5% oil stabilised Sabkha soil S_{J-4} in order to investigate the waterproofing effect of oil residue and long-term permeability.

7.3 Testing procedures

The leaching cell system as described and used by Mohamed et al. (1994) and Yong et al. (2001) was used in this study. The system consisted of leaching cylindrical column and six cells as shown in Plate 7.1. In order to test the effect of prolonged leaching, the following factors were required:

- The entire system had to be able to work simultaneously for a long duration of time.
- The system had to have the ability to remove individual cells without disrupting the rest.
- The system had to be able to accommodate different pressures on samples.

Each cell consisted of a hollow plexiglass cylinder with a 3.0 mm thick wall, an outer diameter of 110 mm, and a total length of 125 mm. A porous stone, 3 mm thick, was placed on the top and bottom of the soil sample. The upper porous stone was used to distribute the leaching solution as uniformly as possible over the cross-sectional area of the soil sample, while the lower stone was used to prevent soil washout. Rubber O-rings were sandwiched between the cylinder and the top cap and the bottom plate, to prevent leaking.

Each soil sample was prepared by mixing dry soil with a specific amount of oil residue. Water was then added to bring the sample to its optimum moisture content. Compaction was performed using the compaction unit until the predetermined maximum dry density (section 4.4.5) was reached. The soil was compacted into a leaching cell in six layers.

Leaching cells were connected to the system via air pipes. Air pressure was applied through the air pipes and controlled using a valve and a gauge system. In addition, another 6 valves were used to allow each cell to be controlled independently. The upper reservoir in each cell was filled with distilled water. Low pressure of 1.2 psi was applied during samples' saturation phase. After leaching of the first pore volume, the pressure was raised gradually to 7.0 psi. The applied pressure was equivalent to a hydraulic gradient of 40, higher than that expected in the field. These parameters were selected for the following reasons:

- The leaching of oil residue and salts in the field was expected to be due to rainfall and accumulation of flood waters. The effect of groundwater movements through the stabilised soil layer was not considered due to the following:
    - Most roads are constructed at elevated level to minimise the effect of groundwater rise.
    - The water table level in general is below the ground level as mentioned in section 3.7.

- Distilled water was used to represent the worst case scenario. Several studies on Sabkha soil samples using distilled and saline water (Al-Amoudi and Abduljauwad, 1994-a; Al-Sanad and Al-Bader, 1990; and Ismael, 1993-a) have concluded that saline water has less capability of dissolving salts in Sabkha soils, while the percolation of distilled water through them causes destruction of the natural cementation, leading to collapse, increase in permeability and large settlement.

- Distilled water has negligible concentrations of cations that could possibly influence the leaching behaviour of the soil (McCallister and Petry, 1992).

- The selection of the hydraulic gradient was based on preliminary tests carried out on stabilised and natural Sabkha soils to determine the pressure required to be applied during the test. It should be mentioned that the maximum pressure that could be applied through the system was 10 psi due to safety considerations. In preliminary tests, pressures of 1 psi, 3 psi, and 7 psi were used. Test results showed that using 1 psi and 3 psi pressure resulted in a very slow flow. Preliminary calculations showed that more than 2 months were needed to collect 20 pore volumes of leachate if 1 psi and 3 psi were used. Results also indicated that using 7 psi pressure yielded the required amount of leachate within a reasonable time. It was therefore decided to use 7 psi pressure, equivalent to a hydraulic gradient of 40, for all tests. This pressure was equivalent to a water head of 4.8 m, and reflected extreme condition unlikely to be encountered in the field but nevertheless applied to ensure environmental safety. The 7 psi pressure had to be kept constant throughout the experiment to produce an almost constant flow that allowed the leaching cells to be used as a constant head permeameter.

The effluent (leachate discharge) was collected in clean, closed containers to minimise volatilisation losses of hydrocarbons and evaporates of water (Plate 7.1). Each container was carefully labelled with the required information to prevent mistakes.

7.4 Results and discussion

Specimens of known amount were taken from each pore volume for analysis. The pore volume of the tested soil in the leaching cell was determined by assuming that it was equal to the amount of water required to saturate the sample. This amount is equal to the initial void which can be calculated given the density, moisture content and specific gravity of the sample. Concentrations of total hydrocarbons were analysed using an Infrared spectrophotometer. Cations and anions in the soil were analysed using ICP-OES (Inductive Coupled Plasma Optical Emission Spectroscopy) and IC (Ion Chromatography), respectively (HMSO, 1980). The major analysed anions and cations were SO_4^{2-}, Na^+, Ca^{2+} and Mg^{2+}

7.4.1 Leachability of oil residue

Leaching column test was conducted to investigate the leaching potential of oil residue constituents from 5% oil stabilised soils. Each pore volume was collected separately in order to carry out chemical analysis at different intervals. The bottles were sealed tightly and labelled with information about soil type, pore volume number, type of analysis required and date of sampling.

Visual inspection had revealed that the effluent was colourless. Results of chemical analysis for different pore volumes are shown in Figure 7.2 which presents the variation in oil concentration with leached pore volume. The Figure shows that oil residue concentration in the effluent of 5% oil stabilised Sabkha soils S_{J-4} and S_{Z-5} was less than 1 mg/litre, in the first pore volume. The concentration of oil residue decreased in subsequent pore volumes, until it reached undetectable values in the 7th and 10th pore volumes for soils S_{J-4} and S_{Z-5}, respectively.

Test results indicated that the leachability of oil residue from stabilised Sabkha soils under permeating distilled water was relatively low. Moreover, this concentration level was considered low compared with information provided in the safety data sheet published by Kuwait Petroleum International (Q8, 2004), which stated that aquatic toxicity was expected to be in the range 10-100 mg/l.

Due to small quantity, low solubility, low volatility and high viscosity of oil residue, main expected mechanisms of oil residue retention in the stabilised soil layer were entrapment in soil capillaries and pores or adsorption at mineral and organic matter surfaces. Physical entrapment is a form of non-adsorptive retention of non-aqueous phase in the subsurface which is affected by fluid properties (Roy et al., 2002). It was expected to be low due to the low quantity of oil residue and the distribution of this quantity through the mixing process.

The adsorption process was the expected main mechanism of oil residue bonding to soil surfaces and through weak bondings (section 4.4.1). The high percentage of calcium carbonate content was expected to increase the rate of adsorption, since the formation of a strong bond between the calcite surface and the adsorbed hydrocarbons is controlled mainly by the strength of the polarity of the adsorbate molecules (Madsen et al., 1996).

The mixing process during soil preparation distributed the oil residue through the soil mass and over Sabkha soil particles' surfaces, which enhanced oil bonding to the soil and reduced the availability of free oil residue in soil pores. In addition, the highly viscous oil residue likely reduced the transportation characteristics and decreased conductivity of the oil mixed soil (Fine et al., 1997; Gerstel et al., 1994). The aqueous solubility of organic compounds is one of the most important physical properties, controlling their transport and fate in the subsurface (Dror et al., 2002). The transportation and transformation characteristics is expected to be low due to the very low aqueous solubility of the oil residue (<1 mg/l).

In general, the low concentration of leached oil residue may be attributed to the physical and chemical properties of the oil residue. Oil residue is considered a hydrophobic organic material, possessing low solubility and high viscosity and molecular weight (Section 3.9), making removal of its hydrophobic material by purely aqueous solutions difficult, since water is an ineffective solvent for this material type (Hirner et al., 1998). A study carried out by Kuyakina et al. (2005) to treat oil contaminated soil indicated the low effectiveness of water washing for the remediation of this soil.

The low percentage of leached oil residue may also be attributed to the increase in density of the compacted Sabkha soil samples due to oil addition (Section 4.4.5). Coated Sabkha fine soil particles were facilitated to enter into the larger pore channels, thus increasing resistance to penetration by reducing porosity and permeability. The same argument was proffered by Andrade et al. (2004) in their study on oil contaminated soil.

The higher concentration of leached oil residue at initial stages of leaching may be attributed to the dissolution of partially coated salts (Plate 7.2) which liberated and removed the lighter fractions of oil residue. The higher flow rate of leached water resulting from high pressure may have generated greater momentum transferred from the leaching water to the oil in the pore fluid, which may, in turn, have enhanced the mobility of a larger portion of the oil in the soil pore fluid (Mohamed, 1995).

The leached oil residue from the stabilised layer in this study was slightly lower than that reported by Mohammed (1995) in his study on Bahrain Sabkha soil, although higher percentages of oil were used to stabilise the soil in the present study. The difference in finding may be attributed to the high amount of moisture content in Mohammed's study (section 2.5) that would have led to significant reduction in the retention of hydrocarbon on the surfaces of mineral and organic matter (Pignatetello, 1989). The higher moisture content amount may also have created higher voids and a lower dry density of compacted soils, contributing to an increase in the leached oil residue reported in Mohammed's (1995) study.

It is worth mentioning that although the hydraulic gradient applied in this study's series of tests was very high compared to that expected in the field, the amount of oil in the effluent was very low. In addition, the amount of effluent collected during the test would likely have occurred over longer time in actual field flow conditions.

7.4.2 Waterproofing effect

During geotechnical soil testing explained in chapters 5 and 6, it was observed that oil residue addition prevented a loss in strength upon soaking, since the strength of soaked stabilised Sabkha soils was higher than that of soaked natural soils. It was also observed that the reduction in strength due to soaking decreased with oil addition. This behaviour may be attributed to low dissolution of different types of salts due to oil addition, since oil residue addition was expected to alter the properties of stabilised Sabkha soil by providing a waterproofing effect, occurring from coating of the soil particles or blocking of the pores of the soil mass (Ingles and Metcalf, 1972).

To investigate the waterproofing effect of oil residue on Sabkha soils, the leaching test was carried out on natural and 5% oil (optimum oil content) stabilised Sabkha soil S_{J-4}. Samples of effluents were collected at different pore volumes and subjected to chemical analysis to determine the concentration of main dissolved salts, such as sulphate, calcium, magnesium and sodium. The selection of anions and cations was based on their existence in Sabkha soil revealed in section (3.8.2). Test results of the concentrations of different salts for different pore volumes are presented in Figures 7.3 to 7.9.

7.4.2.1 Natural Sabkha soil

Concentrations of different salts in the effluent of natural Sabkha soil S_{J-4} are presented in Figure 7.3. The figure shows a clear trend of reduction in the concentration of different salts with pore volume. The rate of reduction was expected to depend on the concentration of salts in the soil and types of salt. For example, Mg^{2+} and Ca^{2+} concentration in the first pore volume was the lowest among the different salts while the concentration of Na^{+} and SO_4^{2-} was the highest. However, the rate of reduction of Na^{+} was the highest and Mg^{2+} was the lowest within the leached salts. The variation in concentrations can be attributed to the solubility of salts and their concentration in the Sabkha soil.

Figure 7.3 also indicates a similarity in the behaviour of different salts with pore volume, despite variation in their initial dissolution in the first pore volume. This similarity in leaching behaviours has caused chemical leaching that led to soil particles' rearrangement.

Results in Figure 7.3, show that the concentration of sodium (Na^+) reduced sharply from 9.772 g/l in the first pore volume to 3.308 g/l in the second pore volume. The concentration of Na^+ continued to decrease at a slower rate until 9 pore volumes, where dissolution diminished.

A similar trend but at a lower rate was observed for sulphate and calcium. Sulphate concentration in the collected pore volumes reduced from 3.8 g/l in the first pore volume to 1.9 g/l in the sixth pore volume and almost reached a steady state beyond that pore volume. Chemical analysis and XRD of tested soil samples (Section, 3.8.2), revealed the high content of calcium-based soluble compounds in the parent Sabkha soil, i.e. gypsum, calcium carbonate, and anhydrite, which was reflected in the continuous and almost constant dissolution of calcium (Ca^{2+}) after the first pore volumes. A similar finding was reported by Al-Amoudi and Abduljauwad (1995a) during their investigations on Sabkha soils and was attributed to the calcareous nature of the leached soil samples.

Magnesium dissolution was the lowest concentration in all leached pore volumes and diminished at 9 pore volumes. This reflected the low concentration of magnesium based salts in the original Sabkha soil. Magnesium dissolution followed the same pattern as calcium dissolution.

Dissolution rates depend upon velocity gradient, flow velocity, salinity of water, and temperature (Liu and Nancollas, 1971). Due to continuous dissolution of different types of salts, cracks and cavities formed in the soil sample at the base of the leaching cell as shown in plate 7.3, which may trigger the collapse of light structures without adequate warning (Al-Amoudi and Abduljauwad 1995-a).

7.4.2.2 Stabilised Sabkha soils

The waterproofing effect of oil residue was investigated by comparing the concentration of leached salts for natural and 5% stabilised Sabkha soil S_{J-4}. Effluent measured in pore volumes was collected and subjected to the same chemical analysis as mentioned in the previous section.

The leached concentrations of different salts at different pore volumes are presented in Figures 7.4. The concentration of leached salts Na^+, Mg^{2+}, Ca^{2+} and SO_4^{-2} from stabilised Sabkha is presented individually with that of natural Sabkha in Figures 7.5 to 7.8 respectively, in order to evaluate the effect of oil stabilisation on salts' dissolution.

Results presented in these Figures indicate that the trend of salt dissolution at different pore volumes for stabilised Sabkha is similar to that for natural Sabkha. However, there is a noticeable difference between salt concentrations values, especially at pore volumes of 2 and greater. For example, Figure 7.5 shows that the concentration of sodium (Na^+) in the effluent of the stabilised Sabkha soil is lower than that in the natural. The concentration decreased sharply in the subsequent pore volume, but at different rate, to reach a value of 3.308 g/l at 2 pore volumes for natural soil and 1.915 g/l for stabilised Sabkha soil. The concentration of Na^+ diminished at 6 pore volumes for stabilised Sabkha and at 9 pore volumes for natural Sabkha. The total amount of leached Na^+ from the stabilised soil, represented by the area under the curve, was 40% of the total amount of leached salts from the natural Sabkha, indicating the effect of oil residue in waterproofing particles, including salts in the Sabkha.

The concentration of magnesium salt dissolution in natural and stabilised Sabkha soils is shown in Figure 7.6. A similar trend in concentration reduction rate was noted for magnesium Mg^{2+}dissolution and other ions. The concentration of magnesium in the effluent of natural and stabilised Sabkha at the second pore volume was 0.3 g/l and 0.19 g/l, respectively, and had diminished at the tenth and fifteenth pore volume, respectively.

The concentration of calcium Ca^{2+}, shown in Figure 7.7, followed a similar trend to that of magnesium but at a slower rate, mainly because of its high concentration in the original soil (Al-Amoudi and Abduljauwad, 1994-a). The concentration of calcium in the effluent of stabilised Sabkha at the second pore volume was about 30 % less due to oil addition than in the effluent of the natural.

The concentration of leached sulphate from natural and stabilised Sabkha is shown in Figure 7.8. This Figure shows that the concentration of SO_4^{-2} in effluent of stabilised Sabkha is higher in the first 4 pore volumes. Higher sulphate dissolution may be attributed to the in-homogeneity of the Sabkha, and higher sulphate concentration in the stabilised sample than in the natural sample. In addition, this dissolution may have been due to the low oil residue percentage which only partially covered soil particles. However, with continuous leaching, leached sulphate concentration was 30% lower than that in the natural sample. Sulphate dissolution continued to decrease at a low rate for both natural and stabilised Sabkha.

Salts' total concentration in the effluent of 5% stabilised and natural Sabkha soils are presented in Figure 7.9. The total amount of leached salts, represented by the area under curve, was 56% lower in the stabilised Sabkha soil than in the natural Sabkha. Moreover, there were no apparent cracks or voids in the leached stabilised sample in the leaching cell as shown in Plate 7.3.

Leachate reduction may be attributed to the formation of a film of oil residue on soil particles' surfaces and the oil acting as a waterproofing agent. Waterproofing can be considered one of the main mechanisms in stabilising Sabkha soils. The adsorbed oil residue is expected to act as a coating layer around the surface of particles or aggregated lumps of particles or blocks the pores of the soil mass which reduces moisture susceptibility. A similar conclusion was drawn by Asi et al. (2002) during their investigation into the stabilisation of Sabkha soil by foamed asphalt. Oil is expected to alter both chemical and physical soil properties, aggregating soil particles in plaques, lowering porosity, and increasing resistance to penetration and hydrophobicity (Andrade, et al., 2004). Kaiser et al. (2000) concluded that the hydrophobic compounds adsorbed on the mineral surfaces form an organic coating that changes the affinity of surfaces to water.

The dissolution of different types of salts was not stopped completely, because the optimum stabilisation percentage (5%) may not have been sufficiently high to completely coat the Sabkha soil particles as shown in Plate 7.2. The waterproofing effect is expected to increase with more oil addition, since this mechanism is expected to be more effective with the formation of thicker film. The effect of high oil residue percentage was observed during geotechnical investigation of soaked samples. Variation in unconfined and CBR strength results between soaked and unsoaked samples was minimised with high oil addition which may be attributed to the thicker formed layers around soil particles preventing the water from leaching the cementing agents.

Different field studies in Kuwait have verified that oil contaminated soils are completely hydrophobic, so that water molecules pass through soil channels without being hindered by adsorption on soil particles (Al-Houty et al., 1993; and El-Baz, 1994).

It is worth mentioning that the hydraulic gradient applied during the test was much higher than that expected in the field. It created a higher water flow rate than that expected in the field. The waterproofing effect in the field is expected to be more noticeable due to a lower hydraulic gradient and less leaching effect in arid environments.

It is acknowledged that the adsorptive behaviour of the oil residue on soil particles was not studied in detail. However, from the experimental results it can be postulated that the presence of oil residue may be responsible for limiting contact between soil particles and water molecules, consequently leading to reduced dissolution of salts. A further detailed study of soil-oil residue interactions is therefore warranted.

7.4.3 Coefficient of permeability

A long-term coefficient of permeability test was carried out on natural and stabilised Sabkha soils S_{J-4}, S_{Z-5} and S_{K-7}. Soils were stabilised with the optimum oil content of 5%. The objective of this test was to investigate the effect of long term leaching on the coefficient of permeability of natural and stabilised Sabkha soils.

Calculation of the coefficient of permeability at different pore volumes was used to evaluate the long-term behaviour of the material. Measurement of the time required to collect each pore volume was taken and, consequently, the flow rate was determined at each pore volume. Flow was induced through the specimen by increasing pressure on the inflow reservoir to 7.0 psi. Similar steps previously mentioned in section 3.8.1.6 were followed to obtain the coefficient of permeability at each interval. Test results are presented in Figures 7.10 to 7.12, where the permeability coefficient, *k*, is plotted as a function of leached pore volume.

7.4.3.1 Natural Sabkha soil

Figure 7.10 shows permeability coefficient, *k*, as a function of leached pore volume for natural soil sample S_{J-4}. On leaching with distilled water, the *k* value initially fluctuated and then remained almost constant after leaching of the first few pore volumes. The initial reduction in *k* can be attributed to the presence of air which caused blockage of passage. A significant drop in the *k* value was observed after the fourth pore volume. The permeability reached 4.45×10^{-8} m/sec, which represented a reduction of about 40% from the initial value. This drop may be attributed to dissolution of different types of salts (section 7.4.2.1), which facilitated the movement and redistribution of cemented soil particles and hence clogging the voids and channels between soil grains. After this stage and due to continuous salts' dissolution, the void ratio increased and the interlocking between soil particles softened or decreased. This may have caused a substantial movement and reorientation of particles and translocation of fine particles in the Sabkha soil structure that may have caused permeability values to fluctuate between 9.56×10^{-8} m/sec at 5 pore volumes and 7.175×10^{-8} m/sec at 6 pore volumes. Similar findings were reported by Ismael and Mollah (1998) and Al-Nouri and Saleam (1994) for cemented soils and gypseous sandy soils, respectively.

With continuous leaching and the dissolution of more salts the permeability coefficient started to increase. The measured *k* values were 14.14×10^{-8} m/sec, 15.4×10^{-8} and 21.42×10^{-8} m/sec at 13, 23, and 30 pore volumes, respectively representing a percentage increase of 94%, 112%, and 194%. The passage of distilled water dissolved the salts (Section 7.4.2.1) and created more voids and channels for the flowing water, resulting in an increase in permeability.

At pore volumes above 30, the coefficient of permeability started to stabilise and reached a constant value of about 21.22×10^{-8} m/sec. This may be attributed to a decrease in the rate of salt dissolution. At this stage, the voids ratio of the leached soil was slightly affected and almost reached a constant value, in turn the quantity of flowing water remained constant.

It is worth mentioning that the increase in the permeability coefficient of the tested soil samples occurred in the early period of water percolation through the specimen when the salts were present at full concentration. Figure 7.10 shows that about 10 pore volumes of percolating water were required to significantly increase permeability to about 90% of the initial value. After that, the increase rate was lower compared to the previous rate. This large increase in permeability in the first pore volumes is indicative of high salt dissolution at the beginning.

A close look at salts concentration in the effluent shown in Figure 7.3 indicates that *k* values of natural Sabkha correlate with the amount of leached salts. The sharp dissolution of salts at the initial pore volumes resulted in readjustment of soil particles, which led to a sudden decrease in permeability. With continuous dissolution, more channels were opened and permeability increased (Al-Amodi and Abduljauwad, 1994-a). It can also be observed from Figures 7.6 to 7.8 that the continuous and low dissolution rate of magnesium, calcium and sulphate and sodium salts beyond the 10th pore volume caused the low rate of increase in *k* values.

These findings are similar to these reported by Al-Amoudi (1992) who concluded that higher values of *k* and its increase with test repetition, may be attributed to salt dissolution which causes more channels to form, thus tending to increase permeability. Ismael (1993-a), in a study carried out on salt bearing soil in Kuwait, noted the phenomenon of halite dissolution from Sabkha soil flats. He also reported that permeability increased by 100% over the leaching test period. Similar findings were also recorded by Al-Amoudi and Abduljauwad (1995-a) for Sabkha soil samples from the same region. On the other hand, studies in Kuwait on soils containing low salts' content have found no variation in permeability, which may be attributed to the low salt content in these soils (Al-Sanad and Al-Bader 1990).

7.4.3.2 Stabilised Sabkha soil

Results for 5% oil stabilised Sabkha soils S_{J-4} and S_{K-7} are presented in Figure 7.11. Results for stabilised soil S_{Z-5} are presented in Figure 7.12 due to the high differences between the values and those of other soils.

Figure 7.11, which shows the coefficient of permeability of the stabilised soil as a function of leached pore volume, indicates a similarity in *k* values of soils S_{J-4} and S_{K-7}. This was expected due to the similarity in their composition and gradation.

The initial permeability values of stabilised Sabkha soils S_{J-4}, S_{Z-5}, and S_{K-7} were $1.27\text{x}10^{-8}$, $37.0\text{x}10^{-8}$ and $1.273\ \text{x}10^{-8}$ m/sec, respectively. These values were lower than that of natural Sabkha soil by 82%, 35%, and 31%, for soil samples S_{J-4}, S_{K-7}, and S_{Z-5}, respectively. This decrease may be attributed to the adsorbed oil residue on soil surfaces that may have blocked the soil pores and caused an obstruction to the flow of water in the pores and hence a reduction in *k* values. In addition, the oil residue addition may have enhanced the densification of soil particles (Section 4.4.5) by facilitating the entry and permanence of coated fine particles in the larger pores and channels, thus reducing the porosity and permeability of the soil (Andrade et al.,2004).

Figures 7.11 and 7.12 show the coefficient of permeability of stabilised Sabkha soils decreased sharply after leaching with the first pore volume. It reduced from $1.287\text{x}\ 10^{-8}$ m/sec to $4.501\text{x}\ 10^{-9}$ m/sec for soil S_{J-4} after leaching with two pore volumes, representing a reduction of 65%. Reductions for soil samples S_{K-7} and S_{Z-5} were 50% and 11% for the same pore volume. The sharp reduction in the permeability of stabilised Sabkha soil samples S_{J-4} and S_{K-7} during the first pore volume may be attributed to the dissolution of partially coated salts which liberated part of the oil residue on the dissolved particles. The liberated oil particles, due to the effect of flow pressure, were pushed and then blocked the voids and channels between soil particles, preventing the movement of water particles. On the other hand, the reduction in the permeability value of soil sample S_{Z-5} was at lower rate due to its coarser gradation and larger soil pores.

Measured *k* values after leaching with eight pore volumes were $3.501\text{x}\ 10^{-9}$ m/sec, $3.32\text{x}10^{-9}$ m/sec and $4.154\text{x}\ 10^{-8}$ m/sec, representing a percentage reduction of 72%, 73% and 88% for soils S_{J-4}, S_{K-7} and S_{Z-5}, respectively. The lower reduction rate with continuous leaching is indicative of lower salts' dissolution and a more stable condition. With more leaching (more than 10) the reduction rate in permeability values almost diminished and the coefficient of permeability started to stabilise until it reached constant values of 3.44×10^{-9} m/sec, 2.75×10^{-9} m/sec and 4.3×10^{-8} m/sec, representing a percentage reduction of 73%, 78% and 88% for soils S_{J-4}, S_{K-7} and S_{Z-5}, respectively. This may be attributed to the decrease in dissolution due to waterproofing effect of the oil residue.

A visual inspection of the leached natural and 5% stabilised soil samples, shown in Plate 7.3, revealed small cavities, holes and irregular channel formations at the bottom of the natural leached sample, resulting from the dissolution of different types of salts. A similar observation was noted by Ismael (1993-a), during laboratory leaching tests carried out on a gypsiferous sandy silt soil sample, where the soil fabric appeared honeycombed due to salt dissolution. There was no visible effect of long-term leaching on the stabilised Sabkha soil sample as shown in the same plate.

7.5 Conclusion

Leaching tests in this part of the research programme were intended to provide information on leachability, waterproofing effect and long term permeability of natural and oil residue stabilised Sabkha soils. A leaching test was conducted using distilled water under a hydraulic gradient of 40 on natural and 5% oil stabilised Sabkha soils. The main conclusions drawn from this part of the study are:

- Although a hydraulic gradient of 40 was applied, less than 1 mg/l of oil residue constituents were leached by distilled water for the tested Sabkha soil samples.
- Waterproofing effect of the oil residue at 5% significantly reduced the dissolution of different types of salts to about 56% by weight of the natural.
- Oil residue stabilisation reduced the long term coefficient of permeability of the stabilised Sabkha soils in the range of 73% to 88%, while the long term permeability for the natural Sabkha soil increased up to 194% of the initial value.

7.6 References

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Al-Amoudi, O.S.B., 1992. Studies on Soil-Foundation Interaction in the Sabkha Environment of Saudi Arabia. PhD Thesis, King Fahad University, Dhahran, Saudi Arabia.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1994-a. Modified Odometer for Arid, Saline Soils. *Journal of Geotechnical Engineering-ASCE*, 120(10): 1892-1897.

Al-Amoudi, O.S.B. and Abduljauwad, S.N., 1995-a. Compressibility and Collapse Characteristics of Arid Saline Sabkha Soils. *Engineering Geology*, 39(3-4): 185-202.

Al-Houty, W., Abdal, M. and Zaman, S., 1993. Preliminary Assessment of the Gulf War on Kuwait Desert Ecosystem. *Environmental Science and Health*, A28 (8): 1705-1726.

Al-Nouri, I. and Saleam, S., 1994. Compressibility Characteristics of Gypseous Sandy Soils. *Geotechnical Testing Journal*, 17(4): 465-474.

Al-Rawas, A., Hassan, H. F., Taha, R., Hago, A., Al-Shandoudi, B. and Al-Suleimani, Y., 2005. Stabilisation of Oil-Contaminated Soils Using Cement and Cement By-Pass Dusts. *Management of Environmental Quality*, 16(6): 670-680.

Al-Sanad, H.A. and Al-Bader, B., 1990. Laboratory Study on Leaching of Calcareous Soil from Kuwait. *Journal of Geotechnical Engineering-ASCE*, 116(12): 1797-1809.

Al-Sanad, H.A., Eid, W.K. and Ismael, N.F., 1995. Geotechnical Properties of Oil - Contaminated Kuwaiti Sand. *Journal of Geotechnical Engineering-ASCE*, 121(5): 407-412.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North-Western Spain). *Journal of Environmental Quality*, 33: 2103-2110.

Asi, I.M., Wahhab, H.I.A.A., Al- Amoudi, O.S.B., Khan, M.I. and Siddiqi, Z., 2002. Stabilisation of Dune Sand using Foamed Asphalt. *Geotechnical Testing Journal*, 25(2): 168-176.

Dror, I., Gerstel, Z., Prost, R. and Yaron, B., 2002. Abiotic Behavior of Entrapped Petroleum Products in the Subsurface During Leaching. *Chemosphere*, 49(10): 1375-1388.

El-Baz, F., 1994. Remote-Sensing. *GeoTimes*, 39(2): 25-25.

Fine, P., Graber, E.R. and Yaron, B., 1997. Soil Interactions with Petroleum Hydrocarbons: Abiotic processes. *Soil Technology*, 10(2): 133-153.

Gerstel, Z., Galin, T. and Yaron, B., 1994. Mass Flow of a Volatile Organic Liquid Mixture (VOLM) in Soils. *J. Environ. Qual.*, 23: 487-493.

Hirner, A.V., Pestke, F.M., Busche, U. and Eckelhoff, A., 1998. Testing Contaminant Mobility in Soils and Waste Materials. *Journal of Geotechnical Exp*, 64: 127-132.

HMSO, 1980. Emission Spectrophotometric Multielement Methods of Analysis for Waters, Sediments and other Materials of Interest to Water Industry. ISBN No. 0117500151, Environment Department, London.

Ingles, O.G. and Metcalf, J.B., 1972. Soil Stabilisation: Principles and Practice. Butterworth's & Co. Ltd., Melbourne, Australia.

Ismael, N.F., 1993-a. Laboratory and Field Leaching Tests on Coastal Salt-Bearing Soils. *Journal of Geotechnical Engineering-ASCE*, 119(3): 453-470.

Ismael, N.F. and Mollah, M.A., 1998. Leaching Effects on Properties of Cemented Sands in Kuwait. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10): 997-1004.

Kaisar, K., Haumaier, L. and Zeck, W., 2000. The Sorption of Organic Matter in Soils as Affected by the Nature of Soil Carbon. *Soil Science*, 165(277-304).

Kuwait Petroleum International Q_8, 2004. Product Safety Data Sheet- Atmospheric Bottom, Kuwait Petroleum Research and Technology B.V., Rotterdam, Netherlands.

Kuyukina, M., Ivshina, I. B., Makarov, S. O., Litvinenko, L. V., Cunningham, C. J., Philip, J. C., 2005. Effect of Bio-Surfactants on Crude Oil Desorption and Mobilisation in a Soil System. *Environment International*, 31: 155-161.

Liu, S.T. and Nancollas, G.H., 1971. The Kinetics of Dissolution of Calcium Sulphate Dihydrite. Journal of the Inorg. *Nuclear Chemistry*, 33: 2311-2316.

McCallister, L.D. and Perty, T.M., 1992. Leach Test on Lime-Treated Clays. *Geotechnical Testing Journal, ASTM,* 15(2): 106-114.

Madsen, L., Grahl, M. L., Gron, C., Lind, I. and Engell, J., 1996. Adsorption of Polar Aromatic Hydrocarbons on Synthetic Calcite. *Organic Geochemistry*, 24(12): 1151-1155.

Meegoda, N.J. and Ratnaweera, P., 1995. Treatment of Oil-Contaminated Soils for Identification and Classification. *Geotechnical Testing Journal*, 18(1): 41-49.

Mohammed, A.O.M., Yong, R.N., Tan, B.K., Farkas, A. and Curtis, L.W., 1994. Geoenvironmental Assessment of a Micaceous Soil for its Potential Use as an Engineering Clay Barrier. *Geotechnical Testing Journal*, 17(3): pp.291-304.

Mohammed, L.F., 1995. Assessment of Saline Soil Stabilisation via Oil Residue and its Geo-Environmental Implications. PhD Thesis, McGill University, Montreal, Canada.

Pignatello, J.J., 1989. Sorption Dynamics of Organic Compounds in Soils and Sediments. In: Reaction and Movement of Organic Chemicals in Soils. SSSA, Madison, I, pp.45-80.

Roy, J.W., Smith, j.E. and Gillham, R.W., 2002. Natural Remobilisation of Multicomponent DNAPL Pools Due to Dissolution. *Journal of Cont. Hydrol.*, 59: 163-186.

Yong, R.N., Yaacob, W.Z.W., Bentley, S.P., Harris, C. and Tan, B.K., 2001. Partitioning of Heavy Metals on Soil Samples from Column Tests. *Engineering Geology*, 60: 307-322.

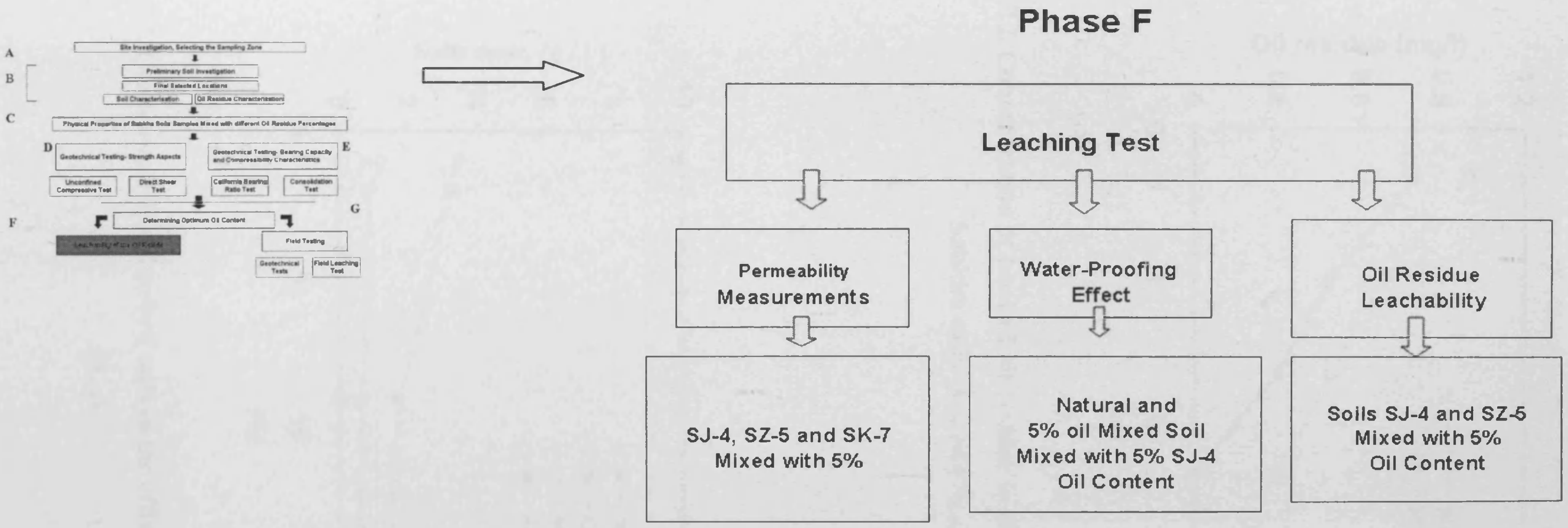

Figure 7.1. Phase F of the experimental programme

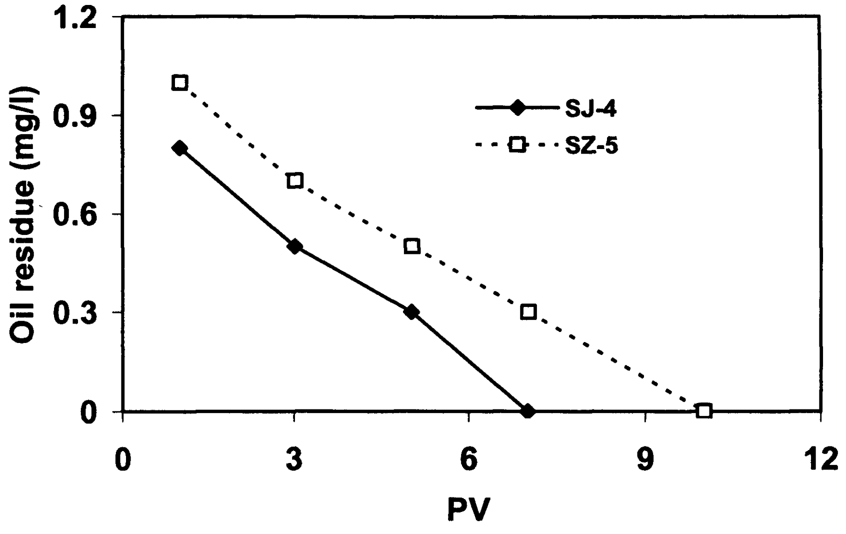

Figure 7.2. Concentration of leached oil residue in the effluent of 5% stabilised Sabkha soils ($S_{J\text{-}4}$ and $S_{Z\text{-}5}$)

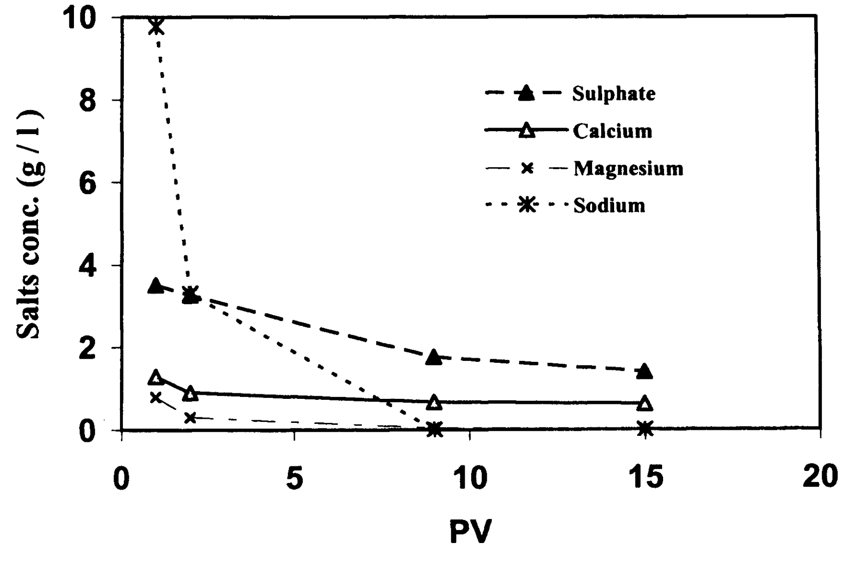

Figure 7.3. Concentration of leached salts in the effluent of natural Sabkha soil ($S_{J\text{-}4}$)

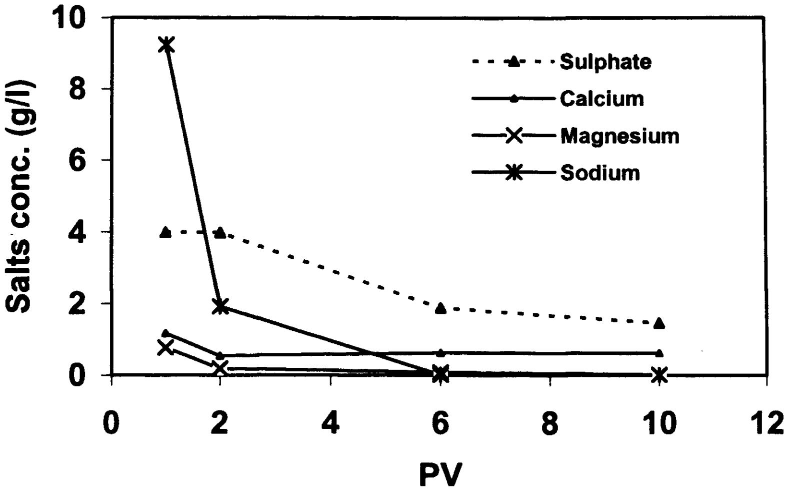

Figure 7.4. Concentration of leached salts in the effluent of 5% stabilised Sabkha soil (S_{J-4})

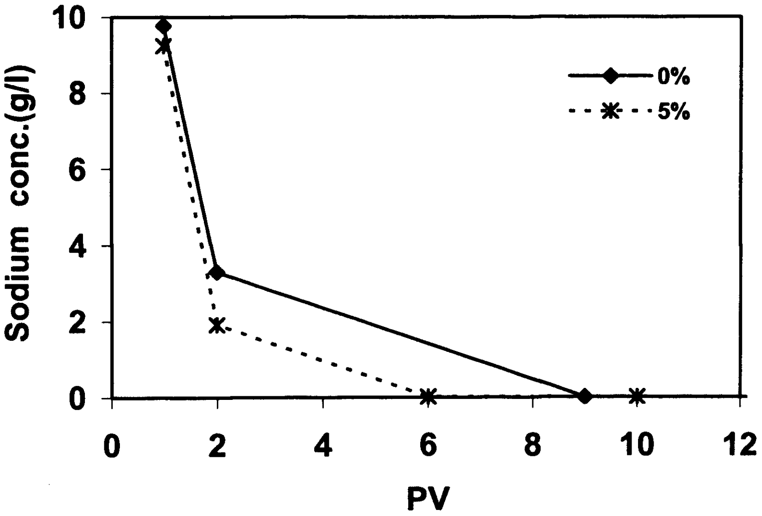

Figure 7.5. Concentration of leached Sodium at different pore volumes for natural and 5% stabilised Sabkha soils (S_{J-4})

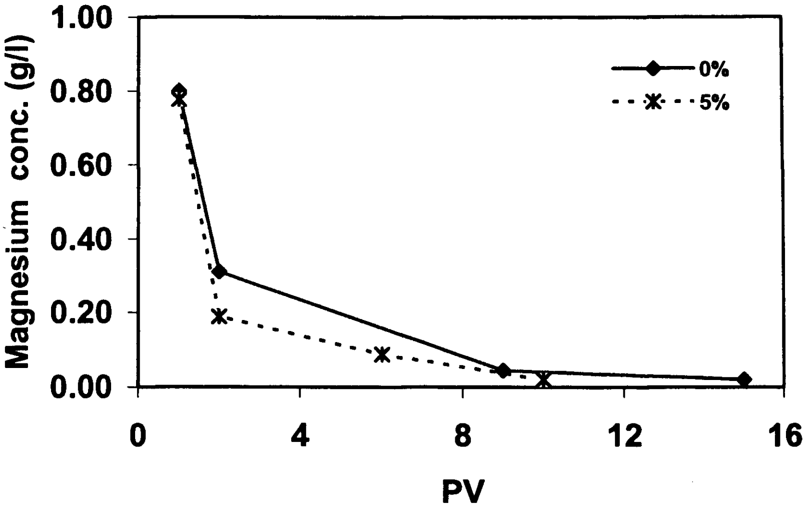

Figure 7.6. Concentration of leached magnesium at different pore volumes for natural and 5% stabilised Sabkha soils (S_{J-4})

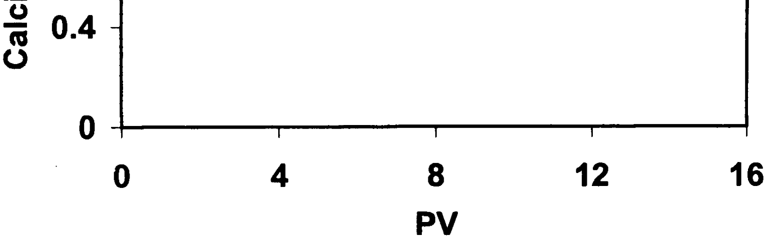

Figure 7.7. Concentration of leached Calcium at different pore volumes for natural and 5% stabilised Sabkha soils (S_{J-4})

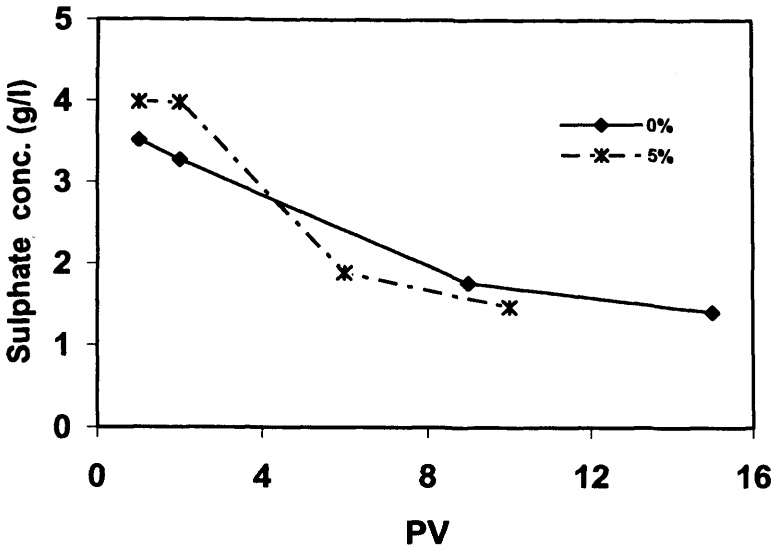

Figure 7.8. Concentration of leached Sulphate at different pore volumes for natural and 5% stabilised Sabkha soils (S_{J-4})

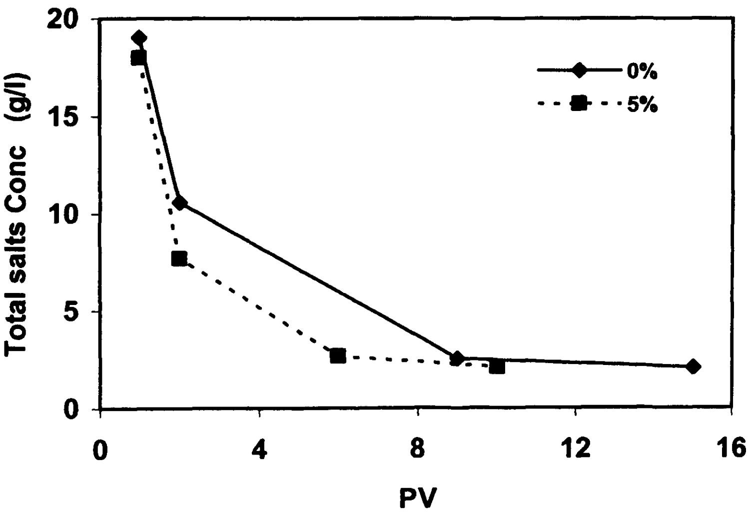

Figure 7.9. Concentration of total leached salts at different pore volumes for natural and 5% stabilised Sabkha soils (Soil S_{J-4})

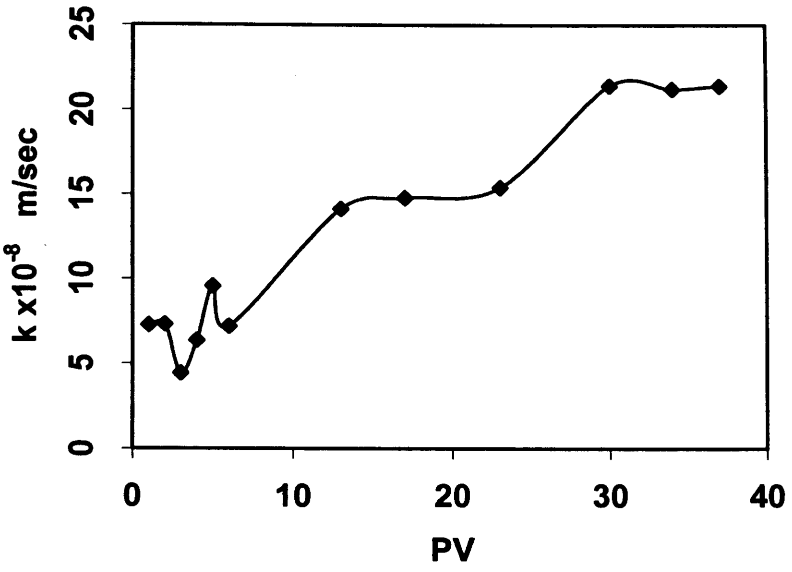

Figure 7.10. Variation of the coefficient of permeability with leached pore volumes for natural Sabkha soils (S_{J-4})

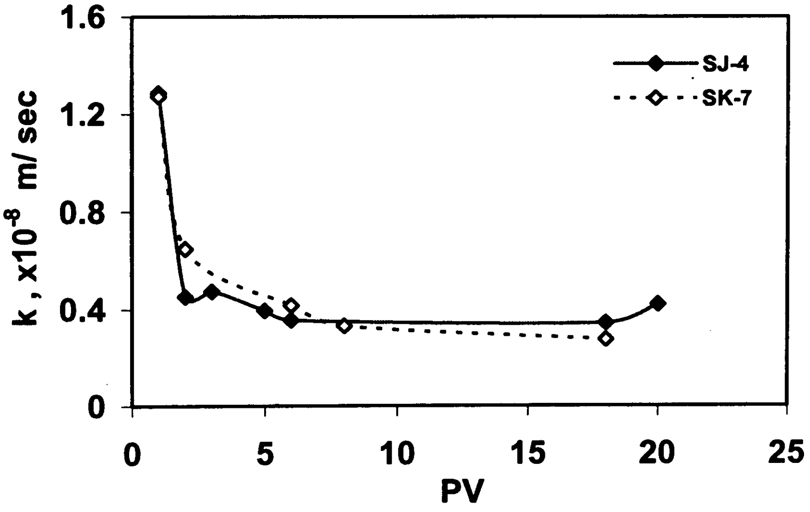

Figure 7.11. Variation of the coefficient of permeability with leached pore volumes for 5% stabilised Sabkha soils (S_{J-4} and S_{K-7})

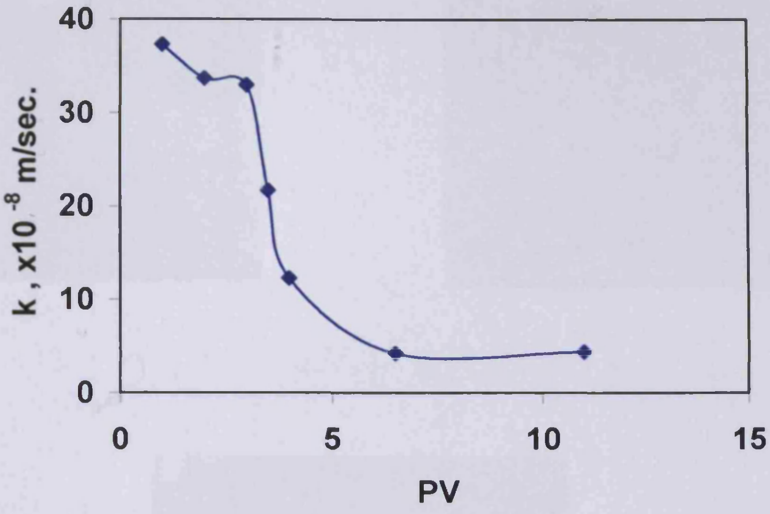

Figure 7.12. Variation of the coefficient of permeability with leached pore volumes for 5% stabilised Sabkha soil (S_{Z-5})

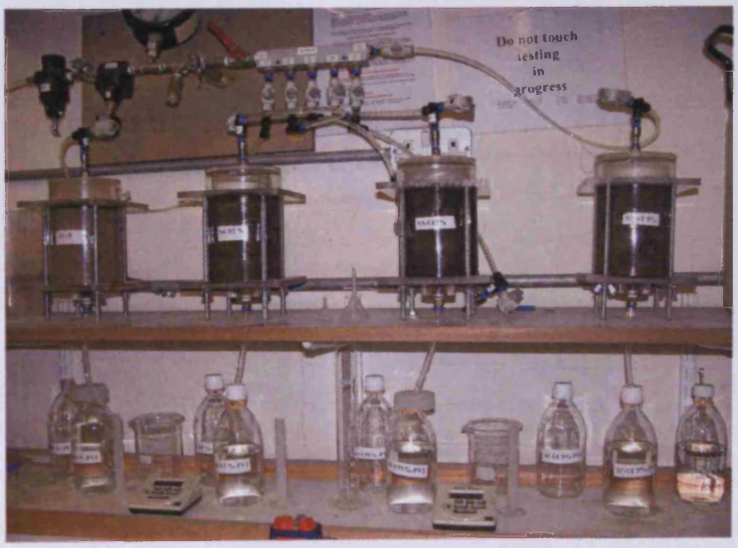

Plate 7.1. Leaching cells' apparatus

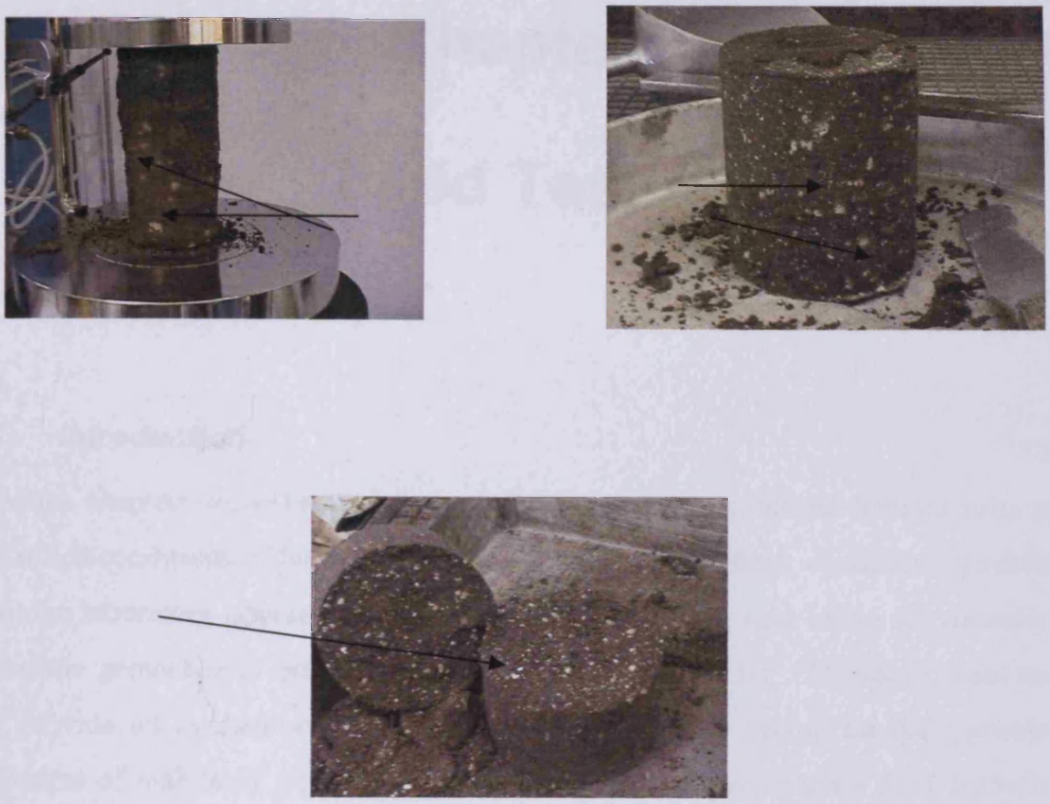

Plate 7.2. Partially coated salts in 5% stabilised Sabkha soil samples

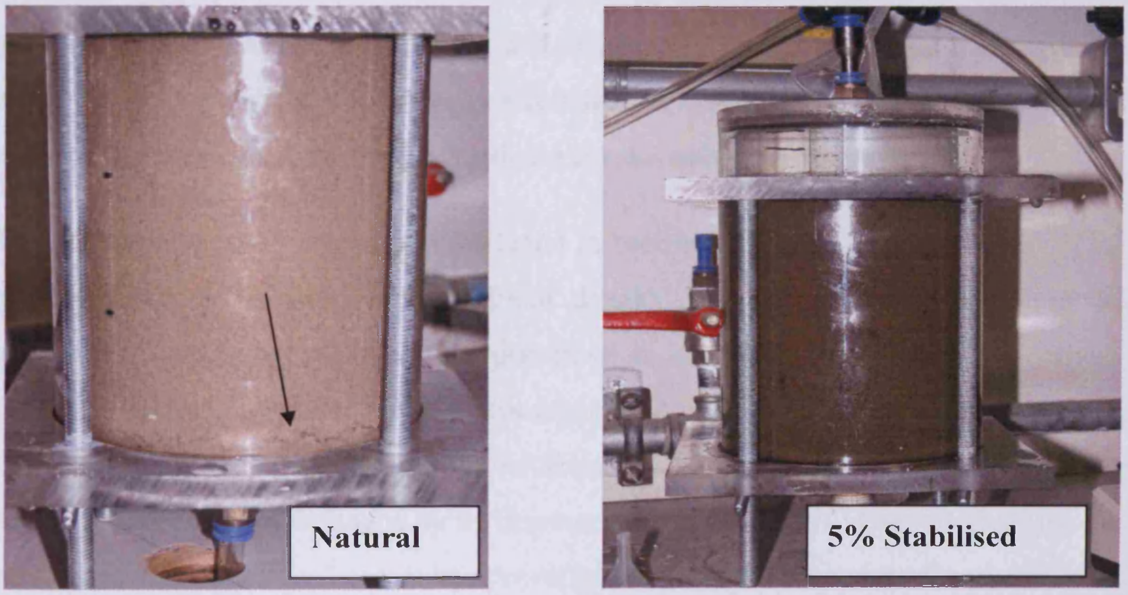

Plate 7.3. Natural and stabilised Sabkha soils after leaching with 20 pore volumes

Chapter 8

Field Testing

8.1 Introduction

Previous chapters have presented the behaviour of the stabilised Sabkha soils under controlled conditions of humidity and temperature. In the field, conditions are different from the laboratory conditions. Climate and other factors may affect oil viscosity and hence the geotechnical behaviour of stabilised Sabkha soils. Therefore, field testing can provide an evaluation of the effect of weather and ageing on the geotechnical properties of stabilised Sabkha soils. However such a small scale field study is not expected to provide complete knowledge of the behaviour of the stabilised Sabkha soil samples under different field conditions. The impact of many individual factors on stabilised Sabkha soil behaviour in the field is beyond the scope of this research programme due to limitations of time and resources. This chapter will investigate the effect of field conditions on the geotechnical properties of stabilised Sabkha soil samples and the leachability of oil residue from the stabilised soil layer.

The experimental programme is introduced in section 8.2 while the preparation of test beds is described in section 8.3. Field density and unconfined compression test procedures, results and analysis are presented in sections 8.4 and 8.5, respectively. Direct shear test and CBR testing procedures, results and analysis are described in sections 8.6 and 8.7, respectively. Consolidation results and analysis follow in section 8.8, while oil residue leachability is discussed in section 8.9. Overall findings and conclusion and a list of references are provided in sections 8.10 and 8.11, respectively.

8.2 Experimental programme

This part of the work covered phase G of the experimental programme, as shown in Figure 8.1. A series of in-situ and laboratory tests were carried out as part of the field testing on samples taken from stabilised and aged layers of soil depending on the test. The testing programme consisted of geotechnical and leachability tests and included:

  - In situ dry density test.
  - Unconfined compression test.
  - Direct shear test.
  - California Bearing Ratio test.
  - Consolidation test.
  - Leaching test.

8.3 Preparation of field soil test beds

The field study area was located in south Kuwait. The site was flat, open and free of overhead obstructions as shown in Plate 8.1. This area was selected due to the following main considerations:

- Representative of Kuwaiti conditions.
- Required approval to fence the area for the duration of field testing (more than one year) was relatively easy to obtain.
- Proximity to the laboratory location:
  - Soil mixing was to be undertaken in the laboratory and mixed material to be transported to the field. Proximity to the laboratory reduced transportation time.
  - Soil specimen disturbance minimised for those samples to be tested in the laboratory due to shorter travel distance.
  - Ease of transporting heavy laboratory equipment.

Due to time and resources constraints, a soil sample from one location was selected for the field test. Sabkha soil $S_{J\text{-}4}$ was used as backfilling material in the field. This soil was selected for the following reasons:

- Chemical composition: results of the chemical analysis presented in chapter 3, revealed that Sabkha soils $S_{4\text{-}J}$ and $S_{K\text{-}7}$ contain higher amounts of salts than other Sabkha soils.
- Field conditions: after detailed soil sampling had been carried out in the first stages, most locations became inundated with heavy rains. The location of Sabkha soil $S_{J\text{-}4}$ was the only area accessible during the time of field testing due to the inundation of other areas with heavy rains. It was possible to collect the required quantities from the location of soil sample $S_{J\text{-}4}$, before the area was affected by the same heavy rains.

Dealing with a large amount of soil and the need to mix different materials required quality control to achieve identical mixing and compaction processes. To carry out the work efficiently, the following steps were taken:

- The work was executed for each pit on a separate day.
- Each mix for each pit was divided into seven different soil mixes.
- The seven mixes were carried out simultaneously by different labourers and in the same place to enable supervision of the work steps.
- Fieldwork tasks including site preparation, mixture spreading, compaction and final levelling were assigned to different labourers.

Five pits of 1.5m x 0.75m x 0.20 m were excavated manually in the selected location. Excavated materials were removed and the excavated pits were levelled, compacted and prepared for the new backfilling materials (Plate 8.1). The required amount of Sabkha soil sample $S_{J\text{-}4}$ was prepared for use in field-testing. The estimated weight of soil needed to fill each pit was about 420 kg.

Each soil patch was air dried and sieved separately in the laboratory. Oil residue needed to stabilise each soil patch was 21 kg, which represent 5% by weight of dry soil.

To prepare a homogeneous soil patch and to minimise difficulties dealing with a large soil amount, each patch was further divided into 7 small patches, making a total of 35, each weighing about 60 kg and mixed with about 3 kg of oil residue. These 7 small patches were mixed individually and simultaneously by two labourers assigned to each patch, making a total of 14 labourers (Plate 8.2). The same mixing methods were followed to obtain a homogeneous mixture. The mixing process was first carried out manually and then an automatic mixer was used to mix it more thoroughly for three minutes. An optimum amount of water equal to the optimum moisture content was added to the 7 patches, and the mixture was then well mixed for another two minutes in the automatic mixer. Optimum moisture content and maximum dry density for 5% oil mixed Sabkha were obtained from laboratory testing detailed in section 4.4.5. The 7 small patches for each pit were mixed together for a few minutes to obtain one uniform mix. Each prepared soil mixture was kept in plastic containers and transferred to the excavated pit.

The mixtures were kept in closed plastic containers to prevent loss of moisture. Each excavated pit was in turn wetted with water so that it did not adsorb the moisture of the mixture. The stabilised soil was spread out uniformly in layers, levelled manually and compacted using a hand operated vibrating plate as shown in Plate 8.3.

After compaction, four of the compacted pits were loaded immediately with concrete blocks representing a load of 420 kg (Plate 8.4). The fifth pit was left without loading and surrounded with concrete blocks (Plate 8.5), and was watered with distilled water at different time intervals in addition to the heavy rainfall in winter. The watering of the fifth pit followed no specific pattern since it was intended to simulate the worst weather conditions.

All compacted pits were surrounded with clear signs and information plates. Their selected location, in a secure area belonging to the Ministry of Defence in Kuwait, minimised the possibility of them being touched or disturbed. Field-testing took place in May 2005, 14 months after preparation. Testing duration was about 5 weeks and completed in June 2005. To prepare field testing, the concrete blocks on the compacted beds were cleared of. The surfaces of these beds were cleared from accumulated fine blown sands as shown in Plate 8.6.

8.4 Field density

8.4.1 Procedures

The dry density of compacted soil is used as a measure for the degree of compaction of the soil. Field dry density for the compacted bed was obtained using the sand cone method described in BS1377 (1990). A hole was excavated in the compacted soil layer, and excavated materials were carefully collected and weighed directly to reduce the possibility of moisture loss due to evaporation. The cone test method was used to measure the volume of excavated materials as shown in Plate 8.7. The water content of the excavated soil materials was determined in the laboratory, ensuring that the oven temperature did not exceed 60°C for three days. Dry density for the compacted soil layer was calculated from the volume and moisture measurement.

8.4.2 Results and discussion

To evaluate the effect of field conditions, results are compared with those of laboratory testing. In the discussion, field samples are designated as (F), while laboratory samples are designated as (L). Field compacted beds as shown in Plate 8.6 exhibited very dense and compacted dark layers. Slight hammering was needed to remove soil aggregations at edges of test beds, indicating stiff cemented stabilised soil formations.

Field densities for two stabilised soil samples in the test beds were found to be 1.885 g/cm^3 and 1.925 g/cm^3. The maximum dry density of the modified proctor test in the laboratory was 2.005g/cm^3 (section 4.4.5). The field density values represented 94% to 96% of the maximum dry density of the modified Proctor test measured in the laboratory. Results revealed the effect of oil residue addition for maintaining the level of soil compactness in compacted oil mixed soil beds, even with ageing effect and harsh environmental conditions. In contrast, the surface running water due to rainfall caused erosion to the natural soil around the test beds.

The adsorbed oil residue on the soil particles reduced the soil friction and facilitated the sliding of soil particles over each other. Better compaction characteristics were achieved with oil addition as was shown in section 4.4.5 due to the lubrication effect of the oil. In addition, the adsorbed hydrophobic oil residue on soil surfaces increased the hydrophobicity of the stabilised soil (Al-Sarawi et al., 1998; and Andrade et al., 2004), which added a waterproofing effect to the compacted soil. This property minimised the dissolution of salts (Ingles and Metcalf, 1972) in compacted stabilised Sabkha soils under an inundation effect during the rainy season, and maintained the tight structure of the compacted bed. It was also expected that the longer contact time increased the bonding mechanism and the waterproofing effect due to slow diffusion (Bayard et al., 2000).

Field density results were in good agreement with Al-Sarawi et al. (1998), who found that contaminated soils in Kuwait exhibited high bulk density, an indication of the tightness of soil particles. Similarly, Andrade at al. (2004) observed that contaminated soil with oil exhibited a dark compacted crust with significantly lower porosity and greater resistance to penetration.

8.5 Unconfined compression test

8.5.1 Sample preparation

Soil sampling for the unconfined compression test was carried out by inserting a 38 mm internal diameter tube of 230 mm length into the soil bed with the sharp cutting edge towards the soil layer. The tube containing the soil sample was placed in a plastic container to minimise moisture loss and transported to the laboratory. Steps followed for extracting and testing the soil sample were as those described in section 5.3.1.

8.5.2 Results and discussion

Stress-strain relationships for field and laboratory 5% stabilised Sabkha soil samples, which represent the applied compressive stress versus the axial strain, are presented in Figure 8.2. The stress/strain curve for the laboratory sample was flatter than that of field sample. This is an indication of larger strain of the laboratory sample than the field sample at the same loading. As an example, at an applied stress of 20 kPa, the recorded strains were 0.25% and 2% for field and laboratory samples, respectively. The Figure also shows that the stress-strain curves for field and the laboratory samples exhibited peaks corresponding to recorded strains of 2.7% and 5%, respectively. Peak compressive strength in the stress-strain curve was considered the unconfined compressive strength (*UCS*) of tested soil samples. As shown in the Figure, the field sample failed at an axial stress of 83.5kPa and the laboratory sample failed at an axial stress of 81.4kPa. Results revealed that the field soils samples exhibited slightly higher stress at lower strain than the laboratory samples.

The higher stress-strain curve for the field sample may be attributed to the higher bonding strength in this sample than the laboratory sample. Two major factors affected the field sample, namely, higher temperature and ageing effect. Due to the high temperature in the field, the reduction in the oil viscosity may have enhanced oil residue cover over more of the surface of the sand particles, thus increasing the area of contact and, in turn, the cohesion (Aiban, 1998). The temperature and ageing effect may also have affected the oil residue adsorption on the soil surfaces, which enhanced the long term performance of the stabilised soil samples. In addition, the long term effect reduced the ductility of the stabilised specimen compared to the laboratory sample.

It can be observed from Plates 8.8 and 8.9 that a brittle type failure occurred among the field samples and, as observed, the tested field samples failed on an inclined plane and a network of cracks appeared on the cylindrical samples. This type of failure pointed to strong bonding between soil grains. The flatter stress-strain curve for tested laboratory samples may be attributed to the viscous oil residue layer between soil particles, which increased the cohesion between the soil particles and this was clearly apparent in the bulging mode failure as shown in Plate 8.9. A close look at the soil specimen textures shown in Plates 8.8 reveals the long term effect on these specimens. The physical appearance of the tested soil samples, including texture, colour and odour, revealed their viscous property. The salty and dry texture of field samples indicated that long term slow diffusion had occurred.

8.6 Direct shear test

8.6.1 Samples' preparation

Direct shear test specimens were obtained using a galvanised steel mould of 60mm x 60mm internal dimensions, 3mm thick, and 20mm high. The internal surface of the mould was oiled before sampling to reduce friction between the mould and the soil. The sampler was placed on the top of a soil bed and pressed into the soil. The specimen was obtained from the central part by pushing the mould slowly, steadily and vertically using a cutter holder and trimming the surplus soil by hand from the front of the sharp edge of the sampler during the depression process. The soil was excavated around the steel mould and was manually retrieved. The top and bottom faces of the specimen were levelled using a sharp blade and a flat glass plate.

The sampler was removed carefully, and was fixed in the direct shear box to prevent sample slippage. The direct shear box was kept in a plastic container to minimise evaporation and was transported carefully to the laboratory to minimise sample disturbance (Plate 8.10). In the laboratory, a direct shear test was carried out immediately following the same steps explained previously in section 5.4.1.

8.6.2 Results and discussion

The shear stress-horizontal displacement curves for the 5% oil stabilised field and laboratory samples at vertical stresses of 50, 100 and 150 kPa are shown in Figure 8.3. This Figure shows that the pre-failure portion of the shear stress versus the horizontal displacement curve for laboratory samples differs from field samples. The resulting peak shear stresses for field samples at normal stresses of 50, 100 and 150 kPa were 50kPa, 123kPa and 155kPa, respectively. On the other hand, the resulting peak shear stresses for laboratory samples at normal stresses of 50, 100 and 150 kPa were 70kPa, 115kPa and 150kPa, respectively. It is clear that there is no general trend between the field and laboratory samples since shear stresses for oil mixed field samples are slightly higher or lower than the shear stresses of oil mixed laboratory soils. One interesting aspect of these curves is that the displacement required to mobilise the peak shear stresses for field soils is higher than that for laboratory samples at the same normal stresses.

Figure 8.4 shows the relationship between maximum shear stresses and corresponding vertical stresses for laboratory and field samples, respectively. The inclination of the failure envelope represents the internal angle of friction, φ_f, while the intersection of that line with the y-axis represents the cohesion intercept, C. The Figure indicates that the failure envelope for laboratory samples is flatter than the field sample envelope, indicating a lower friction angle and a higher cohesion intercept. The internal angles of frictions were 43° and 41° and cohesion intercept values were 20 kPa and 32 kPa for field and laboratory samples, respectively.

It was generally expected that the friction angle for the stabilised field samples would be higher than that for the laboratory samples due to the reduction in the viscosity of the oil layer. High field temperature as mentioned in the previous section facilitated the distribution of oil residue and the long-term adsorption both increased the soil bonding and consequently reduced the thickness of the oil layer between soil particles. The increased contact between soil particles and their roughness resulted in an increase in the internal angle of friction.

Results are in good agreement with Al-Sanad and Ismael (1997) who investigated ageing effect on oil contaminated sand in Kuwait. They noted an increase in shear strength of 17% due to ageing effect of contaminated sand immediately. They attributed this increase to the evaporation of volatile compounds. Test results suggest that the ageing effect and field environmental conditions decreased the cohesion of stabilised Sabkha soil, possibly due to the reduction in oil residue viscosity attributed to the long-term performance of the soil-mixtures and also to the slow diffusion as previously mentioned in section (8.5).

8.7 California Bearing Ratio test

8.7.1 Procedures

A sample of the stabilised soil was excavated from test beds and transported in a plastic container to the laboratory. Thirty kilograms of stabilised soil were oven dried at 60°C for three days. The stabilised soil was mixed at optimum moisture content and used in preparing 3 specimens for the CBR test. The three specimens were compacted so that their densities ranged from 87% to 97% of the maximum dry density of the modified Proctor test. CBR tests were carried out using the procedure explained in section 6.3.1. The CBR value that corresponded to the average density of the stabilised soil in the field was obtained from the dry density-CBR relationship plotted from test results for stabilised Sabkha soil samples.

8.7.2 Results and discussion

Results of the CBR test for field trial soil samples at dry and soaked conditions are presented in Figures 8.5 and 8.6. In Figure 8.5, the value of the load (kN) is plotted against the corresponding plunger penetration (mm). It can be observed from the Figure that the inclinations of the load-penetration curve for the laboratory sample are flatter than field samples tested at dry condition. The field samples showed higher rigidity and resistance to load penetration since higher load was required to reach the same penetrations reached by the laboratory samples.

Load-penetration curves for soaked field and laboratory samples are shown in Figure 8.5. This Figure shows that the load-penetration curves for soaked laboratory soil samples are in the lower part of the figure, indicating more penetration with an applied lower load. On the other hand, the load-penetration curve for soaked field sample was located over that for dry laboratory sample, indicating higher penetration resistance. Soaking effect increased the penetration of the two samples at different rates. However, the soaked field sample showed higher rigidity than the dry laboratory sample.

CBR values for different relative compaction for tested field and laboratory soil samples are shown in Figure 8.6. The relative compaction is the ratio of the maximum dry density of field soils to the maximum dry density of the modified proctor test measured in the laboratory. It should be remembered that the field density results obtained in section 8.4 were found to be 94% to 96% of the maximum dry density of the modified Proctor test measured in the laboratory. It can be observed from the figure that the CBR value for the field samples was higher at the three compaction efforts than the CBR value of laboratory soil samples. At relative compaction of 97%, CBR value was 42 for the field soils tested at dry conditions. The CBR value of the field samples was higher by 25% than that of the laboratory samples. The CBR value of soaked field samples was 39, which was higher than the CBR of the dry laboratory samples by 14%.

In chapter 6, Sabkha soil showed a decrease in dry CBR values with oil addition up to 5%. This was attributed to the lubrication effect of the oil residue. The CBR value for oil mixed Sabkha reduced from 42 for the natural soil to 39 for the 5% oil mixed Sabkha. The reduction in the CBR value due to 5% oil addition for the field sample was 8%, while for the laboratory sample the reduction was 16.6%.

CBR results shown in Figure 8.6 reveal clearly the higher CBR values for field specimens at both conditions for all compaction efforts. The higher CBR values for the field samples may be attributed to the reduction in the viscosity of the oil residue at high temperature which enhanced the distribution of oil residue uniformly around the soil particles (section 8.5.2). In addition, the slow diffusion (Bayard et al., 2000) reduced the thickness of the oil residue layer around the soil particles which, in turn, reduced the lubrication effect of this layer and increased the soil bonding, consequently increasing the CBR value of the soil that increased the waterproofing effect and reduced the salt dissolution of field samples.

These results are in good agreement with results of soil testing reported by Al-Sanad and Ismael (1997), which indicated an increased strength and stiffness due to ageing of oil contaminated soil.

8.8 Consolidation test

8.8.1 Procedures

Similar steps that were employed in section 8.6.1 were followed to prepare the soil specimens for the consolidation test using a galvanised steel ring, 70 mm in diameter and 20 mm in thickness. Test procedures were similar to those previously mentioned in section 6.4.1.

8.8.2 Results and discussion

A consolidation test for the field soil sample was undertaken to evaluate temperature and ageing effect on the compressibility index of stabilised Sabkha soils. The effect will be discussed in terms of void ratio variation, yield stress, compression index, and swelling index.

The void ratio – applied vertical pressure (e-log p) curves of field and laboratory Sabkha soil samples are shown in Figure 8.7. The Figure reveals that field samples have a slightly higher void ratio at the initial stages than the laboratory samples which may be attributed to soil disturbance during specimen extraction. The sampling process may have affected the compactness of the extracted soil samples.

The yield stress values for field and laboratory specimens, which were determined following similar method mentioned in section 6.4.1.2.2, were 110 and 95 kN/m^2, respectively. Higher yield stress value for the field sample than laboratory sample was expected based on previous density and CBR results presented in this chapter.

The compression index, C_c, is an indication of compressibility characteristics. The compression index for both tested samples was determined from the void ratio variation with vertical pressure (e-log p) relationship shown in Figure 8.7. The compression index C_c was 0.041 and 0.044, for field and laboratory samples, respectively. The compressibility characteristic of the field soil is slightly lower than that of the laboratory soil. The lower compressibility of the field sample was expected and attributed to the increase in the bonding of soil particles due to the ageing effect, as explained in sections (8.7).

The swelling index C_s calculated using the void ratio variation with vertical pressure (e-log p) relationship shown in Figure 8.7 was 0.003 and 0.007 for field and laboratory samples, respectively. The lower swelling index for the field soil can be attributed to the higher soil bonding and hydrophobic characteristics of stabilised Sabkha soil due to the ageing effect (Kaisar et al., 2000). In addition, the reduction in oil residue viscosity influenced the compressibility characteristics of the oil mixed soil (Meegoda and Ratnaweera, 1994).

In general, it can be stated that geotechnical properties of oil mixed Sabkha soil were modified due to field conditions. The high field temperature and ageing effect enhanced the sorption of oil residue to the soil matrix, which decreased the thickness of the oil layer around soil particles (Schlebaum et al., 1998; and Trindade et al., 2004). The reduction in the oil layer thickness contributed to an increase in the frictional component of strength. This increase in shear strength is manifested in tested soil samples' stiffness.

8.9 Leachability investigation

8.9.1 Procedures

To provide sufficient information about oil residue release or migration to the underlying layer and to compare it with laboratory scale leaching column tests, two cores were sampled from the test pits as shown in Plate 8.11. It should be explained that one of the cores was taken from the exposed test bed and the other from the loaded test bed. The cores were taken through the stabilisation layer well into the underlying soil using road core drilling equipment type KGB 290. The sample cores were capped and transferred to the laboratory. In the laboratory, the cores were separated carefully between the stabilised layer and underlying soil. The underlying soil was sliced into different layers for chemical analysis. Concentrations of total hydrocarbons were analysed using the Soxhlet Extraction test.

8.9.2 Results and discussion

The cored depth taken below the stabilised layer was divided into 6 sections of 10 cm height. Each section was kept in a plastic container and sent to the laboratory for chemical analysis. Analysis of the top layer of each section was carried out first. Oil residue constituents were not detected in the top sections of the two cores. Chemical analysis was not conducted for the lower sections since oil concentration was not detected in the top layers. It should be mentioned here that the stabilised soil bed was subjected to more severe conditions than would probably be faced in actual usage. These conditions were as follows:

- The test beds were backfilled and placed on the ground surface, where temperature and moisture vary widely on the same day and during different seasons.
- Bed (No. #5) was loosely compacted to increase permeability, left exposed to the harsh environment and to the surface running water, whereas in expected usage it would be covered by road pavements.
- The test bed was irrigated with distilled water at different time intervals in addition to heavy rainfall in winter.

Field test results were in good agreement with the laboratory results in that the leachability of oil residues was very small.

The very low quantity of leached oil residue from the stabilised soil layer in the field may be attributed to the reasons presented and discussed in the laboratory leaching test. Moreover, the high temperature in the field during summer time and ageing of the soil enhanced sorption of the oil residue to the soil matrix and reduced the facility of its removal (Trindade et al., 2004). It should be borne in mind that the low amount, the high atomic weight, the low volatility and very low solubility of oil residue was expected to reduce its leachability.

The possibility of any leached quantity of oil residue from the stabilised soil layer migrating to the water table was very small for the following reasons:

- Low quantity of the leached oil residue.
- Due to the effect of high temperatures and low rainfall, evaporation potential in Kuwait is extremely high and exceeds precipitation by a ratio of 30:1 (Al-Kulaib, 1984). This would minimise the possibility of oil residue migration from the stabilised layer to ground water.
- At depths below 7 metres the surface soil layer in Kuwait consists of more competent calcareous, silty, fine to medium sand with varying degrees of cementation called locally Gatch (Al-Sulaimi et al., 1990; Ismael and Jeragh, 1986). This hard massive calcite (CaCO3) subsoil layer acts as a barrier, and

has been found to be almost impermeable (Al-Yaqout and Townsend, 2004) and thus would prevent the leached oil residue from reaching deeper layers.

The surface oil lakes beds, which consist of oil-contaminated material, vary from hard crusty soil to viscous tarry sludge and have been reported to contain 133 g/kg and 694 g/kg total petroleum hydrocarbons, respectively (Balba et al., 1998). Investigations of soil profiles in the area under study have revealed that soil horizons, in some locations contain high concentrations of hydrocarbons down to a depth of 80-95cm, and in other locations in the upper 50cm (Massoud et al., 2000). These results support the results of this study that the expected leached oil residue from the 5% stabilised soil layer is very low.

It is acknowledged that an intense investigation on the effect of ageing on chemical bonding mechanisms at the soil-oil-water interface is required.

8.10 Conclusion

A field testing programme was carried out on compacted stabilised test beds in Kuwait. Optimum oil content was used to stabilise Sabkha soil S_{J-4}, and compacted beds were left for 14 months under field conditions. From the field investigation performed on compacted test beds, the following conclusions can be drawn:

- The field density of compacted soil beds was in the range 95% to 97% of the maximum dry density of the modified Proctor test measured in the laboratory.
- The unconfined compressive strength of field samples was slightly higher than that of laboratory samples.
- Direct shear strength of the field samples did not vary much from that of the laboratory samples due to the reduction in cohesion and increase in friction angle of the field sample coupled to the laboratory samples
- The CBR values of the field sample for both dry and soaked conditions are higher than those of the laboratory samples.

- The compression index was lower in field samples than that of laboratory samples.
- The leachability investigation indicated that leached oil residue concentrations at layers directly beneath the 5% stabilised Sabkha soil were undetectable.

8.11 References

Aiban, S.A., 1998. The Effect of Temperature on the Engineering Properties of Oil-Contaminated Sands. *Environment International*, 24(1-2): 153-161.

Al-Kulaib, A.A., 1984. The Climate of Kuwait. Directorate General of Civil Aviation (DGA), Meteorological Department, p. 178.

Al-Sanad, H.A. and Ismael, N.F., 1997. Ageing Effects on Oil-Contaminated Kuwaiti Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3): 290-293.

Al-Sarawi, M., Massoud, M.S. and Wahba, S.A., 1998. Physical Properties as Indicators of Oil Penetration in Soils Contaminated with Oil Lakes in the Greater Burgan Oil Fields, Kuwait. *Water Air and Soil Pollution*, 102(1-2): 1-15.

Al-Sulaimi, J., Mohammad, A., Mollah, M.A. and Matti, A., 1990. Geotechnical Properties of Calcrete Soil (Gatch). *Engineering Geology*, 28: 191-204.

Al-Yaqout, A. and Townsend, F., 2004. Applicability of Calcite (Gatch) as Linear/Cover in Arid Climate Landfills: Laboratory and Field Permeability. Practice *Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 8(4): 238.

Andrade, M.L., Covelo, E.F., Vega, F.A. and Marcet, P., 2004. Effect of the Prestige Oil Spill on Salt Marsh Soils on the Coast of Galicia (North-Western Spain). *Journal of Environmental Quality*, 33: 2103-2110.

Balba, M.T., Al-Daher, R. and Al-Awadhi, N., 1998. Bioremediation of Oil-Contaminated Desert Soil: The Kuwait Experience. *Environment International*, 24(1/2): 163-173.

Bayard, R., Barna, L., Mahjoub, B. and Gourdon, R., 2000. Influence of the Presence of PAHs and Coal Tar on Naphthalene Sorption in Soils. *Journal of Contaminant Hydrology*, 46(1-2): 61-80.

BSI, 1990. British Standard 1377: Methods of Test for Soils for Civil Engineering Purposes, British Standards Institution, London.

Ingles, O.G. and Metcalf, J.B., 1972. Soil Stabilisation: Principles and Practice. Butterwoths & Co. Ltd., Melbourne, Australia.

Ismael, N.F. and Jeragh, A.M., 1986. Static Cone Tests and Settlement of Calcareous Desert Sands. *Canadian Geotechnical Journal*, 23: 297-303.

Kaisar, K., Haumaier, L. and Zeck, W., 2000. The Sorption of Organic Matter in Soils as Affected by the Nature of Soil Carbon. *Soil Science*, 165(277-304).

Massoud, M.S., Al-Sarawi, M. and Wahba, S.A., 2000. Variations in the Chemical Properties of Soils Contaminated with Oil Lakes in the Greater Burgan Oil Fields, Kuwait. *Water Air and Soil Pollution*, 118(3-4): 281-297.

Meegoda, N.J. and Ratnaweera, P., 1994. Compressibility of Contaminated Fine-Grained Soils. *Geotechnical Testing Journal*, 17(1): 101-112.

Schlebaum, W., Badora, A., Schraa, G. and Van Riemsddijk, W.H., 1988. Interactions Between a Hydrophobic Organic Chemical and Natural Organic Matter: Equilibrium and Kinetic Studies. *Environmental Science and Technology*, 32: 2273-2277.

Trindade, P.V.O., Sobral, L.G., Rizzo, A.C.L., Leite, S.G.F., and Sariano, A.U., 2004. Bioremediation of a Weathered and a Recently Oil-contaminated Soil from Brazil: A Comparison Study, *Chemosphere*, 58(4): 515-522.

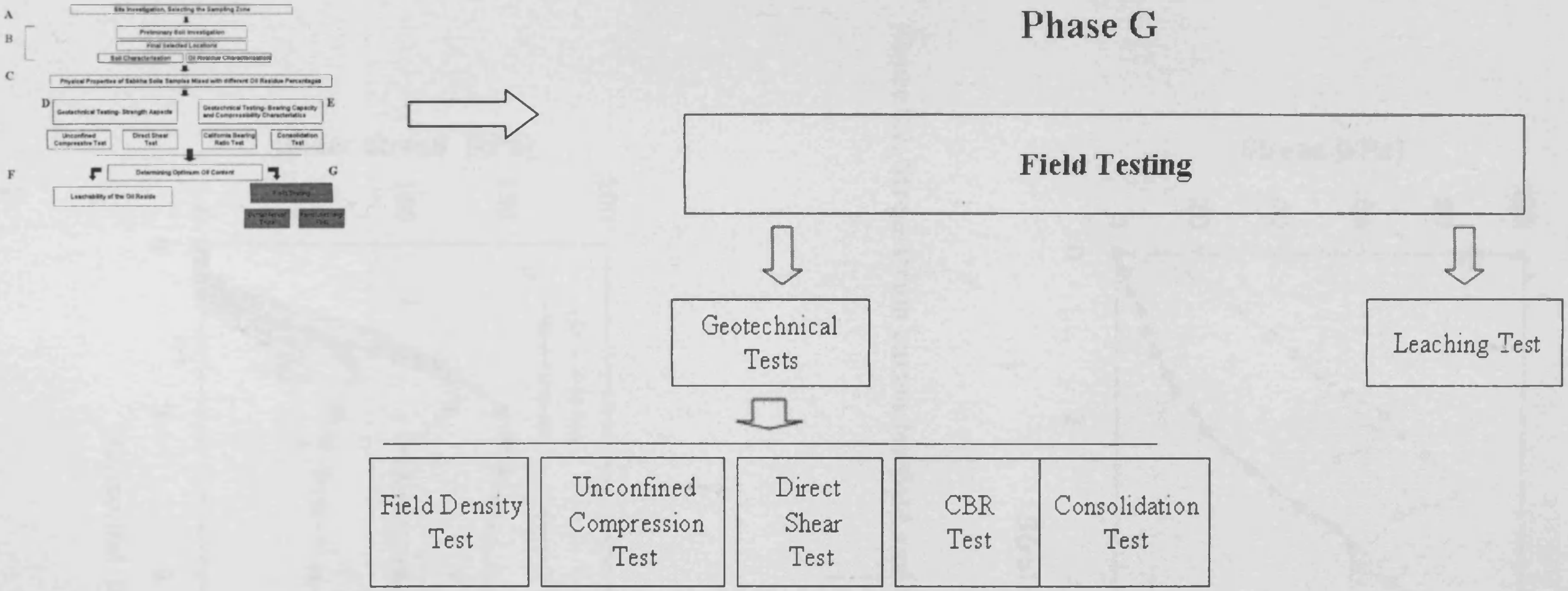

Figure 8.1. Phase G of the experimental programme

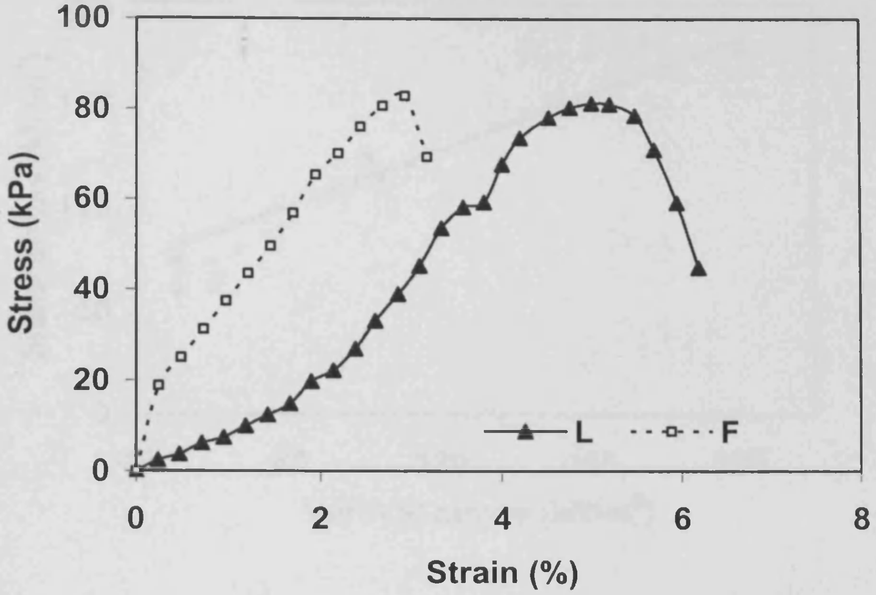

Figure 8.2. Stress-strain curves for field and laboratory stabilised soil samples

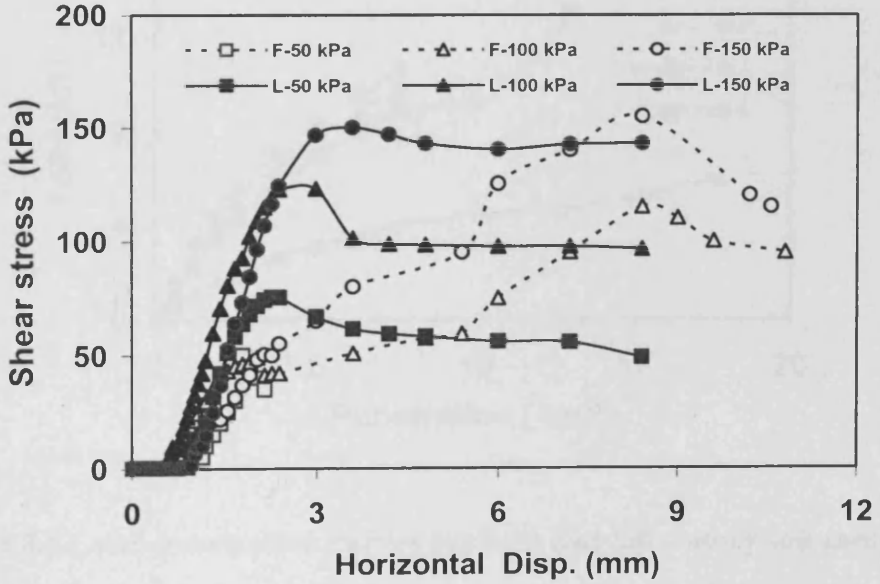

Figure 8.3. Stress-strain curves for field and laboratory stabilised soil sample

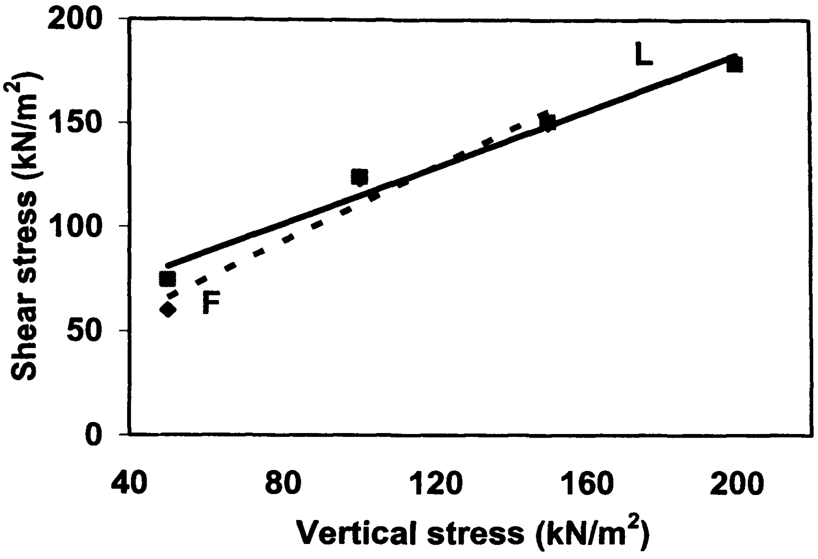

Figure 8.4. Failure envelope for field and laboratory soil samples

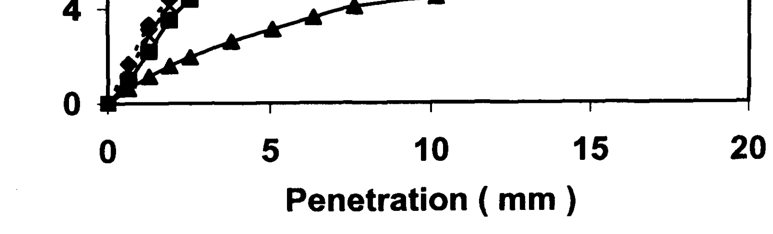

Figure 8.5.Load-penetration curves for field and laboratory soil samples

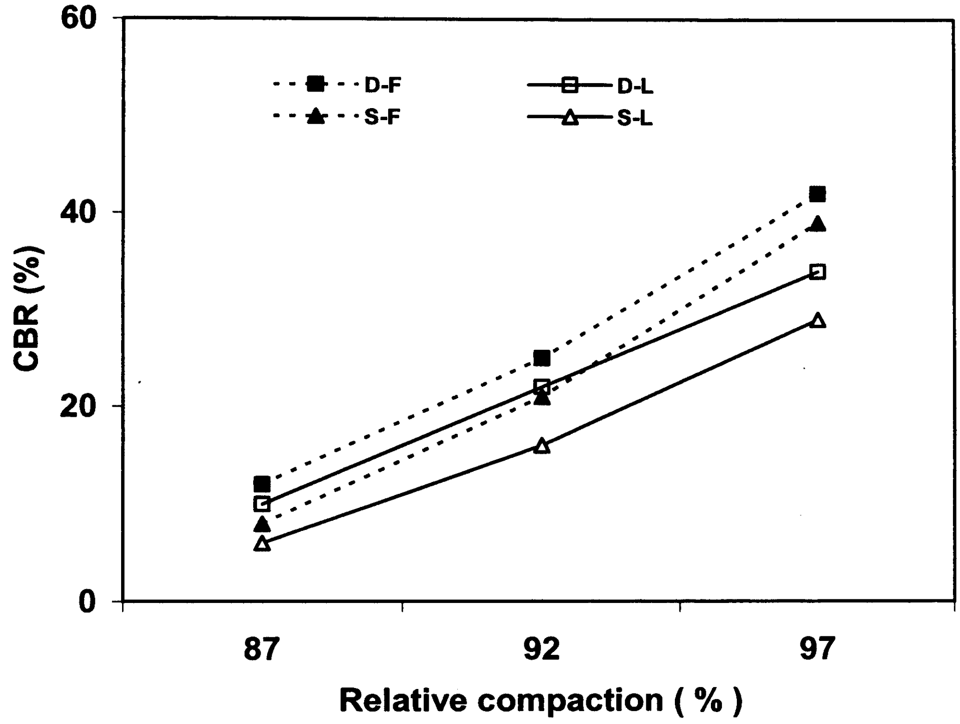

Figure 8.6. CBR values for field and laboratory samples at different compaction effort

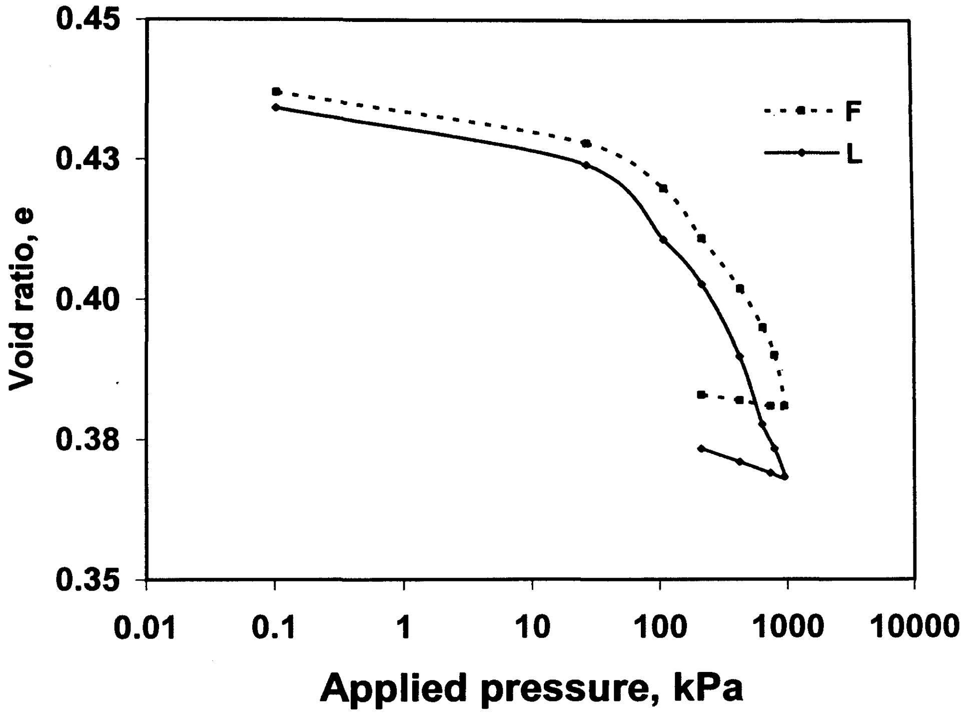

Figure 8.7. Void ratio-applied pressure for field and laboratory soil samples

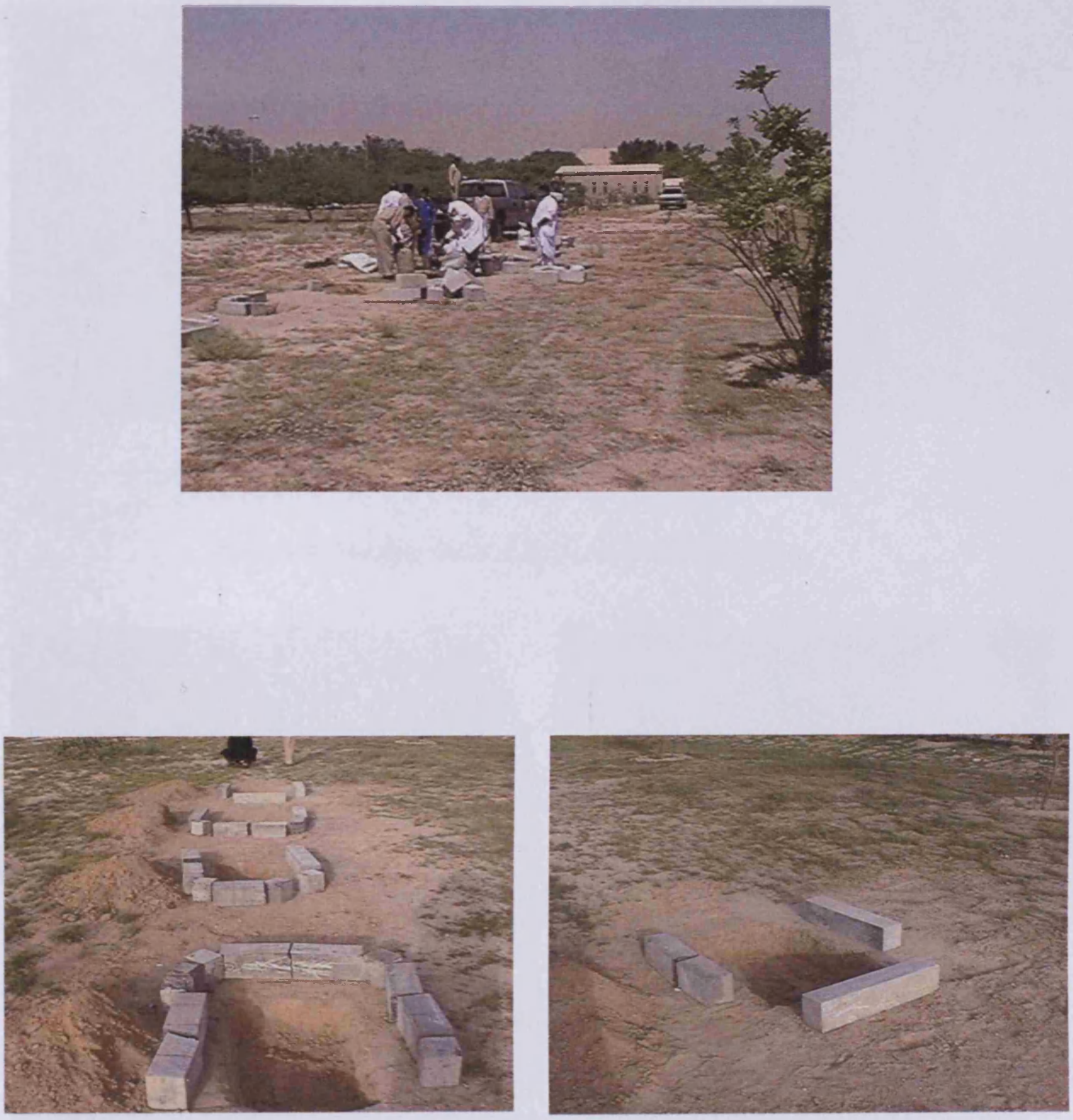

Plate 8.1. Excavation of test beds

Plate 8.2. Mixing the Sabkha soil with oil residue

Plate 8.3. Backfilling and compacting the test beds

Plate 8.4. Loaded test beds

Plate 8.5. Exposed test bed

Plate 8.6. Removal of loads and preparation for field testing

Plate 8.7.Field density test

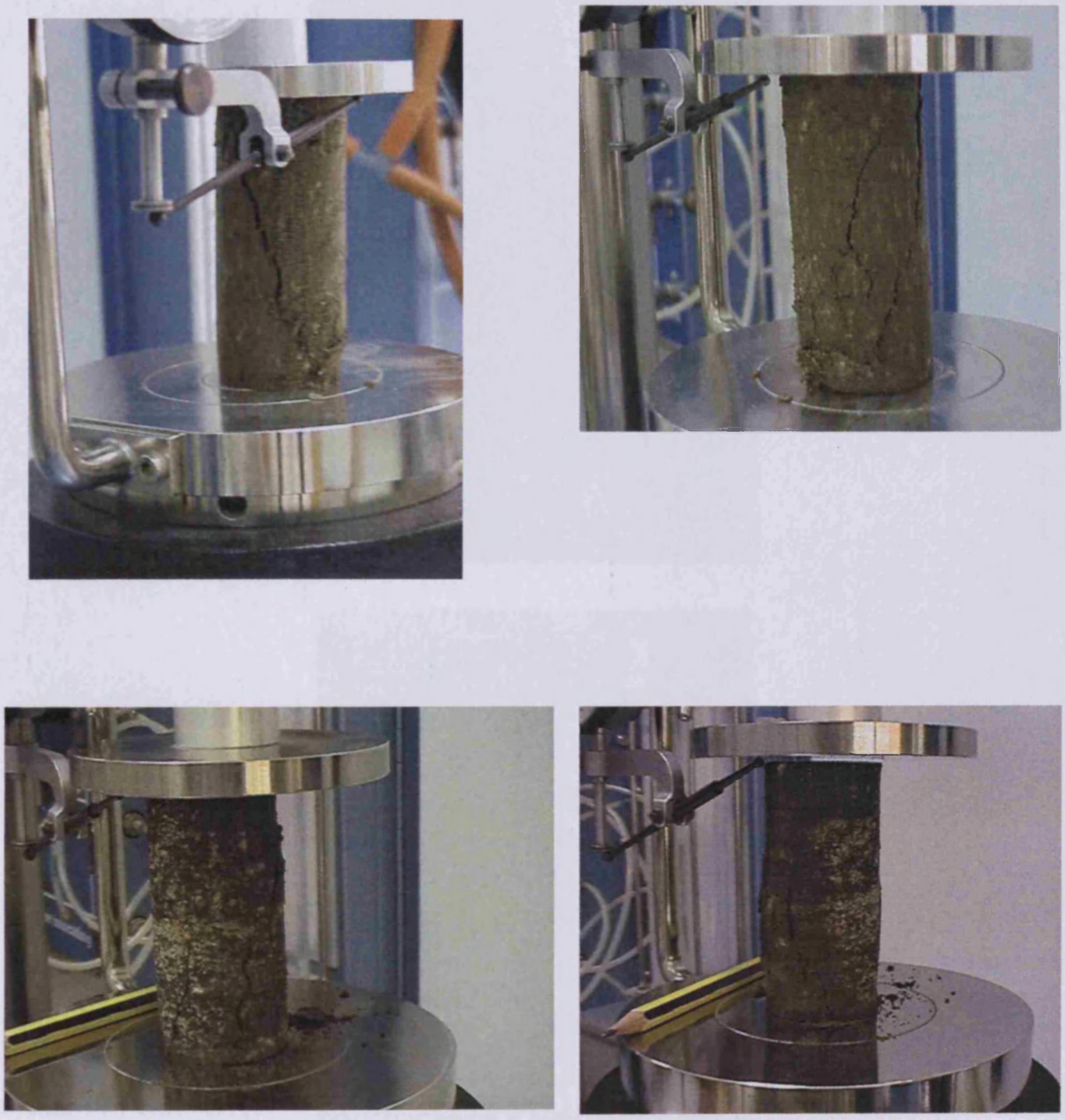

Plate 8.8. Mode of failure of extracted field samples

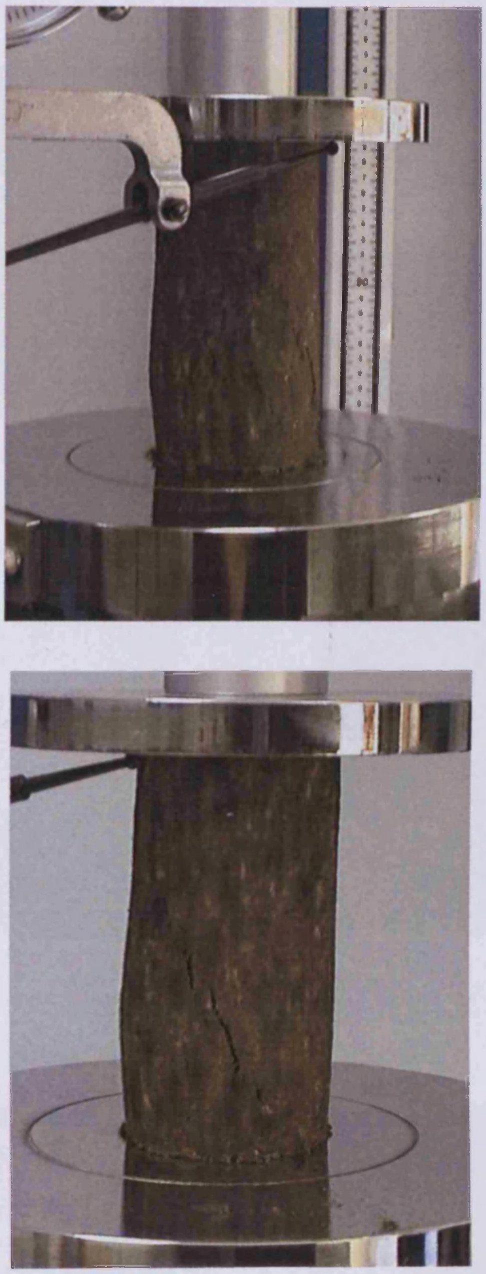

Plate 8.9. Mode of failure of laboratory samples

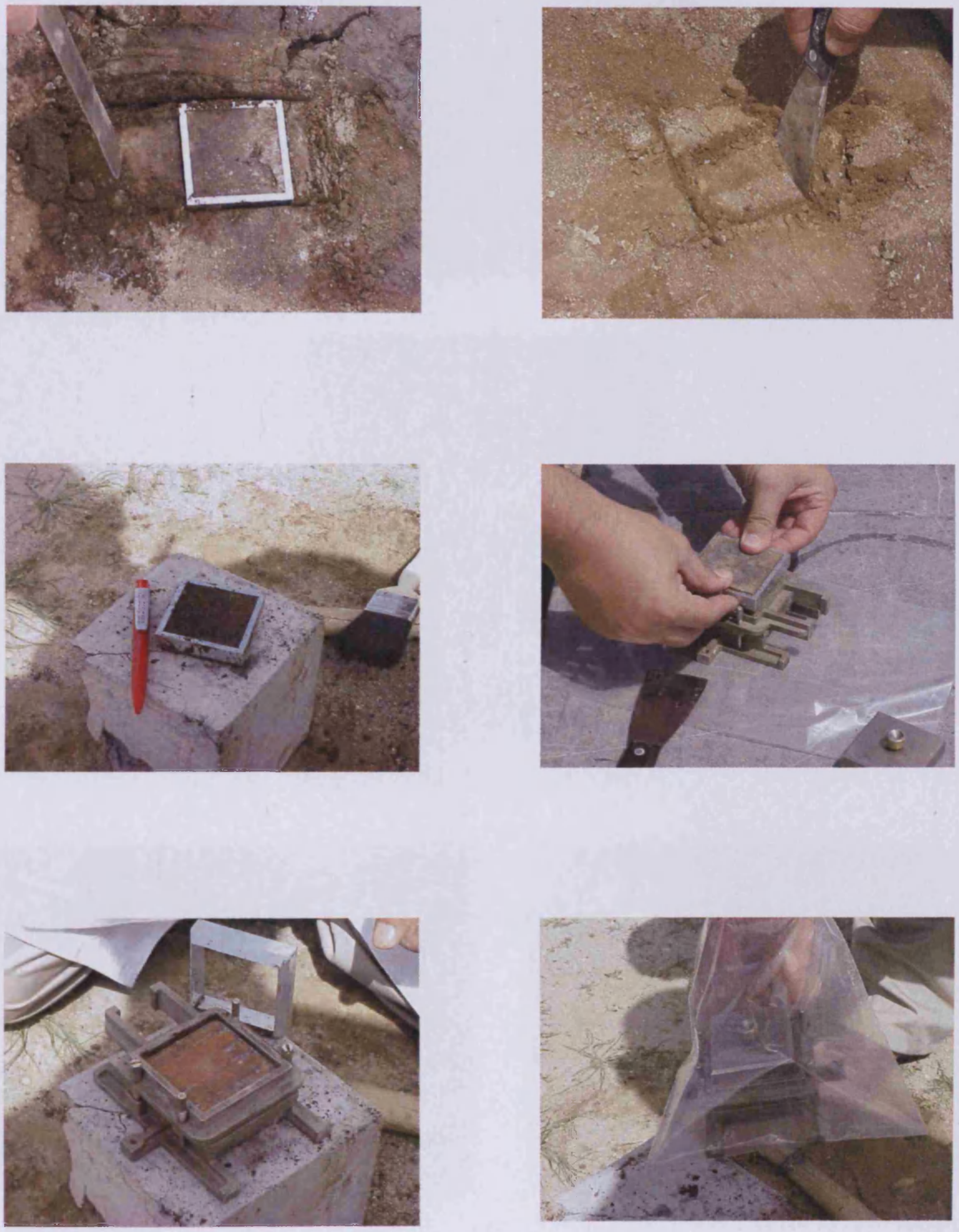

Plate 8.10. Direct shear sampling

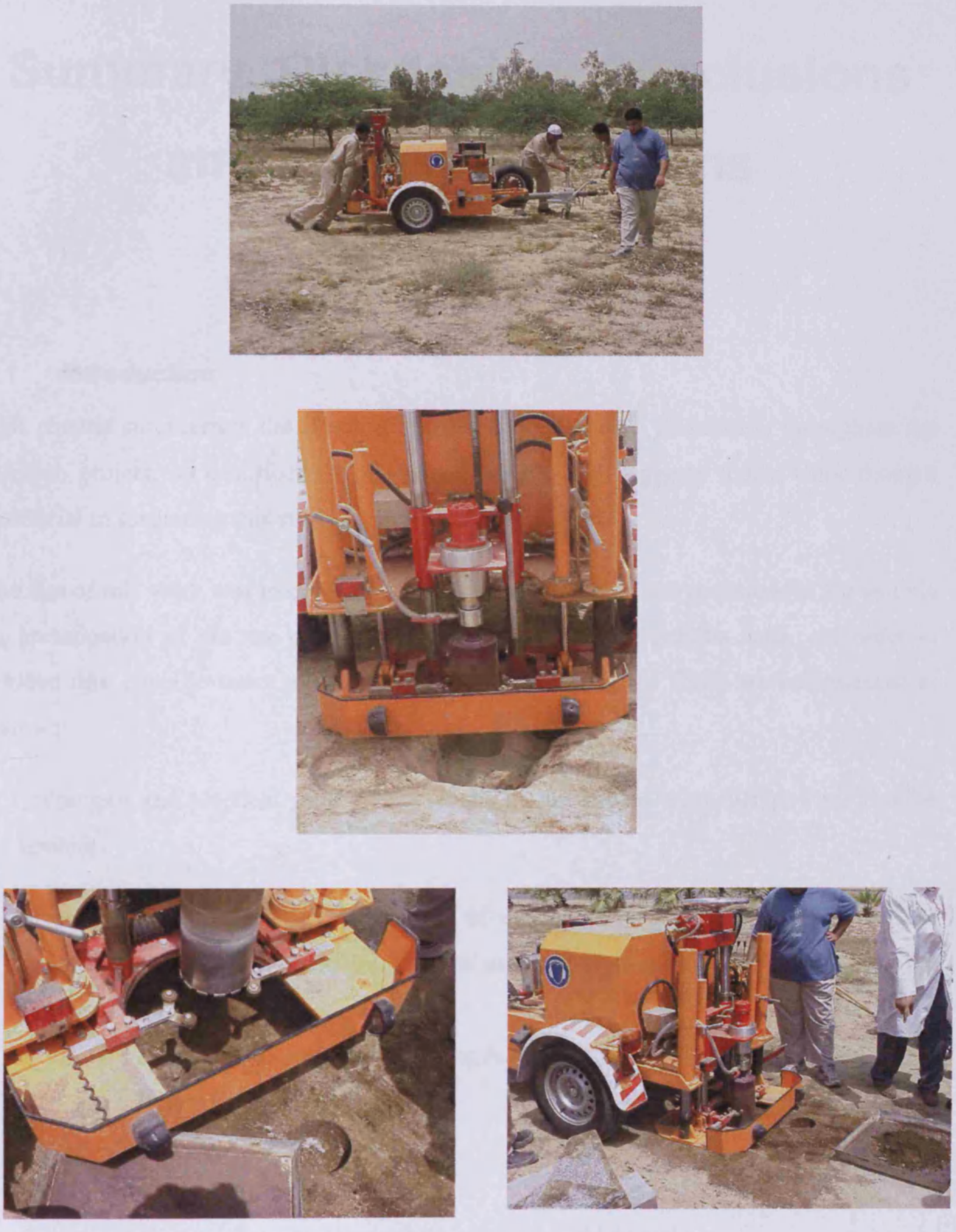

Plate 8.11. Coring of the stabilised layer

Chapter 9

Summary, Discussion, Conclusions and Recommendations

9.1 Introduction

This chapter summarises the findings derived from the work undertaken throughout the research project, as described in previous chapters, and suggests future work thought beneficial in furthering this study.

The aim of this work was to contribute to the preservation of soil resources in Kuwait via an investigation of the use of oil lakes residue to stabilise Sabkha soils. In order to achieve this, specific tasks were set, as stated in Chapter 1. These are summarised as follows:

- Investigate the physical properties of Sabkha soil mixed with different oil residue contents.
- Investigate the geotechnical properties of oil mixed Sabkha soils at different oil residue contents. The main parameters used to evaluate the performance of the stabilised soil were:
    - Unconfined compressive strength.
    - Direct shear strength.
    - Bearing capacity (CBR).
    - Consolidation characteristics.
- Find the optimum oil content required to stabilise Sabkha soils.
- Investigate the leaching properties of stabilised Sabkha soils
- Investigate the geotechnical properties and leachability of oil residue in the field.

9.2 Summary

9.2.1 Materials

Sabkha soil sampling areas were selected through a field survey of a large area of the southern Sabkha flats in Kuwait. Four main locations representing part of the scattered Sabkha soils in Southern Kuwait were selected for the detailed assessment. The Sabkha soils tested were low to non plastic and classified as SM, SP, and SM-SP categories according to the Unified Soil Classification System. Chemical and XRD analysis of tested Sabkha soils indicated the quartz content ranged from 30% to 70% and revealed the presence of about 25% to 40% calcium carbonates and sulphates (section 3.8.2).

The oil residue used in this research was a black coloured light non-aqueous phase liquid (LNAPL), and was characterised by low solubility, density and volatility, and with a boiling point > 350°C. It was a non-polar compound because of the dominance of saturated and aromatic hydrocarbons.

9.2.2 Experimental Work

The experimental work for this research was divided into field work and laboratory work. Phase one field work, which was undertaken at the beginning of the study, consisted of:

- Selecting the test zone in Kuwait.
- Surveying the area to:
  - Obtain information about soil conditions in the area
  - Select representative soil samples.

The laboratory experimental work was designed to investigate the physical, strength, consolidation and leaching aspects of natural and oil mixed Sabkha soils. Physical properties included; soil gradation, consistency limits, compaction parameters and soil permeability, while geotechnical testing included unconfined compression, direct shear, California Bearing Ratio and consolidation tests. Leachability characteristics were investigated through leaching column tests.

Phase two of the field work was undertaken after the determination of the optimum oil content needed to stabilise the Sabkha soils in the laboratory. This phase of field testing consisted of:

- Preparation of the test beds.
- Field testing of the compacted test beds (which were left for 14 months).

The field testing programme consisted of geotechnical and leachability tests and included in situ dry density, unconfined compression, direct shear, California Bearing Ratio, consolidation and leaching tests.

9.2.3 Results

A detailed discussion and summary of the main findings for each aspect of the investigation have already been presented and reported at the end of each chapter. In order to avoid overly repeating those discussions, this section provides a summary and an overview of the main issues of this study as a whole.

Chapter one presented background information on general soil conditions in Kuwait. It also stated the main problems associated with Sabkha soil and oil lake residue that this research sought to address and outlined the proposed approach for solving them.

A review of previous studies on Sabkha soil stabilisation methods and usages of oil-contaminated soils in different types of construction was presented in Chapter two. This literature survey identified limitations in using different methods to stabilise Sabkha soil and variations in the geotechnical properties of the contaminated soil. It was indicated that the use of contaminated soils in road constructions is an accepted approach and has been undertaken in different locations worldwide. It also revealed the lack of information about the physical properties of oil mixed Sabkha soils.

Chapter 3 discussed the methodology implemented in this research and the designed experimental programme. It presented in detail the soil survey and sampling strategy and methods used to evaluate some of the physical and chemical characteristics of Sabkha soil and oil residue. The zone selected for study purposes comprises part of the southern Sabkha flats in Kuwait. The collected Sabkha soil samples fell into SM, SP and SM-SP categories and showed low plasticity and specific gravity. The coefficient of permeability of the soil was in the range of 1.325×10^{-8} m/sec to 53.7×10^{-8} m/sec which is considered to be low. Salt content in Sabkha soils was high and the main cementing agents at all sites were gypsum and calcite.

In Chapter 4, identification of the physical properties of oil mixed Sabkha soil samples with different oil residue contents was undertaken. The investigated properties were particle size distribution, compaction parameters, consistency limits, specific gravity, and hydraulic conductivity. With continuous oil addition, soils showed significant particle aggregation, where fines in Sabkha soils reduced to very low percentage with further oil addition. Consistency limits were slightly affected by oil residue addition. Liquid limits were increased while plasticity was decreased. Plasticity indices for oil mixed Sabkha soils were increased. Compaction characteristics were modified with oil addition of up to 8%, since the maximum dry density values were increased in the range of 5.5% to 12.5% and the optimum moisture content values were decreased in the range of 30% to 78%. The coefficient of permeability of oil mixed Sabkha decreased with oil addition in the range of 31% to 82%, indicating a modification of this property.

In Chapter 5, strength aspects of oil mixed Sabkha soils were examined using unconfined compression and direct shear tests. The UCS of the Sabkha soil improved with oil addition. An increase in the UCS in the range of 34% to 504% of the natural values was observed upon the addition of up to 5% of oil residue to the Sabkha soils. Oil addition of up to 5% increased the shear strength slightly, since the friction angle decreased in the range of 5% to 28% and cohesion intercept increased in the range of 45% to 150%. The brittle failure in natural Sabkha soil changed to more ductile failure with oil addition to Sabkha samples. Test results for soaked soils revealed that oil residue addition prevented complete unconfined shear strength loss upon soaking. Natural Sabkha soils disintegrated upon soaking, while the UCS of 5% oil mixed Sabkha soils was reduced in the range of 42% to 59% from the dry oil mixed values. Beyond 5% oil content, the UCS was reduced in all Sabkha soils at dry and soaked conditions.

Additional soil testing was carried out in chapter 6 to investigate bearing capacity and compressibility characteristics of oil mixed Sabkha soils by conducting California

Bearing Ratio and consolidation tests. Based on experimental programme results, a reduction in the CBR values in the range of 16% to 48% from the natural Sabkha soils values was recorded at dry condition due to oil addition of 5%. Beyond this oil residue percentage, a sharp decrease was observed in CBR value, since the reduction percentage value was in the range of 58% to 85.7% for soil samples at 6% oil residue content. Upon soaking stabilised samples' CBR values were higher than those of natural soil samples by about 1.5 to 2 fold. The addition of oil residue at 5% to Sabkha soil was effective in reducing the compression and swelling indices and collapsibility characteristics of the stabilised Sabkha soil samples. Yield pressures for Sabkha soils increased in the range of 25% to 60% of the natural values with oil residue addition up to 5%. Beyond 5% oil content, the yield stress was reduced in all Sabkha soils.

From findings reported in previous chapters it is concluded that oil residue addition of 5% can be considered as the optimum oil content to stabilise Sabkha soils.

Leaching tests described in chapter 7 were intended to provide information on leachability, waterproofing effect, and long term permeability of 5% oil stabilised Sabkha. Although a high hydraulic gradient, representing a water height of 4.80 metres, was used in this test, the leached oil residue was less than 1.0mg/l. In addition, the hydrophobic characteristics of stabilised Sabkha soil samples reduced the salt dissolution effect of the distilled water. Total leached dissolved salts reduced by about 56% by weight in the stabilised sample. Oil addition also reduced the long-term coefficient of permeability of the stabilised Sabkha in the range of 73% to 88% from their initial values.

In Chapter 8, field testing carried out on compacted soil beds in Kuwait was presented. Five test beds were backfilled using 5% oil stabilised Sabkha soil $S_{j\text{-}4}$. These beds were left for more than 14 months. Field testing consisted of field density, direct shear, CBR, consolidation and leaching tests. Field density of the compacted bed was in the range of 95% to 97% of the maximum dry density of the modified proctor test. Field results were in good agreement with laboratory results and showed that the geotechnical properties of stabilised Sabkha soil samples are modified by the ageing effect. Results of the field samples showed that additional increase in CBR and *UCS* above that of the laboratory results.

9.3 Discussion

The findings of the laboratory and field work undertaken have resulted in a number of conclusions being drawn. These conclusions refer to the effect of different oil residue percentages on Sabkha soil properties. Geotechnical investigations have revealed that Sabkha soils possess very low strength when tested upon soaking. This behaviour is mainly attributed to the dissolution of different types of salts shown in leaching test results for natural Sabkha presented in section 7.4.2.1. The dissolution of these salts is the reason for the problematic behaviour of Sabkha, observed in the disintegration of samples during soaking (section 5.3.3) and the large reduction in CBR strength in soaked natural samples (section 6.3.2.2). This effect derives from the destruction or softening of the cementation bonds between soil grains. The high susceptibility of Sabkha soils to collapse upon soaking necessitates modification of their geotechnical properties. Such modification should be based on modifying their strength properties in both dry and soaked conditions. An effective stabilisation technique for modifying these soils should be based on fully or partially insulating the salts from water contact so as to retain the soil's strength.

A critical parameter in Sabkha soil stabilisation, in addition to density, is the coefficient of permeability. The density parameter affects the packing of the soil particles and the size of pores between them and the size and continuity of void channels. The increase in density of Sabkha soil with oil addition (section 4.4.5) caused a decrease in the void ratio (section 6.4.1.2.1). The coefficient of permeability of 5% stabilised Sabkha soils is less than that of natural by 31% to 82% (section 4.4.6). The reduction in soil permeability with oil addition is a main factor in reducing the dissolution of different types of salts in Sabkha soil. In addition, the compactness of the soil and clogging of voids by the adsorbed oil reduces the void channels and consequently prevent the upward movement of ground water due to capillary rise and downward rainwater percolation. The decrease in soil permeability reduces the soils' susceptibly to soaking. This effect was clearly shown in the leaching test result of stabilised Sabkha (section 7.4.2.2). The susceptibly of natural Sabkha soil to soaking is mainly attributed to dissolution of different types of salts as shown in the leaching test (section 7.4.2.1). Coefficient of permeability for the natural Sabkha soils increased up to 194% of the initial value after long term leaching with distilled water (section 7.4.3.1). The increase in the natural soil permeability resulted in more salt dissolution and more channels to form. The adsorbed oil residue on soil particles and cemented soil lumps and also the reduction in permeability (section 7.4.3.2) reduced the total amount of leached salts in the 5% stabilised sample by 56% (section 7.4.2.2). This mechanism may prevent the loss of stabilised subgrade strength upon soaking.

Although the bonding between Sabkha soil and oil residue is expected to be limited to physical adsorption (section 4.4.1), a noticeable quantity of oil was not leached in either laboratory tests or field testing. Well distributed oil residue due to the mixing process low oil quantity and the chemical and physical characteristics of soil can minimise the leaching of oil even under high pressure.

The aforementioned results indicate that oil residue addition improves the physical properties of Sabkha soil, particularly compaction parameters and coefficient of permeability. The modification of physical properties results in an improvement in strength, bearing capacity and consolidation characteristics. Notably, the modification of geotechnical properties is more pronounced under soaked conditions, where natural Sabkha is significantly affected. Findings indicate that the increase in bulk density, which is a measure of the compactness of oil mixed Sabkha soil, increases the strength properties of this soil. Improvement in the physical and geotechnical properties of stabilised Sabkha soils due to oil residue addition may be attributed to the adsorbed viscous oil residue that coats the soil particles. The coating layer is responsible for the following mechanisms:

- Lubrication effect

The reduction percentage in the internal friction angle for the Sabkha soils due to 5% oil addition ranged from 5% to 28% from that of the natural soils (section 5.4.2.2). The coating oil residue layer reduced the roughness effect of soil particle surfaces. The lubrication effect due to this reduction in friction facilitated the sliding of soil particles over each other and resulted in a percentage increase in the density of compacted Sabkha soil of between 2% to 8.5%. The closer packing of compacted stabilised soil may improve the geotechnical properties of the soil. However, this lubrication effect caused a reduction in the CBR value in the dry condition. The lubrication effect also resulted in a decrease in the optimum moisture content of the compacted Sabkha soil, which can be considered as an advantage in arid conditions.

- Cohesion effect

The apparent cohesion that develops between natural Sabkha soils is due to salt bonding which reduces greatly upon soaking due to salt dissolution as was shown in the strength tests carried out on soaked samples (section 5.4.2.3.2). The oil residue adsorbed on soil surfaces through electrostatic bondings acts as a cohesive material that binds the soil particles. At 5% oil addition, the cohesive component of the soil was shown to increase in the range of 45% to 150% of the natural values, (Section 5.4.2.2). Due to this, the unconfined compressive strength for Sabkha soils varied in the range 50% to 150% of the natural value. This behaviour may be attributed to the adhesive properties of the oil residues which increase the cementation and cohesion.

- Waterproofing effect

The geotechnical properties of natural Sabkha soils are dramatically affected upon soaking, making the possibility of using this material in construction difficult. The low performance of the tested natural Sabkha soil samples may be due to the dissolution of different types of salts, such as Ca^{2+}, SO_4^{2-}, Na^+ and Mg^{2+}, shown in section 7.4.2.1. This results in the weakening and softening of the cementation bonding leading to a huge decrease in both compressive strength and CBR values (section 5.3.3 and 6.3.2.2). The waterproofing effect provided by the oil residue to the stabilised materials is one of the basic mechanisms in oil residue stabilisation. The Hydrophobic oil residue adsorbed on soil surfaces through weak electrostatic bondings (section 4.4.1) forms a layer covering soil particles or lumps which prevents or reduces the dissolution effect of the salts.

Selection of the optimum oil content was based on the combination of strength, bearing capacity and consolidation aspects. At 5%, the *UCS* reached its maximum value at both dry and soaked conditions. At this percentage, the CBR value reached its maximum at soaked conditions and reduced at dry conditions. Shear strength and consolidation characteristics were slightly modified at this oil content. Moreover, at this oil content, salt dissolution reduced to a considerable extent. Although oil addition beyond the optimum content may increase the waterproofing effect due to the formation of a thick oil layer around the cemented soil lumps, the strength of the mixture start to decrease sharply.

The high temperature in the field reduced oil residue viscosity which, in turn, enhanced its distribution around soil particles. In addition, the long-term adsorption effect is expected to reduce the thickness of oil residue layer between soil particles, resulting in a reduction of lubrication and an increase in soil bonding.

9.4 Overall conclusions

Presented results indicate the possibility of stabilising the Sabkha soils using 5% of oil lake residue based on dry weight of soil, since Sabkha soil density increased and the permeability coefficient decreased at 5% oil content. Strength characteristics, such as UCS and shear strength, increased and CBR decreased at 5% oil content. The modification of strength properties was well pronounced at soaked conditions, where 5% oil addition sustained the soaked strength of the Sabkha soil. The compressibility characteristics were slightly modified. The 5% stabilised Sabkha soil's strength properties were well modified under arid field conditions. The leaching of the oil residue for the 5% stabilised layer was very low under laboratory conditions and undetectable under field conditions.

Based on the results of experimental programme and the limited scale field study, results revealed a modification in the physical and strength properties of the 5% oil mixed Sabkha soils.

The possibility of using the stabilised Sabkha soil as a back-filling material for road construction necessitate additional testing for further investigation which will be detailed in the recommended future studies.

Using 5% oil residue to stabilise Sabkha soil is considered a main aspect in achieving a sustainable geoenvironment in Kuwait and, hence, sustainable development. This usage could be considered as an immediate substantial action in the treatment of oil residue and discarded Sabkha soils, which are both considered waste materials.

This solution, if proven by results obtained from the additional future studies, could contribute to the utilisation of locally available Sabkha soils in different construction projects, including road construction. This will minimise the pressure on limited natural sand resources in Kuwait. In addition, the huge amount of oil lakes' residues could be beneficially utilised which will reduce their danger to the Kuwaiti environment.

9.5 Future studies

9.5.1 Future studies relating to limitations of this research

Sabkha soils in this study were characterised by low clay and organic contents which leads to low cation exchange capacity (section 3.8.2). In addition, the high percentage of non-polar compounds in the oil residue due to dominants of saturates and aromatic hydrocarbons (section 3.9). The chemical bonding between the oil residue and the soil was based on weak physical adsorption. For this reason the chemical investigation in this study was not detailed. However, it is acknowledged that an intense investigation on the chemical bonding mechanisms at the soil-oil-water interface is necessary for a better interpretation of the physical and geotechnical behaviours of this composite material. The understanding of the chemical bonding between the oil residue and the soil particle can provide better understanding of dissolution results presented in chapter 7. A further detailed study of soil-oil residue interactions is therefore warranted. Detailed consideration needs to be given to the high salt concentration in the system.

9.5.2 Future expansions of the research

This study has highlighted on the potential use of oil lake residue in construction. This field of investigation could be further extended as follow:

- The heterogeneous nature of Sabkha soil, as explained in chapter 3, and the lack of information on the engineering properties and performance of Sabkha soil make it necessary to carry out additional investigations on the behaviour of Sabkha soils, mixed with oil lake residue to create a databank of information on this behaviour. It was both too costly and too time-consuming to include all Sabkha soils in the test zone.

- The methodology adopted in this study involved assessing the behaviour of Sabkha soil based on the average properties of the tested samples. This has provided a valuable analysis of the Sabkha soil behaviour. However, it is felt that further detailed experimental studies need to be carried out to examine the variability of test results for the same sample and experiment on Sabkha soil behaviour. From this, it is expected that a greater understanding of the material behaviour can be achieved and more confidence in the results will be attained.

- In this study, the main objective was to investigate the modification of the geotechnical properties of Sabkha soils using oil lakes' residue. The acceptability of using stabilised Sabkha soil in road construction as subgrade material necessitates further studies on the use of additives, such as cement, to increase its strength to meet the required specification for this usage. Several researches revealed that hydrocarbons delay the cement hydration without affecting the final strength (section 2.4.8). It is expected that the waterproofing effect of the oil residue in the oil-cement stabilised Sabkha will reduce the corrosiveness of the Sabkha on cement material, which is a contributory factor to the deterioration if cement only is used to stabilise the Sabkha.

- In the course of this study, it became evident that further large scale field investigation is required. The field study in this research was a small scale to gain sufficient understanding of the behaviour of stabilised Sabkha in the actual field conditions and under actual field temperature. It did not concentrate on the influential factors individually. From the experience gained during the experimental and field work, factors that may affect work in this field are stated below:
    - Partially wet Sabkha soil: laboratory soil testing was carried out on oven dry soil samples. However, the adsorption of oil residue may be affected

  by the wetness of soil in the field. Such moisture in the field may affect the bonding mechanism between soil particles and oil residue, which may change the behaviour of stabilised soil.
  - Dealing with a large amount of oil residue and Sabkha soil may reduce the efficiency of the mixing and compaction processes, leading to poor distribution of oil residue around soil particles, which in turn may affect geotechnical properties and the leachability of the oil residue.
  - Distribution of large amounts of stabilised Sabkha during field work delays the compaction process which may affect geotechnical properties.

- The leaching test that was carried out in this study was part of an environmental risk assessment to investigate the leachability of oil residue into the environment. To establish sufficient understanding of the effect of different factors, detailed leaching behaviour should be studied with respect to the following properties:
  - pH: Sabkha soils from different locations were moderately alkaline (section3.8.2). pH value of the calcareous Sabkha soils were above 8, and was mainly attributed to high calcium carbonates. This pH value may affect the adsorption of oil residue to the soil particles.
  - Salts' content: the adsorption of oil residue to high salt content may affect the bonding strength. Additional testing can be carried out on oil mixed natural and washed Sabkha soil samples to evaluate the strength of bonding.
  - Temperature: leaching tests were carried out in the laboratory at certain temperature. This test could be carried at higher temperature to evaluate the temperature effect on the amount of leached oil residue. Although the amount of oil residue leached in the field was not detectable, test should be carried in the laboratory under same pressure to evaluate the amount of leached oil residue under same condition.
- Although the leached oil residue in this study was less than 1mg/l, the potential effect of oil residue on the environment should not be neglected. Additional investigations should be carried out to study this effect.

- The experimental and field results with other previous studies on this field could be used to develop a model for the geotechnical and leachability characteristics of stabilised Sabkha soil samples. The developed model could be used to investigate the long-term behaviour of stabilised soil.