IMPROVEMENT OF EASTERN SAUDI SOILS UTILIZING INDIGENOUS INDUSTRIAL BY-PRODUCTS

BY

ABDULLAH AHMED KHALED AL-HOMIDY

A Dissertation Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In

CIVIL ENGINEERING

MAY 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This dissertation, written by ABDULLAH AHMED KHALED AL-HOMIDY under the direction of his thesis advisor and approved by his dissertation committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY IN CIVIL ENGINEERING.

Prof. Omar S. Baghabra Al-Amoudi
(Advisor)

Prof. Nedal T. Ratrout
Department Chairman

Prof. Sahel N. Abduljauwad
(Member)

Prof. Salam A. Zummo
Dean, Graduate Studies

Prof. Mohammed Maslehuddin
(Member)

25/11/13
Date

Prof. Hamad I. Al-Abdul Wahhab
(Member)

Prof. Muhammad H. Al-Malack
(Member)

DEDICATED TO

MY WIFE

&

MY CHILDREN

ACKNOWLEDGEMENTS

All praise be to ALLAH, the Most Beneficent, the Most Compassionate, and prayers and peace be upon his last and final Messenger "Mohammed".

My deep thanks go to my main advisor, Prof. Omar S. Baghabra Al-Amoudi, and to Prof. Mohammed Maslehuddin, a committee member, for their continuous help, support and advices that made this work possible. Thanks and appreciations are extended to all the other committee members of this dissertation, Prof. Sahel Abduljauwad, Prof. Hamad Al-Abdul Wahhab and Prof. Muhammad Al-Malack, for their constructive guidance and support during this work.

My special appreciation is due to Dr.Tawfik Saleh, assistant professor of analytical chemistry, Eng. Syed Imran and Mr. Hatim Dafalla for their assistance. Special thanks are for all the technicians and the scientists at King Fahd University of Petroleum & Minerals (KFUPM) who made this work a reality.

I wish also to express my thanks and sincere gratitude to KFUPM for providing me the chance to use the facilities during the entire research period.

Special recognition is given to my family at home for their patience and sacrifices during the course of my study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Full Name : **ABDULLAH AHMED KHALED AL-HOMIDY**

Thesis Title : **IMPROVEMENT OF EASTERN SAUDI SOILS UTILIZING INDIGENOUS INDUSTRIAL BY-PRODUCTS**

Major Field : **CIVIL ENGINEERING (GEOTECHNICAL)**

Date : **MAY 2013**

There is a tremendous increase in the construction activity in the Kingdom of Saudi Arabia to accommodate the rapid industrialization programs and immigration of rural population to the urban areas. Since the major industrial and residential areas are located in the coastal areas and/or on weak soils, improvement of the base materials, i.e., soil stabilization, is an integral part of the construction activity. Weak soils are generally stabilized utilizing cement or lime in addition to the mechanical effort. Since cement and lime are relatively costly, there is worldwide research on the use of other "cheap" materials. Such an effort is also required to improve the local soils utilizing indigenous industrial by-products.

The main objective of this study was to evaluate the possibility of improving the mechanical properties of local soils utilizing indigenous industrial by-products, such as oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD). Three types of eastern Saudi soils, namely sand, non-plastic marl and sabkha, were treated with different dosages of the selected industrial by-products. The mechanical properties of the stabilized soils were evaluated by determining the unconfined compressive strength and the durability of the developed mixtures. Micro-characterization methods, such as x-ray diffraction (XRD) and scanning electron microscopy (SEM), were utilized to

qualitatively study the mechanisms of soil stabilization due to the use of the selected industrial by-products.

Results of this investigation indicated that non-plastic marl stabilized with 7% cement was found to be suitable for base course in rigid pavements while the same soil stabilized with 5% cement or with 30% EAFD plus 2% cement or with 30% CKD plus 2% cement was found to be suitable for sub-base course. Non-plastic marl stabilized with 20% EAFD plus 2% cement was found to be suitable as a sub-base in rigid pavements.

Dune sand stabilized with 7% cement or with 30% CKD plus 2% cement or with 20% EAFD plus 2% cement was found to be suitable for sub-base course in rigid pavements. Sand stabilized with 30% EAFD was found to be an appropriate material for sub-base in flexible pavements. However, sabkha stabilized with 7% cement or with 30% CKD plus 2% cement was found to be suitable for sub-base course in rigid pavements.

Furthermore, toxicity tests and economic analyses of soils stabilized with 2% cement and local industrial by-products, CKD or EAFD, indicated that stabilizing soils using these waste materials is eco-friendly and cost-effective.

ABSTRACT (ARABIC)

الاسم الكامل : عبدالله بن احمد خالد الحميدي

عنوان الرسالة: تحسين التربة في المنطقة الشرقية في المملكة العربية السعودية بإستخدام مخلفات صناعية محلية

التخصص : هندسة مدنية (جيوتقنية)

تاريخ الدرجة : مايو 2013م

هناك زيادة هائلة في النشاط العمراني في المملكة العربية السعودية لمواكبة برامج التطور الحضري السريع والتوسع السكاني إلى المناطق غير الحضرية. ولأن المناطق الصناعية والسكانية في المنطقة الشرقية تقع في المناطق الساحلية وعلى تربة ضعيفة، فإن تحسين التربة الاساسية، مثل تثبيت التربة، يعتبر جزءاً مهماً في النشاط العمراني. ويتم عادة تثبيت التربة الضعيفة بإستخدام الاسمنت او الجير بالإضافة إلى الجهد الميكانيكي. ولان الاسمنت والجير مكلف مالياً، فإن هناك بحوث عدة حول العالم عن بدائل رخيصة. ولذلك، لابد من بذل جهد مماثل ضروري لتحسين التربة المحلية بإستخدام مخلفات صناعية اصلية، والتي سوف تسهم في المحافظة على البئية وفي دعم الإقتصاد الوطني على المدى البعيد.

الهدف الرئيسي من هذه الدراسة هو تقييم إمكانية تحسين الخواص الميكانيكية للتربة المحلية بإستخدام مخلفات صناعية اصلية ومحلية. المخلفات الصناعية المتوفرة التي يمكن إستخدامها في تثبيت التربية المحلية تشمل الاسمنت (للمقارنة)، غبار افران الاسمنت (CKD)، رماد الوقود النفطي (OFA) الناتج من محطات توليد الطاقة التي تستخدم النفط الثقيل، والغبار المتطاير من افران صهر الحديد (EAFD). ونظراً لوجود ثلاثة انواع من التربة في المنطقة الشرقية وهي

التربة الكلسية (المارل)، والتربة الرملية والتربة السبخية، فقد تم معالجتها بكميات معينة من هذه المخلفات. وقد تم تقييم التربة الغير معالجة والمعالجة بإستخدام تقنيات مكيانيكية شملت الدمك ومقامة الإنضغاط الغير محصور والتحمل والمتانة. وكذلك بإستخدام تقنيات دقيقة مثل اشعة اكس والتصوير الألكتروني الميكروسكوبي لمعرفة ميكانيكية التحسن في التربة المعالجة.

وتدل نتائج الدراسة ان التربة الكلسية المعالجة ب 7% من الاسمنت مناسبة للطبقة الاساسية للطرق الخرسانية والمعالجة ب 5 % من الاسمنت او ب 30% من (EAFD) مع 2% من الاسمنت او ب 30% من (CKD) مع 2% من الاسمنت مناسبة للطبقة الثانوية في الطرق الاسفلتية. وقد وجد أن التربة الكلسية المعالجة ب 20% من (EAFD) مع 2% من الاسمنت مناسبة للطبقة الثانوية في الطرق الخرسانية .

كما تدل النتائج ان التربة الرملية المعالجة ب 7% من الاسمنت او ب 30% من (CKD) مع 2% من الاسمنت او ب 20% من (EAFD) مع 2% من الاسمنت مناسبة للطبقة الثانوية في الطرق الخرسانية والمعالجة ب 30% من (EAFD) مع 2% من الاسمنت مناسبة للطبقة الثانوية في الطرق الاسفلتية.

كما أن التربة السبخية المعالجة ب 7% من الاسمنت او ب 30% من (CKD) مع 2% من الاسمنت مناسبة للطبقة الثانوية في الطرق الخرسانية .

علاوة على ذلك، فإن إختبارات السمية والحسابات الإقتصادية للتربة المعالجة ب 2% من الاسمنت ومخلفات صناعية محلية مثل غبار افران الاسمنت او رماد صناعة الحديد اظهرت إن معالجة التربة بإستخدام هذه المخلفات غير ضارة بالبيئة وذات جدوى إقتصادية.

CHAPTER 1

INTRODUCTION

The rapidly growing population and industrialization in Saudi Arabia is exerting tremendous pressure on the construction industry to build the necessary infrastructure. The newly developed infrastructure is mostly concentrated along the coastal areas, mainly on weak soils. These soils need to be stabilized utilizing chemical and/or mechanical methods. Portland cement and lime are commonly utilized for chemical stabilization. Some other materials, such as fly ash, are also utilized for this purpose.

The industrialization has also resulted in the production of significant quantities of industrial by-products. Considerable resources are utilized to get rid of the waste materials to meet the environmental restrictions. Consequently, there is a need to assess the alternative possibility of utilizing the waste materials in the stabilization of indigenous soils. Such possibilities will satisfy the economic and environmental requirements.

While some work has been conducted to evaluate the possibility of utilizing cement and lime for stabilizing the local soils, in Saudi Arabia, research work needs to be conducted to study the possibility of utilizing the indigenous industrial by-products for soil stabilization. Besides; there is a strong desire to reduce the consumption of cement through the effective utilization of industrial waste materials in order to decrease greenhouse effect and environmental problems.

1.1 Significance of This Study

Since cement kiln dust (CKD), oil fuel ash (OFA) and electric arc furnace dust (EAFD) are considered as waste materials, it would be a noble task to use them in civil engineering applications, such as soil stabilization. Usage of these waste materials will result in:

1. Saving money;
2. Preserving the environment by beneficial utilization of these waste materials; and
3. Conserving the energy being utilized in the production of cement and lime.

There are four types of soil in the eastern province of Saudi Arabia, namely, clay, sabkha, marl and dune sand. Clayey soils are only located in limited regions in Al-Qatif and Al-Ahsa, further, these soils also well known to be treated with lime and, therefore, clay was excluded from this study. While marl is often being used in many projects in eastern Saudi Arabia, sabkha and dune sand are problematic soils and their usage in construction projects is risky and very limited. Therefore, this research was intended to investigate the possibility of incorporating CKD (cement by-product), OFA (produced during burning of heavy oil in power plants) and EAFD (by-product of manufacturing steel using electric arc furnace) for the stabilization of the three selected indigenous eastern Saudi soils, namely, non-plastic marl, dune sand and sabkha.

1.2 Objectives

The general objective of the proposed study was to assess the possibility of improving the engineering properties of local soils utilizing indigenous industrial by-products. The specific objectives were the following:

1. To improve the mechanical properties and durability of eastern Saudi soils (i.e. non-plastic marl, dune sand and sabkha) utilizing indigenous industrial by-products, including oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD),

2. To study the mechanism by which the selected industrial by-products affect the properties of the local soils and

3. To develop charts, guidelines and/or models that would help the practicing engineers to select and estimate the appropriate dosage of the industrial by-product(s) in terms of strength, durability and cost.

To achieve these objectives, the selected soils were treated with different dosages of cement, CKD, OFA and EAFD. Cement was included to be a reference stabilizer. The stabilized soils were evaluated through macro-characterization tests, such compaction, CBR, unconfined compressive strength and durability. Micro-characterization studies were conducted utilizing SEM and XRD. Based on the results of these tests, models were developed to help the users to select the dosages of the stabilizers for each of the three selected local soils.

CHAPTER 2

LITERATURE REVIEW

2.1 Materials

2.1.1 Soils

The rapid expansion in the civil and industrial activities in the eastern area of Saudi Arabia has made the improvement of local soils an indispensable task. It is essential for the designers and builders to be able to select an appropriate stabilizer to fulfill the engineering, environmental and economic requirements of the local soils. A background on the selected soils, namely non-plastic marl, dune sand and sabkha, is provided in the following sub-sections.

2.1.1.1 Geology and Origin of Marl in Eastern Saudi Arabia

Marl is considered to be one of the four predominant types of soils found in eastern Saudi Arabia (i.e., sand, marl, clay and sabkha). Due to the unsuitability of the other three soils, marl soils are uniquely used in the construction of almost all types of road bases, embankments and foundations. Many researchers [Netterberg, 1982; Qahwash, 1989; Al-Amoudi et al., 2010] defined marl as a soil or rock-like material containing about 35–65% calcareous material as well as varying percentage of clay. The term ‘‘marl” is often used to represent indefinitely all types of calcareous materials. Marl, being primarily calcareous in nature, is influenced by the mineral composition, type of parent carbonate mineral present, origin and the formation process, grain-size distribution and degree of cementation. In addition, the variation in density and moisture content, and post depositional changes affect the behavior of this type of soil [Aiban, 1995]. Consequently, marl generally exhibits a wide variation in terms of its characteristics, engineering properties and definitions. Hence, there is no unanimous consensus on the proper definition of marl. Calcareous means containing calcium carbonate. Geologically, marl is classified from pure clay stone to pure limestone, depending on the clay and carbonate content. A primary sedimentary rock formed from calcium carbonate segmentation is limestone. Limestone can be dolomitized to dolomite [Shallinor, 1978, quoted by Ahmed, 1995]. Dolomitic limestone is a rock which contains double carbonate, $MgCO_3.CaCO_3$. While the magnesium limestone contains magnesium carbonate alone [Blyth and de Freitas, 1985, quoted by Ahmed, 1995]. Ahmed [1995] reported that the eastern Saudi marl is of specific gravity between 2.64 and 2.92.

Few studies have been carried out at King Fahd University of Petroleum and Minerals (KFUPM) and the results of these investigations indicated that the calcareous soil is acutely water sensitive; though the strength of marl is usually high when it is dry [Aiban et al., 1998a; Aiban et al., 1998b]. Such a concern is ascribable to the fact that an almost complete strength loss may result upon inundation, particularly when the material is compacted on the wet side of optimum moisture content. The difficulty in obtaining good substitutes for the local marl for the construction of all types of earthwork has forced the researchers and practicing engineers to explore the possibility of upgrading this soil. Fig. 2-1 shows the location of major quarries of marl in eastern Saudi Arabia. Accordingly, the characterization of this soil should consider its inferior properties and the possible chemical stabilization to minimize or control its inferior behavior in moist condition. The success in improving the performance of these soils will have a tremendous cost saving impact on the maintenance and life cycle of structures that are built on them.

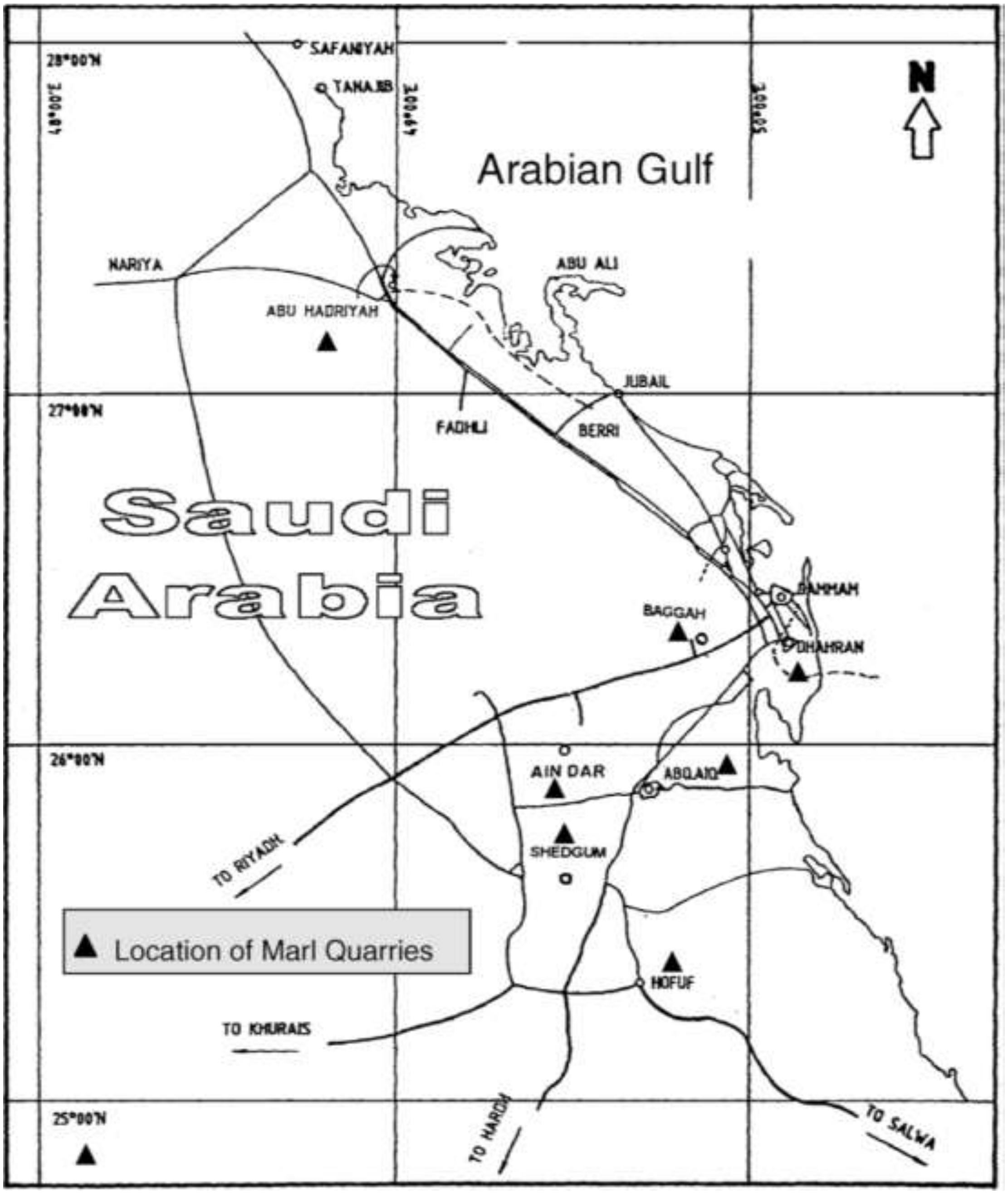


Figure 2-1: Vicinity Map Showing Locations of Major Marl Quarries in Eastern Saudi Arabia [Aiban et al., 1998a]

2.1.1.2 Geology and Origin of Sand Dune in Saudi Arabia

Approximately one third of the Arabian Peninsula is covered by sand. This sand, being cohesionless, may have slight inter-particle cementation in some area. There are two types of sandy soils: beach sand and dune sand; both of which are aeolian in nature [Al-Gunaiyan, 1998].

Geographically, the sand dunes in the Arabian Peninsula are divided into three major zones. The great Al-Nafud in the north (57,000 km^2) links to Ar-Rub Al-Khali (the Empty Quarter) in the south (600,000 km^2) through the Arch Ad–Dahna that runs in another direction extending about 1,300 km. The sands of these two zones, Ad-Dahna and the great Al-Nafud, are medium to fine in size and bright red-orange in color due to a coating of iron oxide on the quartz grains. On the other hand, Ar Rub' Alkhali (Empty Quarter) sands are buff to tan in color due to the presence of carbonates. The primary source of most of the sands is the large granite batholiths underlying the Arabian shield [Al-Sayari and Zolt, 1978, quoted by Ahmed, 1995].

In these regions, the unconsolidated surface sediments are drifted by wind. In eastern Saudi Arabia, annual drift rates could reach 30 m^3/m width and the average yearly rate of movement of dunes is about 15 m [Watson, 1985]. The majority of soils in desert areas are granular and their behavior is related to their gradations [Fooke, 1978, quoted by Ahmed, 1995]. Figure 2-2 shows the distribution and the direction of the deserts in the Arabian Peninsula mentioned above.

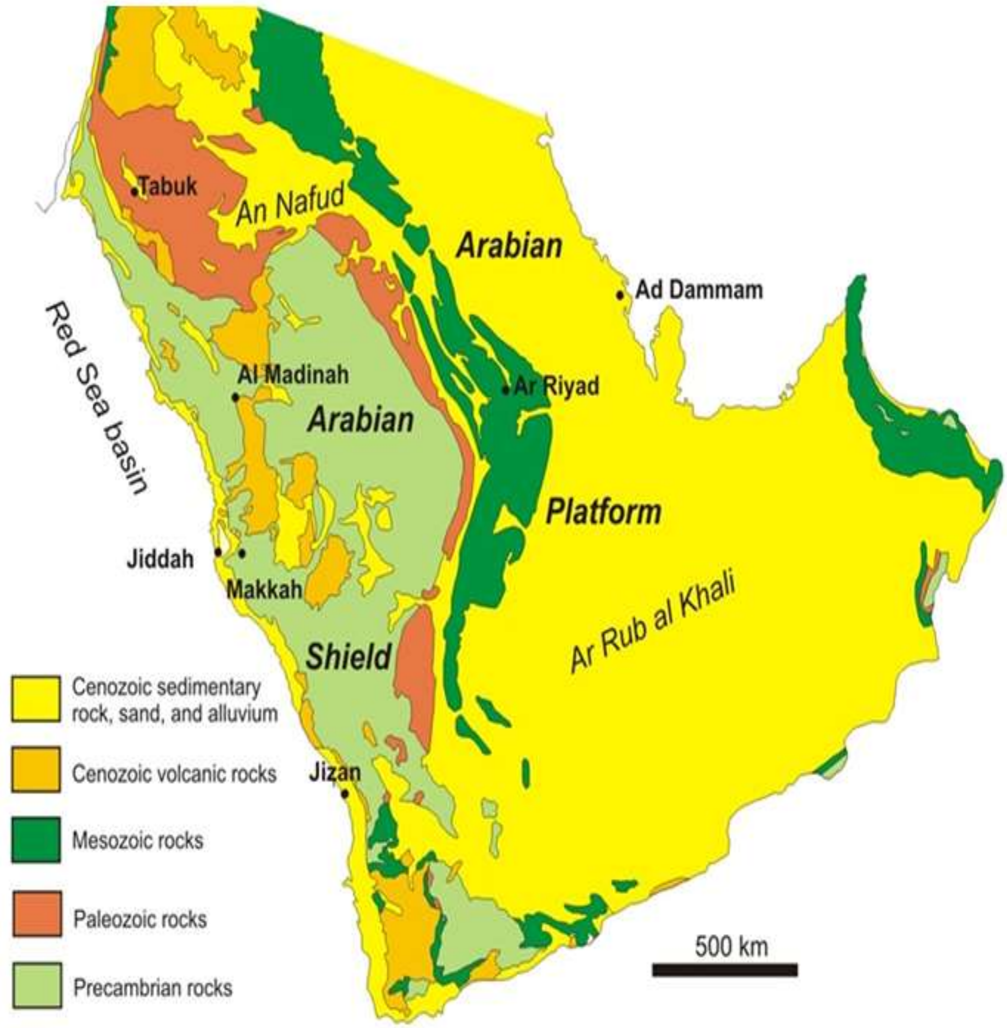


Figure 2-2: Sand Terrains in the Arabian Peninsula [Saudi Geological Survey]

Aeolian deposits cover about 35% of the Arabian Peninsula surface. These deposits have been subdivided into four types, depending on their mode of occurrence and genesis: sand sheet, sand dunes, sand drift and aeolian fill sand deposits [Bate and Jackson, 1980].

Aeolian sands are made up of quartz that is composed of silica tetrahedral groups in such a way as to form spiral, with all the tetrahedral oxygen's bonded to silicon. Quartz is an oxide and thus has no weakly bonded ions in its structure. It has, also, high hardness. All of these factors make it very stable; the most common among rock-forming minerals. Bagnold [1971] relates the predominance of quartz in dune sands to its ability to survive under the different erosive agents.

The bulk of Saudi sand falls short of good gradation, quality and activity for commercial exploration as well as for use in routine concrete construction as a filler. Most, if not all, dune and beach sand is classified as poorly graded sands (SP), according to Unified Soil Classification System (USCS), and mostly as (A-3), according to the American Association of State Highway and Transportation Officials (ASSHTO) system [Maslehuddin et al., 1991].

Dune sand has specific gravity ranging between 2.62 and 2.70 and median grains diameter between 0.2 and 0.4 mm and particle sizes ranging between 0.1 and 0.7 mm. Sands in the Eastern Province have fineness modulus median of 1.8 and ranging between 0.9 and 3. The coefficient of uniformity, C_u, ranges between 2.0 and 4.0 and the coefficient of curvature, C_c, ranges between 0.94 and 1.27 [Al-Gunaiyan, 1998].

Dune sand is often difficult to compact as a fill material, even after careful laboratory test, due to the poor gradation and lack of fine particles. However, they are not collapsible soils, not sensitive to water. These sands cannot be used as construction materials in their natural condition, however, when they have been subjected to treatment, they can be used in many applications [Aiban, 1994b].

2.1.1.3 Geology and Origin of Sabkha in Eastern Saudi Arabia

Sabkha is an Arabic word meaning salt flat and is applicable to both coastal and interior salt flats. There are two types of sabkha, sandy sabkhas and muddy sabkha. Sandy sabkhas are very loose to medium dense and may sometimes be partially cemented by salts. Muddy sabkhas are lagoon sediments consisting mainly of sandy carbonate mud. According to their location, sabkhas are found at coastal and inland (continental) areas [Juillie and Sherwood, 1983].

Both coastal and inland sabkhas usually form in hot, semi-arid to arid climates and are associated with shallow ground water table. When dry the surface of a sabkha flat is usually hard enough to support a medium-weight vehicle, but becomes too weak to support a medium-weight vehicle when wet and any vehicle may sink in it [Renfro, 1994]. The sabkha soil is a type of soil that has compounded construction problems, when it comes wet, such as large concentration of salts, increasing compressibility, very low shear strength and other associated problems.

Some sabkha soils have gravel mixtures within their matrices; the presence of these gravelly sediments is more common in the continental sabkha soils rather in the coastal ones [Ghazali et al., 1985]. Further, the natural moisture content of sabkha deposits ranges from 8 to 65% [Abu-Taleb and Egeli, 1981]. Consequently, this large variation in the water content frequently leads to large changes in density, volume, consistency and strength. The concentrated nature of sabkha brines is reflected by total dissolved solids (TDS) of as much as four to six times those present in a typical sea water from the same region, as presented in Table 2-1.

The above review conveys the impression that sabkha soils are highly variable materials with inferior "natural" strength capacity thereby leading to several constructional problems. The major factor that contributes to these problems is the low bearing capacity of the sabkha soils. Moreover; sabkha soils are very sensitive to moisture; complete collapse and reduction in the bearing capacity is anticipated whenever they get into contact with water [Al-Amoudi, 1995b]. Such a behavior is attributed to the fact that the cementing materials that bond the mineral grains of sabkha together are relatively soluble in water, such as halite, gypsum, aragonite or calcite, thus making the sabkha soils susceptible to collapse upon exposure to moisture.

Saudi Arabia has a large number of sabkhas, both coastal and inland. The coastal sabkhas extend along both the Arabian Gulf and the Red Sea shores, while inland sabkhas are mainly found in creeks scattered in the northeastern and the eastern parts of the Arabian Peninsula, as shown in Figure 2-3. Sabkhas in the coastal plains of the Eastern Province are well documented [Johnson, et al., 1978; Al-Amoudi et al., 992b], while the Red Sea coastal sabkhas exist at Obhor, Al-Lith, Yanbu and Jazan. In the North, continental sabkhas are reported to exist in Wadi As-Sirhan (Sabkhat Hadhoud) and in many other creeks in the region that usually run parallel to either the Red Sea or the Gulf of Aqaba. Coastal sabkhas in Saudi Arabia are quite extensive and pose many problems to the construction activities along its shorelines. Figure 2-3 shows the distribution of sabkha in the Arabian Peninsula and Figure 2-4 shows the generalized cross section across costal sabkha with typical surface feature

Table 2-1: Chemical Analysis of Sabkha Brine and Seawater [Al-Amoudi, 1995]

Ion	**Sabkha brine***	**Sea water ***
Na^{+}	78.8	20.7
Mg^{++}	10.32	2.3
K^{+}	3.06	0.73
Ca^{++}	1.45	0.76
Sr^{++}	0.029	0.013
Cl^{-}	157.2	36.9
Br^{-}	0.49	0.121
$(SO4)^{-}$	5.45	5.12
$(HCO_3)^{-}$	0.087	0.128
pH	6.9	8.3
Conductivity (Micro Siemens)	208,000	46,200

* Concentration is in parts per thousand

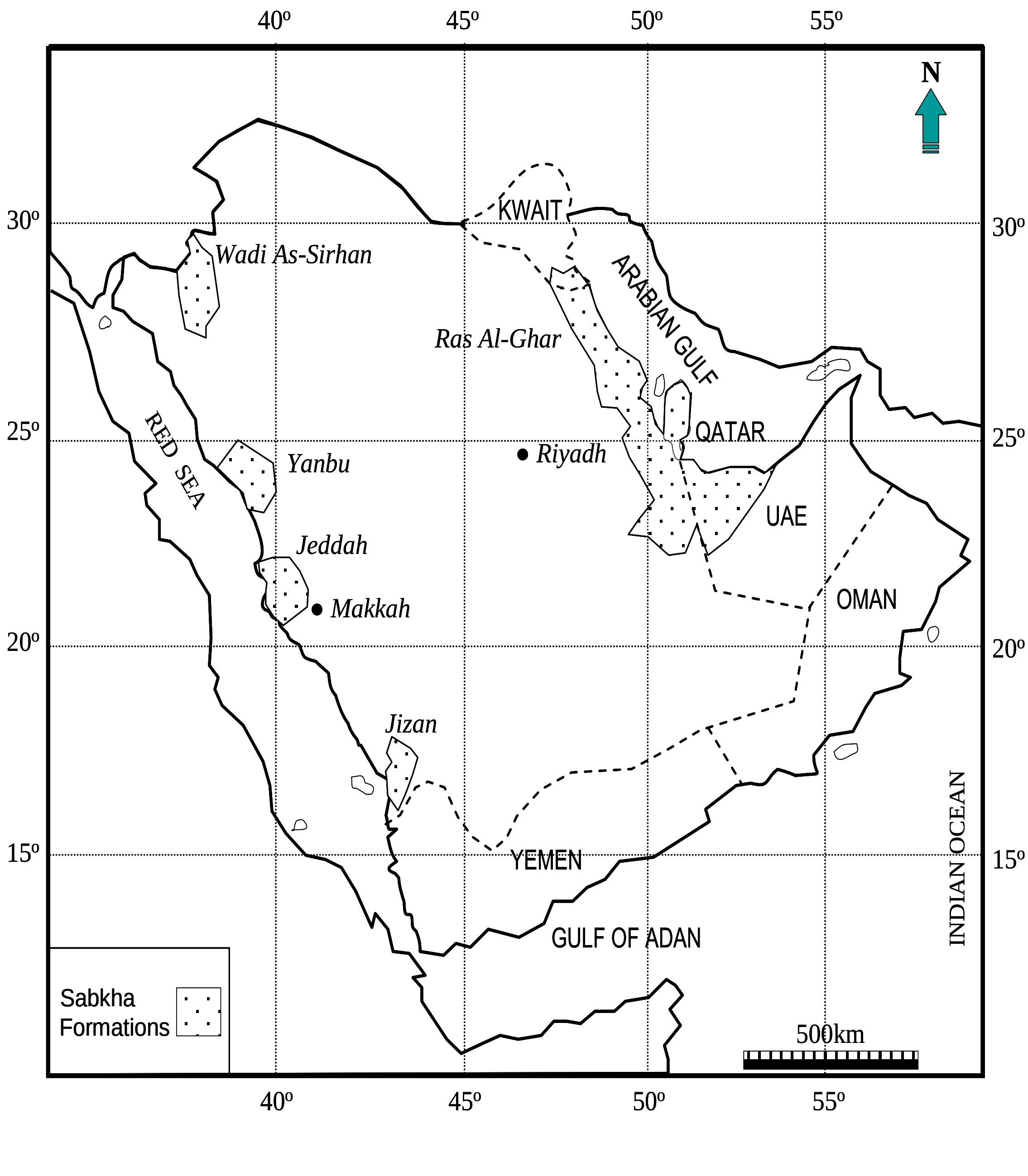


Figure 2-3: Distribution of Sabkha in the Arabian Peninsula [Al-Amoudi et al., 1992]

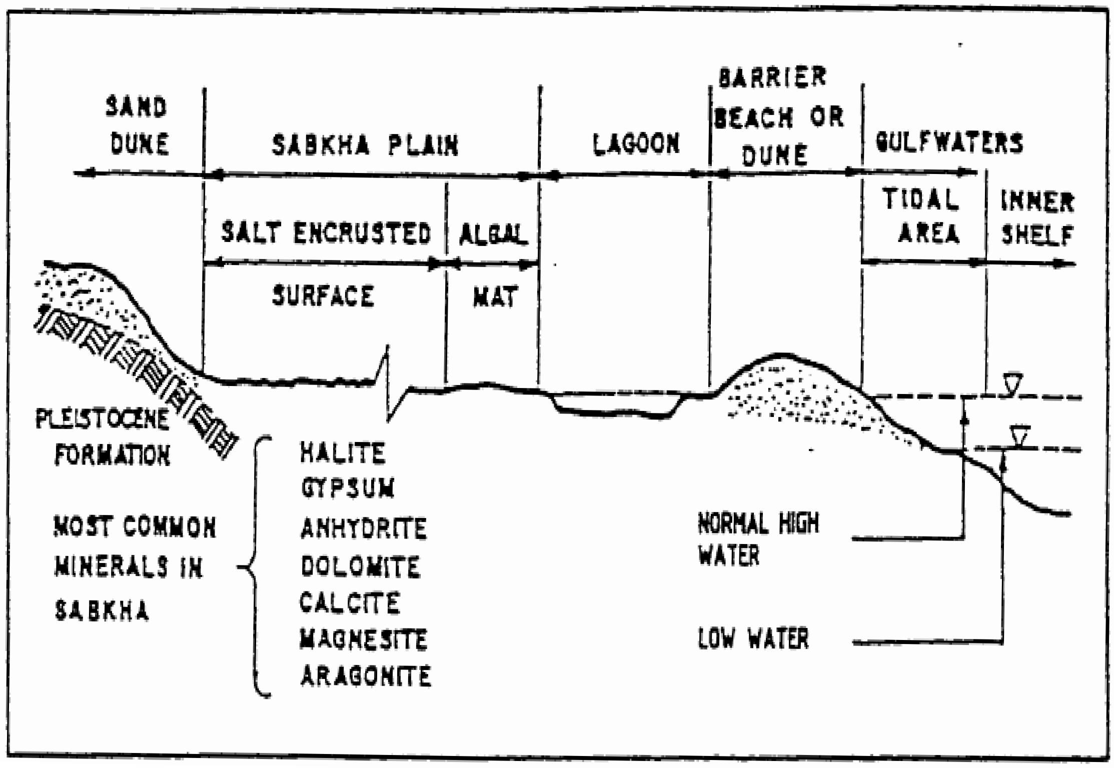


Figure 2-4: Generalized Cross Section Across Costal Sabkha with Typical Surface Features [Alkili, 1981]

2.1.2 Stabilizers

Weak soils need to be stabilized in order to improve their mechanical properties and durability. Stabilization can be done mechanically or chemically. The selected stabilizers should be environment-friendly, easy to be used, available locally and economical.

The following sub-sections describe the industrial by-products used in this investigation.

2.1.2.1 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is generated during the manufacturing of cement clinker. As the raw feed travels through the Portland cement kiln system, particulates of the raw materials, partially processed feed, and components of the final product are entrained in the combustion gases flowing counter current to the feed. These particulates and combustion gas precipitates are collected in the particulate matter control device. The collected materials are referred to as cement kiln dust (CKD).

Generation of CKD is estimated to be about 30 million tons/year [Dyer et al., 1999]. Large quantities of CKD are produced during the manufacture of cement by the dry process. While modern dust-collecting equipment is designed to capture virtually all CKD and much of this material can today be returned to the kiln, for various reasons, a significant portion, in some cases as much as 30–50% of the captured dust, must be removed as industrial waste [Kessler, 1995 and USEPA, 1998]. As a result, in the United States, more than 4 million tons of CKD, unsuitable for recycling in the cement manufacturing process, require disposal annually [Todres et al., 1992]. CKD contains a mixture of raw feed as well as calcite materials with some volatile salts. It is derived from the same raw materials as Portland cement but, as the CKD fraction has not been fully burnt, it differs chemically from the former. The chemical composition may, however, vary with the cement manufacturing process and type of the raw materials.

There are many cement factories in the Kingdom of Saudi Arabia that produce thousands of tons of cement daily. Some of these factories face a problem of producing large quantities of CKD, a Portland cement by-product. For example, the Arabian Cement Company Ltd.

(ACCL), Jeddah, produces around 1,000 tons of CKD/day, which is expected to double after the completion of its expansion project. Due to the high levels of chlorides and alkalis in CKD, many cement manufacturers are reluctant to recycle CKD into the production line [Kessler, 1995; USEPA, 1998]. Though, the figures on CKD production are not precise. CKD production in Saudi Arabia was about 1.2-1.4 million ton/year in 1998. It has been projected to increase the cement production and the restrictions on air pollution in the Kingdom will be fully applied [Al-Refeai and Al-Karni, 1999].

Due to its chemical composition, CKD has a potential to be used in stabilization of eastern Saudi soils. Typical analyses for UK cements and CKD are given in Table 2-2**.**

Table 2-2: Typical Chemical Composition of CDK and Cement [Aidan and Trevor, 1995]

Constituent	**CKD**	**OPC**
Al_2O_3	3-6	5
CaO	38-50	64
Cl	0-5	<0.1
Fe_2O_3	1-4	3
Free CaO	1-10	2
K_2O	3-13	<1
Loss On Ignition(LOI)	5-25	1
MgO	0-2	1
Na_2O	0-2	<1
SiO_2	11-16	22
SO_3	4-18	3

2.1.2.2 Electric Arc Furnace Dust (EAFD)

Electric arc furnace dust (EAFD) is a by-product of smelting iron ore to separate the metal fraction from impurities. It can be considered to be a mixture of metal oxides and silicon dioxide. However, slag can contain metal sulfides and metal atoms in the elemental form. While slag is generally used as a waste removal mechanism in metal smelting, it can also serve other purposes, such as soil stabilizer, assisting in the temperature control of the smelting; and also minimizing any re-oxidation of the final liquid metal product before the molten metal is removed from the furnace and used to make solid metal. It can be used as stabilizer for concrete and mortar [Fredericci et al., 2000].

It is widely reported that about 20 kg of dust is produced for each ton of steel produced. It is a complex, fine-grained, high-density material containing high amounts of zinc and iron, and significant amounts of calcium, manganese, magnesium, lead and chromium [De Sauza et al., 2010].

There are four groups for steel production in Saudi Arabia: SABIC, Al Ettefaq, AlRrajhi and Al Yamama that produce crude steel. The annual production of steel in Saudi Arabia is about 5 million tons in 2012 and it is expected to increase in 2013 to 6.9 million tons [The Saudi Economist Magazine, 2012; Asharq Al-Awsat, 2012].

About 15 to 20 kg of EAFD is produced per ton of steel [Recupac, 2012]. Consequently, 100,000 tons of EAFD is produced annually. Therefore, slag, a steel by-product, is available and it would be wise to investigate the potential use of it for the improvement of the mechanical properties of eastern Saudi soils.

Yildirim and Prezzi [2009] reported that the specific gravity of the EAFD is in the range of 2.71 to 3.04

2.1.2.3 Oil Fuel Ash (OFA)

Oil fuel ash is a powdery residue generated by the power stations that use heavy oil as the source of fuel. It consists of inorganic substances, such as SiO_2, Al_2O_3, Fe_2O_3, with 70~80% of unburned carbon and heavy metals, like vanadium and nickel, that are present in the crude petroleum at the initial stages.

Saudi Arabia has the largest proven reserves of oil in the world and it is available and economically feasible for generation of power. Saudi Arabia's Water and Electricity Ministry has estimated the demand of the country for electricity power to be at least 30 Gigawatts by 2023-25. Saudi Arabia is investing heavily in increasing the power and drinking water capacity. Shuaibah is the first power and water project in Saudi Arabia, and the first of a total of four planned major projects. The goal of these projects is to increase the power plant capacity by 4,500 MW and to provide an additional 2.2 million cubic meters of drinking water daily [Najamuddin, 2011].

Saudi Arabia has been utilizing gas for power generation utilities as part of the government's plans to expand gas utilization. Moreover, it is also known that the biggest power plants in Saudi Arabia are fueled by oil. It is to be noted that Saudi Arabia is not utilizing, at the time being, coal or nuclear power, future plans will witness large increase in the use of oil as fuel for power plants [Dincer and Al-Rashed, 2002]. However, just like coal, which is being used for electric power generation in many countries, the process of power generation produces huge quantities of oil fuel ash as a solid waste.

The literature indicates a lot of research being undertaken to find ways and means of reusing the fuel ash produced from burning coal in the power plants. However, the fly ash produced from fuel oil is not widely investigated, which is different in many of its characteristics and chemical composition from the coal fly ash. Its contents of hydrocarbons, heavy metals, sulfur, and residue ash are different. Hence, its impact on the environment is different and its uses and ways of disposal are different. Therefore, further research studies are needed to explore ways and means of utilizing the heavy oil fuel ash and its safe disposal, particularly in Saudi Arabia, which produces large quantities of this type of ash. The typical physico-chemical properties of heavy oil fuel ash are as shown in Tables 2-4.

Table 2-3: Typical Physico-Chemical Properties of Oil Fuel Ash [Kwon et al., 2005]

Constituent	**Percentage by Weight**
Carbon (C)	80.61
Hydrogen (H)	0.62
Nitrogen (N)	0.97
Magnesium (Mg)	0.02
Vanadium (as V)	0.44
Sulfur (as S)	3.5-5.16
Non-soluble in acid	84.79
PH 1 % solution	2.30
Ash	2.87-4.5
Residual moisture	7-9
Volatile matter	11.01

Oil fuel ash contains relatively high heavy metal content, particularly vanadium (as V_2O_5) and nickel (as NiO). In addition, the residual carbon level in the fuel ash is very high. Typical fuel oils contain Fe, Ni, V, and Zn, in addition to aluminum (Al), calcium (Ca), magnesium (Mg), silicon (Si), and sodium (Na). Transition metals [iron (Fe), manganese (Mn), and cobalt (Co)] and alkaline-earth metals [barium (Ba), calcium (Ca), and magnesium (Mg)] may also be added to the ash collector for the suppression of powder or for corrosion control [Bulewicz et al., 1974; Feldman1982, quoted by Abdulah, 2009].

Toxic heavy metals, such as vanadium (2.08% as V_2O_5) and nickel (0.37% as NiO) are also present in the heavy oil fuel ash. The high carbon content and presence of toxic heavy metals suggested that this oil fuel fly ash is a hazardous dust that requires careful handling and safe disposal to ensure proper environmental protection.

2.2 Review of Previous Stabilization Studies

Improvement of mechanical properties of the soil in terms of strength, durability and cost, to be used as construction materials is the key point from engineering point of view. Stabilization of weak soils could be mechanical or chemical, adding agents that help in the improvement of engineering properties of treated soils. Stabilizers to be utilized have to satisfy noticeable performance, durability, low price, eco-friendly and can be easily implemented. Since OFA, CKD and EAFD are industrial by-products, it would be a noble task if these waste materials could be utilized in the stabilization of indigenous soils. Many researchers have studied stabilization of soils with different stabilizers. Therefore, previous research work would be reported to provide clear picture related to those stabilizers which might help investigate the possibility of incorporating them in the stabilization of three selected indigenous eastern Saudi soils (namely, sand, marl and sabkha).

Yildirim and Prezzi [2009] investigated the usage of EAF slag with 5 and 10% of Type C fly ash as sub-grade materials. They used mechanical evaluation techniques that included unconfined compression, long-term swelling response, large-scale direct shear and environmental tests in their study. It was reported that 10% fly ash with EAFD was suitable from mechanical and environmental point of view to be used as sub-grade construction material.

Al-Amoudi [2002] investigated the use of cement and lime to stabilize sabkha soil from Al-Qurayyah, eastern Saudi Arabia. The bearing capacity of plain and chemically-stabilized sabkha mixtures was evaluated using CBR, unconfined compressive strength, and Clegg impact value for different dosages of lime and cements ranging from 0 to 10% and at different moisture contents. He reported that cement improved the performance of stabilized sabkha much more than lime, particularly at high moisture contents. Further, the 7% cement addition satisfied the strength requirements to enable sabkha soil to be used as a base course in rigid pavements and a sub-base in the flexible pavements.

Al-Amoudi et al. [2006] investigated the stabilization of four eastern Saudi soils using CKD. The addition of CKD to the different types of soil, namely sandy sabkha, white marl with low plasticity, non-cohesive marl and plastic marl, resulted in a decrease of the dry density and increase in the optimum moisture content. The unconfined compressive strength exhibited substantial increase of about 5.66, 1.69, 1.41 and 13.2 times by the addition of

50% CKD to the sandy sabkha, white marl with low plasticity, non-cohesive marl and plastic marl soils, respectively.

Al-Guniayan [1998] carried out his study on the stabilization of eastern Saudi marl mixed with sand in addition to cement and bitumen. Dosages 25, 35, 50, 65 and 90% sand were studied. 3, 5 and 7% of cement, Type V, with sand-marl mixture were investigated. Unconfined compression (sealed and exposed curing), durability, stability and CBR tests were conducted. Sand-marl mixtures 35 and 65% with 5% cement was found to be adequate for stabilization of eastern Saudi marl.

Shabel [2006] investigated the stabilization of Jazan sabkha using cement mixed with CKD. CBR, durability and unconfined compression tests on sealed cured specimens were used as the evaluation techniques. Different dosages of CKD and CKD-cement mixtures with sabkha soil were tested. It was concluded that Jazan sabkha treated with 2% cement + 20% CKD satisfied the USACE 7-day strength and durability requirements to be used as a sub-base material in rigid pavements. The low dosage (20% CKD plus 2% cement) of the CKD that satisfied the strength requirement, here, was due to the low LOI (8.32%), low alkalis (1.65) and the free chloride CKD used. Further, the low salinity of the investigated sabkha may be the other factor for the good performance of soil stabilized with low dosage of CKD.

Aiban et al. [2006] carried out a study to upgrade the load carrying capacity of pavements constructed on sabkha soils using geotextiles, and to assess the effect of geotextile grade, base thickness, loading type (static and dynamic) and moisture condition (as-molded and soaked) on the performance of soil-fabric aggregate (SFA) systems. Further, the sabkha soil was treated with different dosages (5, 7 and 10%) of Portland cement and the performance of cement-stabilized sabkha was compared to that of the SFA system under different testing conditions. CBR and load plate tests were used for the evaluation. It was reported that the use of geotextile has a beneficial effect on sabkha soils, especially under wet conditions. Although the improvement in the load-carrying capacity of sabkha samples with high dosages of cement showed better results than the inclusion of geotextile, an economic analysis showed that the use of geotextiles would be superior.

Al-Amoudi et al. [2010] carried out California Bearing Ratio (CBR), Clegg Impact Hammer (CIH), unconfined compressive strength and durability (standard and modified) tests to assess the improvement of indigenous marl under different field-simulated conditions, for its use as a road base material with and without chemical treatment (lime and cement). Cement was found to be superior to lime, both in terms of strength improvement and durability requirements. Sealed conditions showed lower improvements than exposed one.

Mohamedzain and Al-Rawas [2011] summarized the outcomes of many studies that were carried out to stabilize sabkha soils using cement. The results are shown in Figure 2-5.

The differences in the results might be due to the variation of curing conditions (sealed or exposed curing), type of cement used, size of the specimens, the gradation and chemical compositions of soils.

Solanki et al. [2007] evaluated the effectiveness of different percentages (5, 10 and 20%) of CKD as a soil stabilizer, relative to the implementation of new mechanistic-empirical pavement design guide (MEPDG). Cylindrical specimens of CL-ML soil were compacted and cured for 28 days in a moist room having a constant temperature and controlled humidity. After curing, the specimens were tested for resilient modulus (MR), modulus of elasticity (ME) and unconfined compressive strength (UCS). Scanning electron microscope (SEM) was utilized, too. The increase in resilient modulus and strength of stabilized soil with CKD was reported. Mixtures of silty soil with 15% CKD substantially improved resilient modulus (Mr) value of soil up to 425%. The UCS was found to be 34 kPa for the raw soil. Soil mixed with 5%, 10% and 15% CKD had UCS of 179, 923 and 1,323 kPa, respectively.

Al-Aghbari and Dutta [2008] investigated the effect of cement and cement bypass dust on the engineering properties of sand. They found that sand with ordinary Portland cement can be a good material for base or sub-base course application whereas sand with cement by-pass dust can be used for improving the bearing capacity of sand to support low to moderate rise building.

Daous [2004] studied the utilization of CKD and OFA blended in cement in Saudi Arabia. CKD produced in a local cement production plant along with fly ash resulting from combustion of heavy fuel oil in a local power generation plant were utilized as waste material blends with Portland cement, produced from the local plant, at various proportions. He reported that satisfactory mechanical strength (a minimum of 94% of compressive strength of ordinary Portland cement) can still be achieved in blends utilizing 90% cement and not more than 4% fly ash. Adequate mechanical strength (a minimum of 80% of compressive strength of Portland cement) was achieved in blends utilizing as little as 70% cement when only kiln dust was blended.

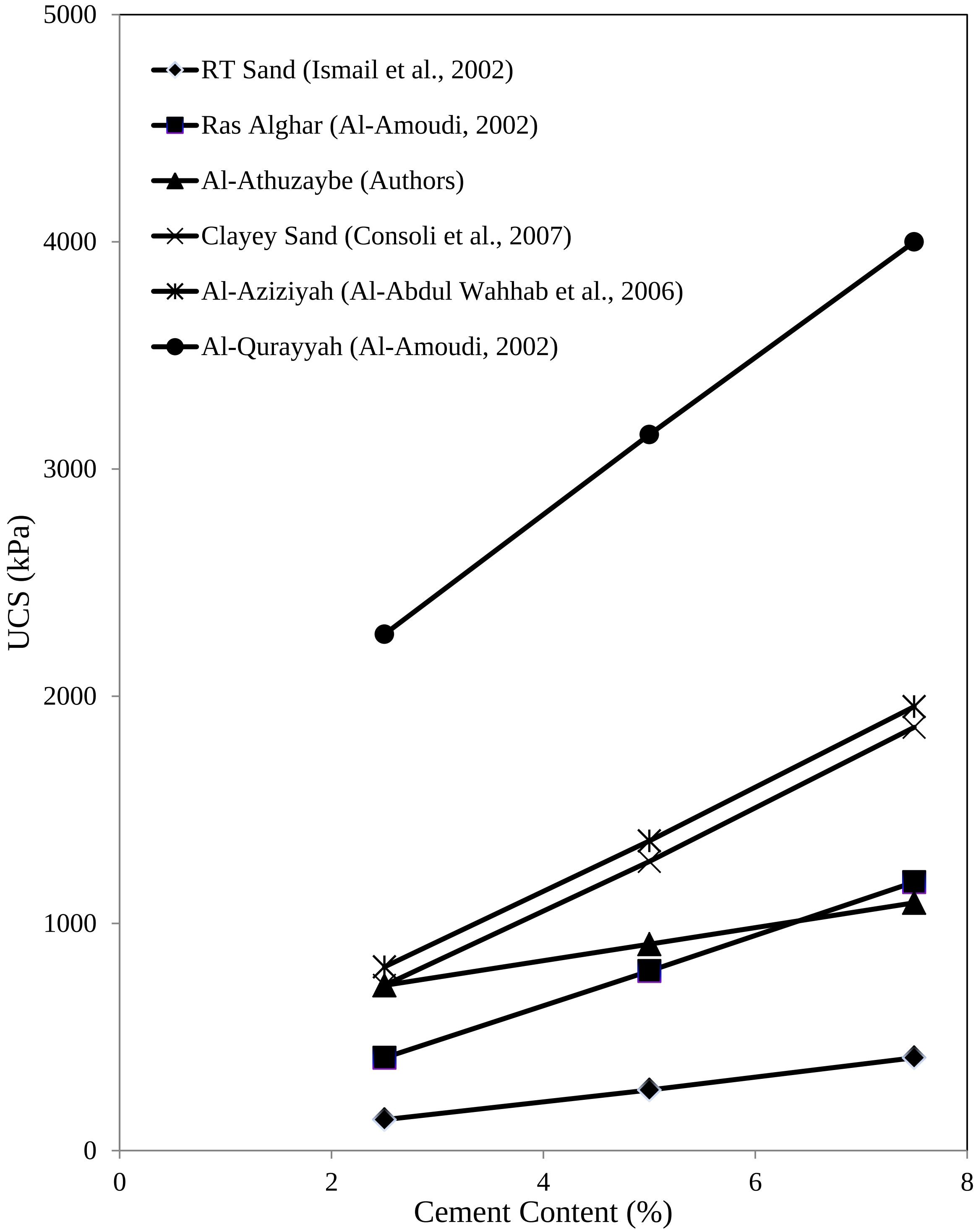


Figure 2-5: Unconfined Compressive Strength for Different Sabkha-Cement Mixtures (7-Day Curing) [Mohamedzain and Al-Rawas, 2011]

Abdullah [2009] investigated the potential use of OFA and CKD in the stabilization of two indigenous soils (i.e. sand and non-plastic marl), in terms of strength and durability. The two types of soil were treated with different dosages of OFA and CKD. The mixtures of the stabilized soils were thoroughly evaluated using compaction, CBR, unconfined compression and durability tests. A CKD content of 30% was found to be adequate for the effective stabilization of sandy soil. His findings were due to the gradation of the sand studied. A CKD content of 20% plus 2% cement was found to be adequate for the effective stabilization of non-plastic marl. That was probably due to the good quality of the marl investigated. An OFA content of 5% plus 5% cement was found to be adequate for the effective stabilization of non-plastic marl. In my investigation, stabilization of the three soils with three candidate stabilizers was studied. In addition, the mechanism of the performance of each stabilizer was explained. Furthermore, the effect of the stabilizers on the soaked CBR for the stabilized soils, which most probably reflects the eastern Saudi field condition, was studied.

Seco et al. [2011] carried out tests to investigate the effect of curing on the stabilized marl with lime. Specimens of marl with different dosages (1, 2, 3, 4, 5 and 6%) were prepared and cured for 7, 14 and 28 days before testing. The improvement in the mechanical properties of treated marl was evaluated using CBR and unconfined compression tests. The results showed that 3% of lime achieved the maximum improvement in the mechanical properties of marl.

Rahman et al. [2011] presented a review on CKD from the literature search and the experimental investigation carried out in their studies. The authors carried out tests to evaluate the improvement in the dry density and compressive strength of different Saudi eastern soils and came up with the conclusion that that CKD is potentially useful in stabilizing a variety of soils (i.e. sandy and clayey). The authors reported, too, that the stabilizing effect is primarily a function of the chemical composition, fineness, and dosage level of the CKD as well as the type of parent soil. For 0% to 50% CKD additions, sealed curing for 14 days specimens, the improvement of the unconfined compressive strength was reported: For sabkha soils, the increment was from 214 to 2,752 kPa; for low plasticity white marl, the increment was 1,033 to 2,303 kPa and for non-plastic marl, the increment was from 357 to 4,709 kPa. The durability of the stabilized soils was not reported.

El-Sayed et al. [2000] conducted tests to find out a by-product from the Saudi industry that can consolidate friable sand formations. They used steel-making slag (SMS) and blast furnace slag (BFS) obtained from a steel plant in Jubail. The slag was mixed with chemicals as activator and with sand and cured at 95°C for 24 hours. The compressive strength and the absolute permeability of consolidated sand were evaluated. The effect of aging in kerosene as representative to crude oil and water to show the effect of produced fluids on the consolidated sand was also investigated. The results showed that the steel making slag mixed with calcium chloride and calcium hydroxide at a 30% to 50% by weight of water is able to consolidate the friable sands. The permeability of the consolidated sand lies between 70 to 28% of the absolute permeability of the friable sand which is considered reasonable. Immersing specimens in kerosene or in water increased both the permeability and compressive strength. The increment in the absolute permeability was from 0.40 to 0 .95 Darcy and the increment in the compressive strength ranged from 3,450 to 1,7230 kPa.

Azzam [2012] studied stabilization of swollen clay by polypropylene. He studied 5, 10 and 15% polymer. Polymer content reduced the values of free swelling, swelling pressure and increased the unconfined compressive of the stabilized soil, was reputed. Free swelling was reduced from 30 to 10%. Swelling pressure was reduced, accordingly, from about 260 to about 70 kPa and UCS increased from 75 to 140 kPa. Also, he reported that the proposed stabilizing technique increased the bearing capacity under the model footing and modified the settlement-stress relationship.

Alhassan [2008] studied stabilization of A-7-6 lateritic soil with 2-12% rice husk ash (RHA) by weight of the dry soil. He used British standard light (BSL) compaction energy level. Compaction characteristics, California bearing ratio (CBR) and unconfined compressive strength (UCS) tests were used for the evaluation. A general decrease in the maximum dry density (MDD) and increase in optimum moisture content (OMC) with increase in RHA content were reported. Slight improvements in the UCS and CBR with increase in the RHA content were reported, too. The peak UCS values were recorded at between 6-8% RHA.

Homauoni and Yasrobi [2011] studied stabilization of dune sand utilizing poly methyl methacrylate and polyvinyl acetate. Physical and mechanical tests were carried out. The California bearing ratio test was used to measure the engineering properties of the stabilized materials under dry and the wet environmental conditions. Results indicated that both polymers have good potential for increasing the strength of dune sands in the dry state and that there is little decrease in the CBR strength in the saturated state in comparison with the dry state. The results also demonstrated that the optimum added quantity of polymer for maximum effect was 3% by weight and that the curing time for maximum effect was 28 days. The amount of polymer added was an important factor for improving the California bearing ratio strength in comparison with curing time of the stabilized specimens.

Sobhan and Mashnad [2002] conducted a research to evaluate the split tensile load-deformation, strength and toughness properties of a granular soil that was chemically stabilized with cement and fly ash, and mechanically reinforced with recycled plastic strips (0.5, 1, 1.5 and 2% of recycled plastic strips with different lengths). 1.5 % of recycled plastic strips has made the highest improvement regardless of the lengths of the strips. It was found that the inclusion of HDPE fibers reduces the compressive strength. However, fiber reinforcement does not meaningfully improve the tensile strength, but significantly enhances the overall toughness of the composite.

2.3 Summary of Literature Review

The review literature indicated that the engineering properties of weak soils need to be improved either chemically or mechanically. Mechanical stabilization of soils is done by compaction. On the other hand; chemical stabilization of soils is done using additives. Additives should be environmentally friendly, easy to be used, available locally and economical.

Researchers over the world have carried out many studies to improve weak soils utilizing available resources such as coal fly ash, polymers, geotextiles, geogrids and rice husk ash in addition to the conventional materials such as cement and lime as the stabilizing agents.

Consequently, soils in the eastern Saudi area are weak in their existing condition. Further, marl and sabkha soils are sensitive to water, which requires stabilization prior to use them as construction materials. Besides; the variation of the chemical compositions of the investigated soils and the harsh environmental conditions in the area such as the high humidity made the problem pro-compounded. Furthermore, urbanization resulted in plenty of indigenous by-products in eastern Saudi areas. Some of Those by-products have toxic characteristics, which makes them hazardous for human and disposal of those by-products is very expensive. Besides; in the eastern Saudi area, some researchers have investigated the potentiality of using some by-products in engineering applications such as in the improvement of the concrete properties.

Also, only a few researchers have conducted studies utilizing some of those by-products in stabilization soils at different conditions. Though, the mechanism of the performance of the investigated stabilizers was not fully understood, the by-products are of different characteristics and soils are of different chemical composition which affect significantly the the engineering properties of the stabilized soils. In addition, insufficient studies of using some of the by-products such as CKD and OFA in stabilizing some soils, namely marl and dune sands, in eastern Saudi area have been performed under different conditions, which does not match the field status such as modified compaction energy, sealed curing and soaked CBR. Similarly; using of CKD in stabilization of Jazan sabkha was studied. Furthermore, using of EAFD indigenous by-product in stabilizing local soils has not been studied yet.

Therefore, this study covered stabilization predominate soils in eastern Saudi with all of the available by-products considering the field conditions and environmental restrictions. Moreover; the mechanism of the performance of the available indigenous by-products in the investigated stabilized soils was fully studied using the appropriate techniques. That made this investigation advanced and commendable to be carried out.

CHAPTER 3

EXPERIMENTAL PROGRAM

The main objective of this study was to assess the possibility of improving the properties of local soils utilizing indigenous industrial by-products. To achieve this objective, three different types of soils, namely sand, non-plastic marl and sabkha from the Eastern Province of Saudi Arabia, were treated with different dosages of the selected industrial by-products, namely oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD).

A comprehensive test program consisting of seven tasks was carried out in accordance with the following schematic plan shown in Figure 3-1.

Firstly, the soil samples and industrial by-products were collected. In the second task, the chemical composition and physical properties of the soils and industrial by-products were determined. Besides; Atterberg limits and sieve analyses of the soils were also determined. Thirdly; the determination of maximum dry density and optimum moisture of the suggested mixtures was carried out. Fourthly; the unconfined compressive strength of the proposed mixtures was determined. Fifthly; the soaked CBR of the mixtures that satisfied the strength requirement was carried out. Sixthly; the mixtures that satisfied strength and CBR requirements were subject to durability tests. Seventhly; the toxicity of the mixtures satisfied the strength was determined. The seven tasks that were identified earlier will be discussed in detail in the following sub-sections.

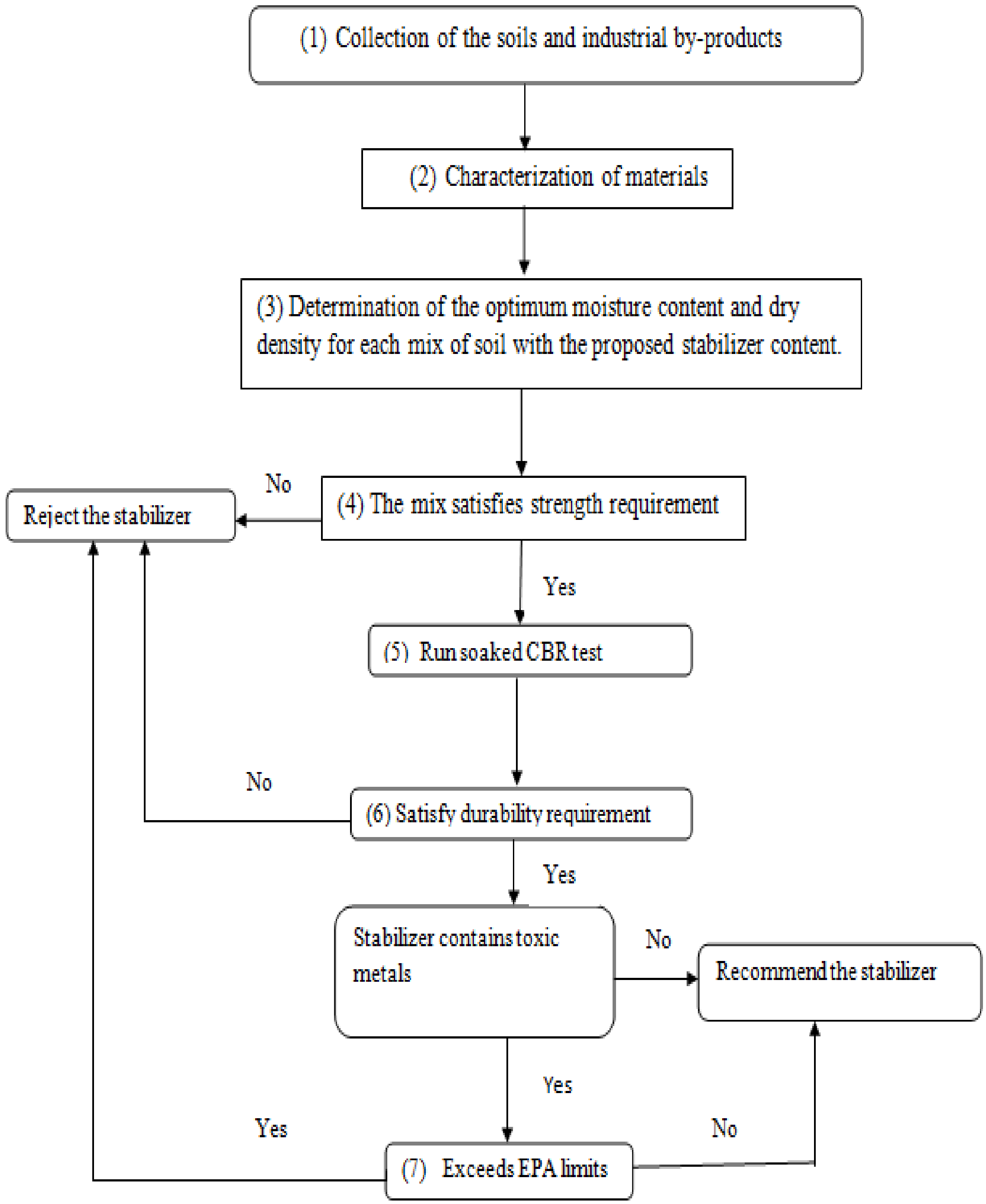


Figure 3-1: Flow Chart for the Experimental Program

3.1 Collection of Soil Samples

Three eastern Saudi soils, namely non-plastic marl, sand and sabkha samples, were collected from different places. The non-plastic marl sample was collected from the KFUPM campus (material excavated between Building #3 and Building #26). The sand sample was collected from Dhahran dune sands. Sabkha soil was retrieved from Ras Al Ghar site, the same area used in the PhD dissertation of professor Al-Amoudi [Al-Amoudi, 1992]. Figure 3-2 shows the location of sabkha sampling point.

3.2 Procurement of the Industrial By-Products

The industrial by-products were procured from the local market. CKD was obtained from the Saudi Arabian Cement Company, Jeddah. EAFD was procured from the Saudi Iron and Steel Company (HADEED). OFA was procured from the Saudi Electricity Company (Al-Shuaibah Power Plant, Western Saudi Arabia).

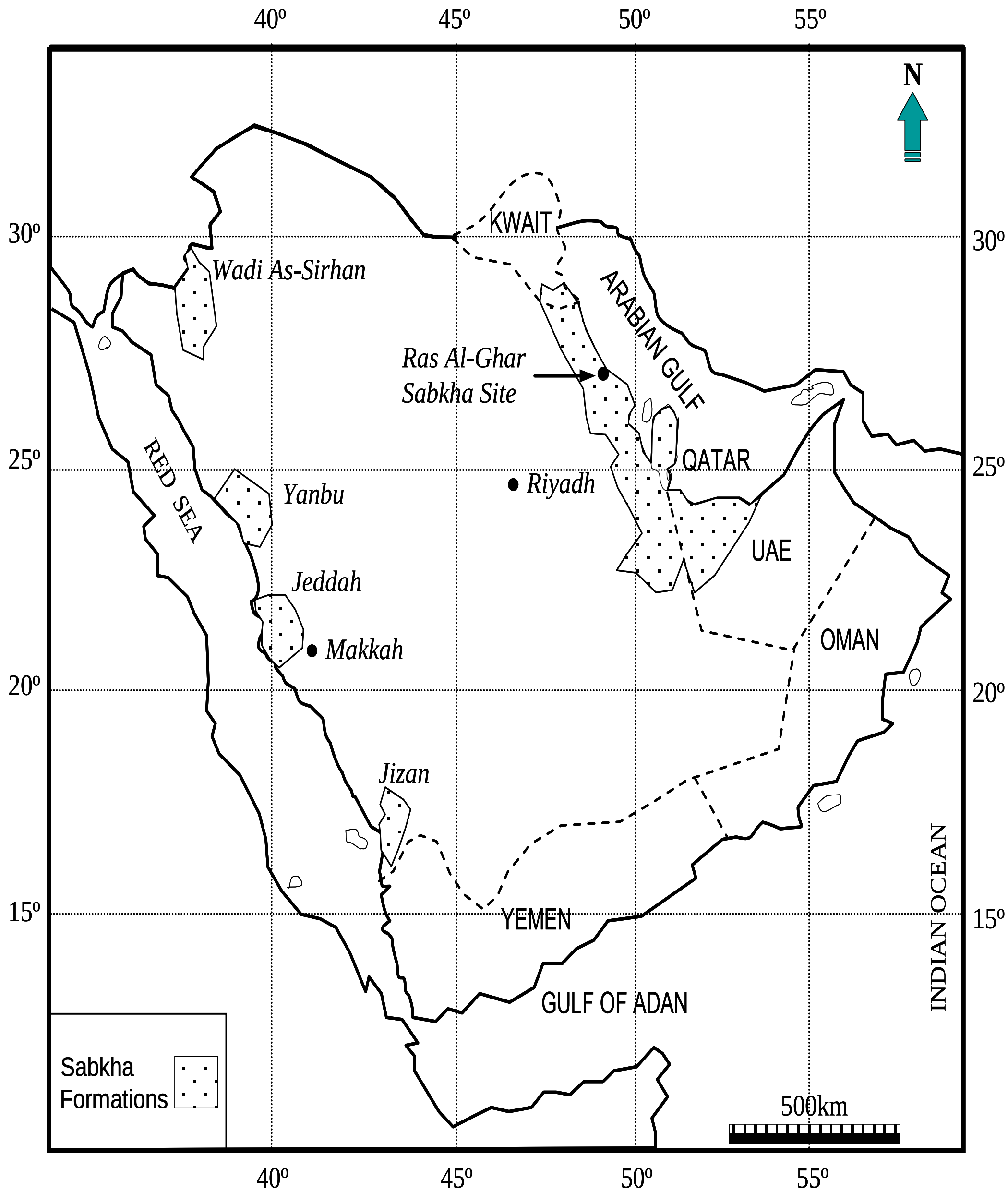


Figure 3-2: Location of Sabkha (indicated by the arrow)

3.3 Preparation of Soil Samples

The marl and sand soil samples were brought to the Geotechnical Laboratory at KFUPM and, thereafter, sieved through ASTM sieve #4 to remove particles greater than 4.75 mm. then the soil materials were thoroughly mixed, oven dried and stored in plastic drums until testing.

The sabkha soil was collected from Ras Al-Ghar site, eastern Saudi Arabia, as shown in Fig. 3-2. The sabkha surface was observed to be covered with non-crystallized halite, which extended 3 to 4 cm in depth. Layers of gypsum were also observed during the excavation. Samples were retrieved from all layers above the groundwater table, excluding the salt crust. Once the soil was brought to the Geotechnical Laboratory, it was first spread on plastic sheets, on area of 5 by 10 meters, outside the laboratory and it was regularly turned upside down every day for air drying for about 10 days. Thereafter, plastic hammers were used to gently break the soil lumps to pass ASTM #4 sieve. Finally, the whole soil was thoroughly and homogeneously mixed and preserved in plastic drums until testing.

Sand was collected from Dhahran dune sands, which provided for researchers at the Civil and Environmental Engineering Department, from that materials used for construction purposes.

3.4 Characterization of Materials

The selected soils and industrial by-products were tested to determine their mineralogical and physical properties.

3.4.1 Mineralogical Analyses

Knowledge of the mineralogical composition of a material helps in predicting its behavior and reaction under different environmental conditions. The mineralogical analyses of the soils and the industrial by-products were performed at the Research Institute (RI), KFUPM.

The soils were initially air dried, sieved using sieve #10 and thoroughly mixed well for homogenization. They were then pulverized and sieved using sieve #200. Thereafter, the pulverized soil samples were oven dried at 70 ^{o}C for 72 hours [Conklin, 2005; Brady and Weil, 2010]. Finally, about 10 grams of each soil sample was utilized for the mineralogical analyses. The mineralogical composition of the soils and industrial by-products was determined by X-ray diffraction method. The x-ray diffractometer used in this investigation was RIGAKU ULTIMA IV X-RAY DIFFRACTOMETER. The generator settings were 40 kV and 40 mA at an angle between 6 and 90^{o} (2ɵ).

Further, samples of each cast specimens that satisfied the strength and durability requirements were prepared and utilized for mineralogical analyses in order to determine the chemical products that might be behind the improvement developed by the stabilization using various types of industrial by-products.

3.4.2 Specific Gravity

The specific gravity is needed for the calculation of void ratio, unit weight of soil, and soil particle size analysis. Since the three investigated soil samples were sieved through ASTM sieve #4 and the particle sizes of the proposed stabilizers are smaller than 4.75 mm, the specific gravity was determined in accordance with ASTM D 854. The test was conducted on two representative "disturbed" dried samples from each material and the average was taken as the specific gravity value.

However, for sabkha soil, the soil was oven dried to 70 °C until a constant weight was observed as recommended by Al-Amoudi [1995a].

3.4.3 Atterberg Limits

The liquid and plastic limits of each soil were conducted on the material passing ASTM sieve #40 using distilled water in general accordance with ASTM D 423 and ASTM D 424, respectively. The water content at 25 blows was measured as the liquid limits while the water content required to roll the soil to a thread of 1/8 in (3.2 mm) was the measure of plastic limit.

3.4.4 Grain Size Distribution

Grain size distribution of each soil was carried out in accordance with ASTM D 442. This test is a basic requirement in any soil investigation. It is also essential in almost all soil classification systems. Both dry and washed sieving techniques were used for the three types of soil.

In the wet sieving method, a representative dry soil sample was taken and washed through a set of sieves, including ASTM # 10, 20, 40, 60, 80, 100, 140 and 200 sieves until the water passing through each sieve was clear. For sabkha soil, the soil was oven dried at 70 °C until a constant weight was observed, as recommended by Al-Amoudi [1995a]. Then, the soil portion retained on each sieve as well as that passing through #200 sieve was dried in an oven and then weighed. The difference in weights of the (sieves + dry soils) and the (empty sieves) was used to determine the material percentage passing each sieve.

3.5 Stabilization of the Investigated Soils

The aim of soil stabilization is to improve its engineering properties. The degree of improvement is different from project to project and from soil to soil. The improvement depends on the amount and type of stabilizer, the environmental conditions, and the construction conditions as well as the properties of the soil itself. Considering all conditions which contribute positively or negatively, an optimum level of stabilizer should be determined which should also be economical and satisfy the minimum strength and durability requirements.

In this investigation, the three stabilizers, namely cement kiln dust (CKD), oil fuel ash (OFA) and electric arc furnace dust (EAFD) were studied as chemical admixtures. Ordinary Portland cement was used as a reference. These additives are considered as waste materials; and out of theses, those meeting minimum strength, high CBR and high durability requirements, would be chosen and recommended.

3.5.1 Additive Content and Specimen Preparation

In this investigation, the additive content is defined as the percentage of the weight of additive to that of oven-dry soil. Because cement is expensive, it is important to study and optimize the amount of the waste material that can replace or reduce the amount of cement required to stabilize soil in order to achieve targeted engineering properties, which depends on the soil type and its physical and chemical characteristics. Therefore, with maintaining maximum dry density, plain soil specimens, to serve as reference #1 and stabilized soil specimens, with varying dosages of the selected industrial by-products, were prepared with the optimum moisture contents from each soil sample. The dosages of industrial by-products that were studied are shown in the Table 3-1.

Table 3-1: Dosages of Stabilizers Studied

Stabilizer	**Dosage (by dry weight of soil)**
Cement (Reference)	2%, 5% and 7%
Cement Kiln Dust (CKD)	(i) 10%, 20% and 30% (ii) 2% cement plus 10%, 20% or 30% CKD
Oil Fuel Ash (OFA)	2% cement plus 5%, 10% or 15% OFA
Electric Arc Furnace Dust (EAFD)	2% cement plus 5%, 10%, 20% or 30% EAFD

Two percent cement by the weight of dry soil was added with the stabilizer content that could not improve the unconfined compressive strength of the stabilized soil (when it is used alone) to meet the strength requirement.

3.5.2 Curing Regime

Urban development and infrastructure construction have resulted in covering of the soil surface with impervious materials, which is known as soil sealing. Further, compaction of the soil that leads to impermeability is termed soil sealing. Remolded sealed soil specimens have showed lower strength than the exposed specimens [Al-Amoudi et al., 2010; Shabel, 2006; Al-Guniayan, 1998; Ahmed, 1995]. Therefore, to simulate the field condition and to adopt worst cases only, sealed regime was adopted for curing, in this study. All specimens were sealed and cured at laboratory condition (22 ± 3^{o}C) for 7 days before testing. Furthermore, since the ground water table is relatively very close to the ground surface for the majority of the soils in the region, soaked CBR tests were also performed.

3.6 Moisture Content-Dry Density Relationship

Modified Proctor compaction test was performed in this investigation. The purpose of any compaction test is to determine the compaction characteristics, especially the optimum moisture content at which the maximum dry density of the soil is attained. This test provides a relationship between dry density and moisture content for a given compaction method. The moisture-density relationship reflects the behavior of soils during compaction. Dry density and moisture content control the structure of the soil which directly often relates to the properties of the soil, such as strength, compressibility and permeability. Thus, the soil to be used as a construction material needs to be compacted to maximum dry density.

Depending on the grain size distribution of the soil sample, different compaction testing procedures are used. In this investigation, the modified Proctor compaction test (ASTM D 1557) was used, as illustrated below.

The following procedure was followed during the compaction of the investigated soils (non-plastic marl, sand or sabkha) with the stabilizers: The required amount of soil was placed in Hobort mixer (0.3 m^3 capacity), and the dosage of additive was added. Mixing was, thereafter, started in a dry state for about 1 minute, the water was then added to the mixture and mixing was continued for about another 3 minutes till the whole mixture was totally mixed and the final product was homogeneous. Compaction was made in five layers in the compaction mold that is of a height of 4.6 inch (116.8 mm) and a diameter of 4 inch (101.6

mm) and the number of blows per layer was 25. The dry density with moisture content were calculated and recorded. The compaction curves (i.e., dry density vs water content) were plotted for each mixture. The optimum moisture content and maximum dry density were recorded.

In order to maintain same energy (2710.5 kJ/m^3), the energy used for compaction was calculated based on the following equation.

$$CE=\frac{\text{Soil layers}\times\text{Blows per Layer}\times\text{Wieght of the Rammer}\times\text{Rammer fall}}{V} \tag{3.1}$$

Where:

CE = Compaction Energy (kJ/m^3)

V= Volume of the mold (m^3)

Equation (3.1) was used in the adjustment of the number of blows that needed in casting all the specimens prepared for all tests, in order to maintain same compaction energy.

3.7 Evaluation Techniques

In the macro-characterization study, modified proctor compaction test (ASTM D 1557), was conducted on untreated and treated samples of the three soils to assess the optimum moisture content corresponding to the maximum dry density. Plain and stabilized soil specimens were prepared at the optimum moisture content and compacted with compaction energy that met the maximum dry density. The specimens were tested after a sealed curing period of 7 days (in order to maintain consistency in the results). The following standard tests were carried out on the plain and stabilized soil specimens:

- Unconfined compressive strength (ASTM D 2166);
- Soaked CBR (ASTM D 1883); and
- Durability (ASTM D 559).

The specimens that meet the strength, durability and environmental requirements, were utilized to qualitatively explain the mechanism behind the improvements achieved by the additives. This was done by conducting XRD and SEM. The macro-characterization tests are described in details in the following sub-sections.

3.7.1 Unconfined Compressive Strength

Unconfined compressive strength (UCS, q_u) has commonly been used for the evaluation of the stabilized soils as well as untreated ones. qu test is frequently used in many standards and codes for stabilized earth materials and often a minimum UCS value is specified for different applications [Al-Amoudi, 2002]. q_u was adopted as a basic test in this investigation. UCS was measured in accordance with ASTM D 2166. Specimens with an h/d (height by diameter) ratio of 2 were prepared for all UCS testing. The required soil and additive content for each specimen were mixed first and then the corresponding (optimum) moisture content was added and mixed thoroughly in the mechanical mixer for 3 minutes. Thereafter, the mix was compacted in the mold in 3 layers and number of blows was adjusted according to Equation (3.1) into 69 blows/layer in a mold of 100 mm diameter and 200 mm height (h/d = 2) to the maximum dry density of the treated soil according to the modified Proctor compaction test. The mold used was of a split type with longitudinal slit along its axes. The slit was tightened and opened with the help of bolts. After compaction, the specimen was taken out of the mold by loosening the bolts, as shown in Figure 3-3.

Figure 3-3: Split Mold Used for Casting the Specimens for UCS Test

The specimens were wrapped in three layers of nylon sheets in order to inhibit any loss of moisture, as shown in Figures 3-4 and 3-5. The specimens were then put on the table in the laboratory and kept to cure for 7 days at the laboratory temperature (22 ± 3 ^{o}C). Then, each specimen was subjected to unconfined loading till failure, as shown in Figure 3-6. The deformation rate of the test was 1.25 mm/min. To ensure reliability of the results, two replicate specimens for each case were prepared, tested and the average UCS of the value two specimens was considered in the evaluation.

First, two machines, 300 kN that belong to the Structural Laboratory and one of 100 kN that belong to the Geotechnical Laboratory, were used for testing the unconfined compressive strength of 4 replicates of specimens treated with cement in order to check the calibration of the machines. Second, the machine of 100 kN capacity was calibrated. Third, the machine of

100 kN was used for testing of non-cemented specimens and the machine of 300 kN was used for conducting experiments of cemented specimens.

Figure 3-4: Some of Wrapped Stabilized Specimens Used for UCS Tests

Figure 3-5: Some of Wrapped Stabilized Specimens Used for CBR Tests

Figure 3-6: The UCS Test Setup

The mixtures that satisfied the strength requirements were taken into consideration for further tests that included CBR and durability.

According to ASTM D 4609, an immediate strength gain of 50 psi (345 kPa) is suggested to qualify the stabilizer as "effective". However, according to ACI [1990], the minimum 7-day qu specified for sub-base and sub-grade layers in rigid and flexible pavements construction by the USA Corps of Engineers (USACE) are shown in Table 3-2.

Table 3-2: USACE Minimum Unconfined Compressive Strength for Stabilized Soils [ACI Committee, 1990]

Stabilized Layer	**Minimum UCS, at 7-Day, psi (kPa)**	
	Concrete Pavement	**Flexible Pavement**
Base Course	500 (3,450)	750 (5,175)
Sub-base Course	200 (1,380)	250 (1,725)

3.7.2 Soaked CBR

California bearing ratio (CBR) test was originally developed in California, USA, as a means to evaluate the suitability of a soil to be used as a sub-grade material in pavements and, thereafter, adapted by the engineering communities as a test to empirically measure the strength of soil under controlled moisture and density conditions. The test is recognized worldwide because of its simplicity and applicability. Therefore, the test can easily be used to quantify the material for use in pavement construction.

According to the state-of-the-art report on stabilized soil by the Transportation Research Board [1987], quoted by Shabel [2006], the CBR test is not appropriate for characterizing the strength of cured stabilized soil and can only be used for relative comparison, and has little practical significance or meaning as a measure of strength or stability other than as a relative indicator test.

In this investigation, soaked CBR tests were conducted in compliance with ASTM D 1883. However, only the mixtures that satisfied the strength requirements had to be selected and subjected to soaked CBR tests. Therefore, all proposed contents of the candidate stabilizers that satisfied the minimum strength requirements were subjected to soaked CBR tests. The CBR mold has a height of 5 in (127 mm) and a diameter of 6 in (152 mm). The mixtures that satisfied the strength requirements were mixed at the optimum moisture content and compacted in the CBR mold in 5 layers and the number of blows per layer was 56 to satisfy the compaction energy requirement (Eq. 3.1).

After preparation, the specimens were sealed by plastic sheets and left to cure in laboratory conditions ($22 \pm 3^{o}C$) for 7 days, as shown in Figure 3-4. Since the ground water table is relatively very close to the ground surface for the majority of the soils in the region, the prepared specimens were subjected to surcharge load of 4.5 kg and submerged in water for 96 hours before testing, as shown in Figure 3-7. No swelling was observed; therefore, volume change was not reported.

Table 3-3 indicated the required CBR for soils classified according to unified soil classification (USC) and ASSSHTO systems to be used as a construction material in subgrade, sub-base and base structures.

Table 3-3: Soil Ratings for Roads and Runways [Bowels, 1978; and the Asphalt Institute, 1962; quoted by Liu and Evett, 2009]

CBR (%)	General Rating	Uses	Classification System	
			USC	AASHTO
0-3	Very Poor	Subgrade	OH, CH, MH, OL	A5, A6, A7
3-7	Poor to Fair	Subgrade	OH,CH, MH, OL	A4, A5, A6, A7
7-20	Fair	Sub-base	OL, CL , ML, SC, SM, SP	A2, A4, A6, A7
20-50	Good	Base, Sub-base	GM, GC, SW, SM, SP, GP	A1b, A2-5, A3, A2-6
> 50	Excellent	Base	GW, GM	A1a, A2-4, A3

Figure 3-7: Some of Soaked Specimens Used in CBR Tests

3.7.3 Standard Durability

Moisture, combined with temperature, can produce wet and dry or freeze and thaw cycles. The stabilized soils need to be strong and should maintain stability and durability to resist physical loads under the various cyclic environmental and exposure conditions. Rise and fall of water table, irrigation water, leakage from septic tanks and adjacent utilities, and seasonal variation of rainfall are responsible for these wetting and drying cycles. These conditions may result in weight loss and/or volume change which, in turn, induce tensile and compressive stresses in the stabilized soils [Al-Ayedi, 1996].

Standard indicate that the maximum allowable weight loss is 14% according to the Portland Cement Association (PCA) and 11% according to the USA Corps of Engineers (USACE) for soils classified as SP and soils having plasticity index of PI < 10, respectively [ACI Committee, 1990].

In this investigation, the durability of stabilized soils was evaluated using ASTM D 559. Specimens of stabilized soil that satisfied the strength requirements were prepared at the optimum moisture content. The mold used to prepare the soil specimens was 4 in. (101.6 mm) in diameter and 4.6 in. (116.8 mm) in height. Each specimen was compacted in three layers to its modified Proctor maximum dry density. The number of blows was adjusted to 41 blows for each layer in order get the same modified Proctor maximum dry density. After compaction, all specimens were extruded from the molds. Two replicates were prepared for each mix. These specimens were designated as the weight loss specimens.

All the specimens were cured for 7 days at the laboratory environment (22 ± 3^{o}C) and 100% relative humidity. Thereafter, they were placed in a water tank for 5 hours at room temperature and, thereafter, transferred to an oven at 71^{o}C and kept there for 42 hours. This process constituted one cycle of wetting and drying for the stabilized soils. At the end of this cycle, the specimens designated as volume change were dimensioned using a vernier caliper, and were weighed. The other two specimens were brushed using a standard brush with two strokes on the whole surface with a force of about 3 Ib. (1.36 kg). To apply the 3 Ib (1.36 kg) force, each sample was placed on a balance, and was then brushed while observing the specified force on the scale of the balance. The weight of the specimens before and after brushing was measured. Similar measurements were taken for the remaining 11 cycles thus subjected each specimen to 12 cycles, according to the standard ASTM D 559. At the end of each cycle, the weight loss of the respective specimens was recorded. At the end of 12 cycles, the specimens were dried to a constant weight at 110^{o}C. Therefore, the weight loss was determined according to the following equation (ASTM D 559):

$$WL(\%) = \left(\frac{W_i - W_f}{W_i}\right) * 100 \tag{3.2}$$

Where:

WL = Weight loss of the specimen after f cycles (%);

w_i = Initial oven-dry weight (kg); and

w_f = Final corrected oven-dry weight (kg).

It is worth mentioning that a correction was applied on the oven-dry weight, which could be determined according to the following equation (ASTM D 559):

Corrected oven-dry weight = A/B * 100 (3.3)

Where:

A = Oven-dry weight after drying at 230^{o}F (110^{o}C); and

B = Percentage of water retained on specimen plus 100.

3.7.4 Toxicity Characteristic Leaching Procedure (TCLP)

In order to take the environmental impact into consideration, the percolation of toxic metals into the ground water table, the TCLP set by the United States Environmental Protection Agency, (USEPA) [1998] was performed on specimens of treated soils that was stabilized with the stabilizers containing toxic elements and had already satisfied the minimum unconfined compressive strength requirements and durability considerations. The specimens were prepared at the same conditions of compaction and 7 days sealed curing. The test was carried out in accordance with the USEPA Method 1311. After 7 days of sealed curing, the specimens were crushed to pass through a 9.5 mm sieve then stored in plastic bags for the extraction.

7.5 g of the sieved crashed soil were inserted in TCLP extraction flask and 150 ml of TCLP buffer (1:20) ratio was added. Since the sample pH was greater than 5, the TCLP buffer fluid # 2 was used. Fluid # 2 was prepared by adding 5.7 ml of glacial acid to 500 ml double distilled water (DDW) in 1 L volumetric flask and a pH of 2.99 was recorded. The TCLP extraction flask was then installed in a TCLP rotary apparatus which was made to rotate at 30 rpm for 18 hours. The leachant was then taken out from the extraction flask and filtered using Whatman 42 filter paper. Thereafter, all the samples were acidified to pH 2 using 2% of nitric acid. Then, the TCLP metals were determined by inductively coupled plasma (ICP) apparatus.

The eight USEPA-regulated-TCLP metals are arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver. The concentrations of the regulated metals that leached from the stabilized soil specimens would be compared with the maximum "allowable" concentrations set by the USEPA for toxicity characteristics of the regulated metals. Table 3-4 shows the allowable limits of the toxic elements.

3.7.5 Micro-Characterization Study

For the micro-characterization studies, scanning electron microscopy (SEM) was utilized to study the morphology of the mixtures that satisfied the strength, durability and environmental requirements. A JEOL 500LV scanning electron microscope utilizing the secondary electron mode was used. Initially; cylindrical specimens (100 mm in diameter and 200 mm in height) were prepared at the optimum moisture content, compacted using compaction energy of modified Proctor and sealed cured at laboratory condition for 7 days. Thereafter, specimens of about 10 mm in diameter and 5 mm in height were carefully cut from the cast cylindrical specimens using a sharp knife and submitted to the Research Institute at KFUPM for testing. The specimens were coated using gold (Au), to eliminate the conductivity of the specimen, before testing.

Back-scattered electron images (BEI) and SEM with energy dispersive X-ray analysis were conducted for each specimen.

Table 3-4: Allowable Limits of the Toxic Elements [USEPA, 1998]

Metal		**EPA**
Name	Symbol	(mg/l)
Silver	Ag	5
Arsenic	As	5
Barium	Ba	100
Cadmium	Cd	1
Chromium	Cr	5
Mercury	Hg	0.2
Lead	Pb	5
Selenium	Se	1
Nickel	Ni	NR
Vanadium	V	NR

NR: Not regulated by EPA

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of the experimental program are presented and appropriate interpretations for such data are addressed to explain the mechanisms for the behavior of the soils before and after their stabilization with cement, cement kiln dust, electric arc furnace dust or oil fuel ash.

The results are presented in three main sections, namely characterization of materials and macro and micro-characterization studies.

4.1 Characterization of Materials

The results of characterization tests conducted on the selected soils and industrial by-products are discussed in the following sub-sections.

4.1.1 Mineralogical Analyses

The mineralogical composition of the investigated soils (namely non-plastic marl, dune sand and sabkha) and the stabilizers were determined according to the procedures described in Chapter 3.

4.1.1.1 Mineralogical Composition of the Investigated Soils

The mineralogical composition of the investigated soils was performed using the X-ray diffraction (XRD) technique. Figures 4-1 through 4-3 show the X-ray diffractogram of the investigated soils.

Figure 4-1 shows the X-ray diffractogram of marl. These X-ray peaks therein reveal the presence of about 60% dolomite [$CaMg(CO_3)_2$], 30% quartz (SiO_2) and 6% calcite ($CaCO_3$) in addition to traces of other minerals. The relatively high percentage of calcite and quartz is responsible for the non-plastic and fine–grained nature of this type of marl [Al-Amoudi et al., 2010].

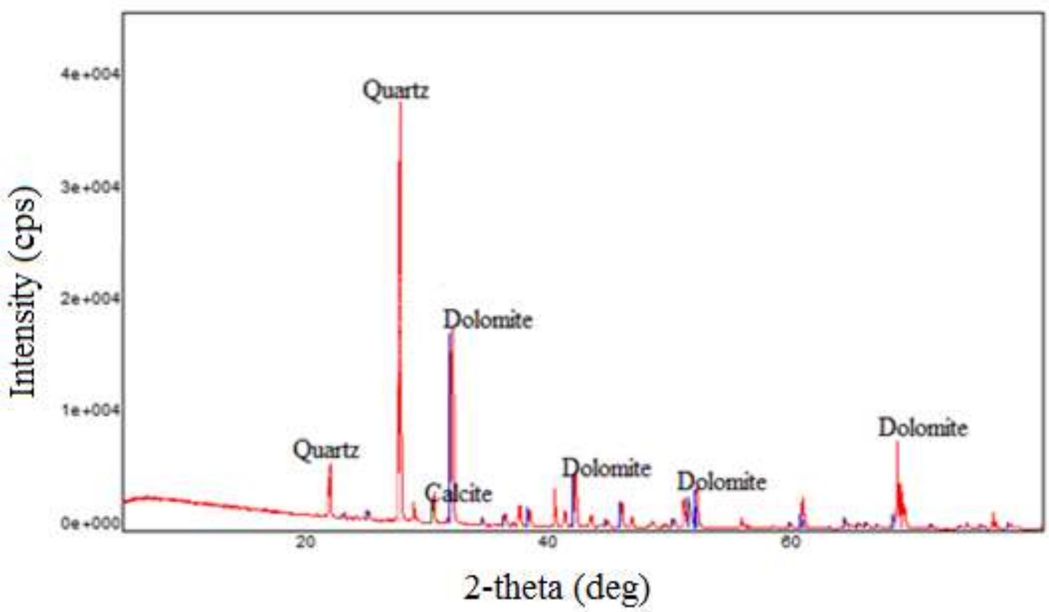


Figure 4-1: X-Ray Diffractogram for Non-Plastic Marl

Figure 4-2 shows the X-ray diffractogram for sand. The peaks for quartz were noted in this diffractogram. Quartz (SiO_2) constitutes about 100% of the sand.

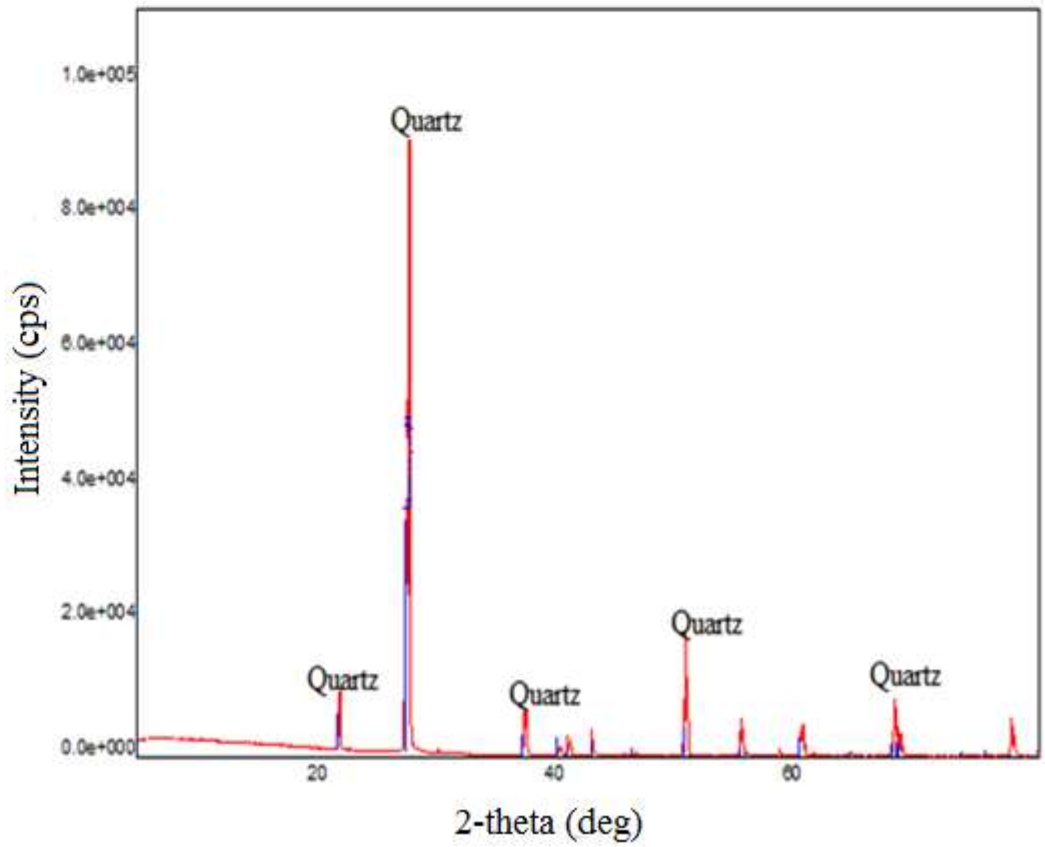


Figure 4-2: X-Ray Diffractogram for Dune Sand

Figure 4-3 shows the X-ray diffractogram for sabkha from Ras Al-Ghar. Peaks for quartz (75%), gypsum (12%) and halite (10%) were noted in addition to traces of other minerals. The high percentage of quartz is responsible for the non-plastic and fine–grained nature of this type of sabkha [Al-Amoudi et al., 2010].

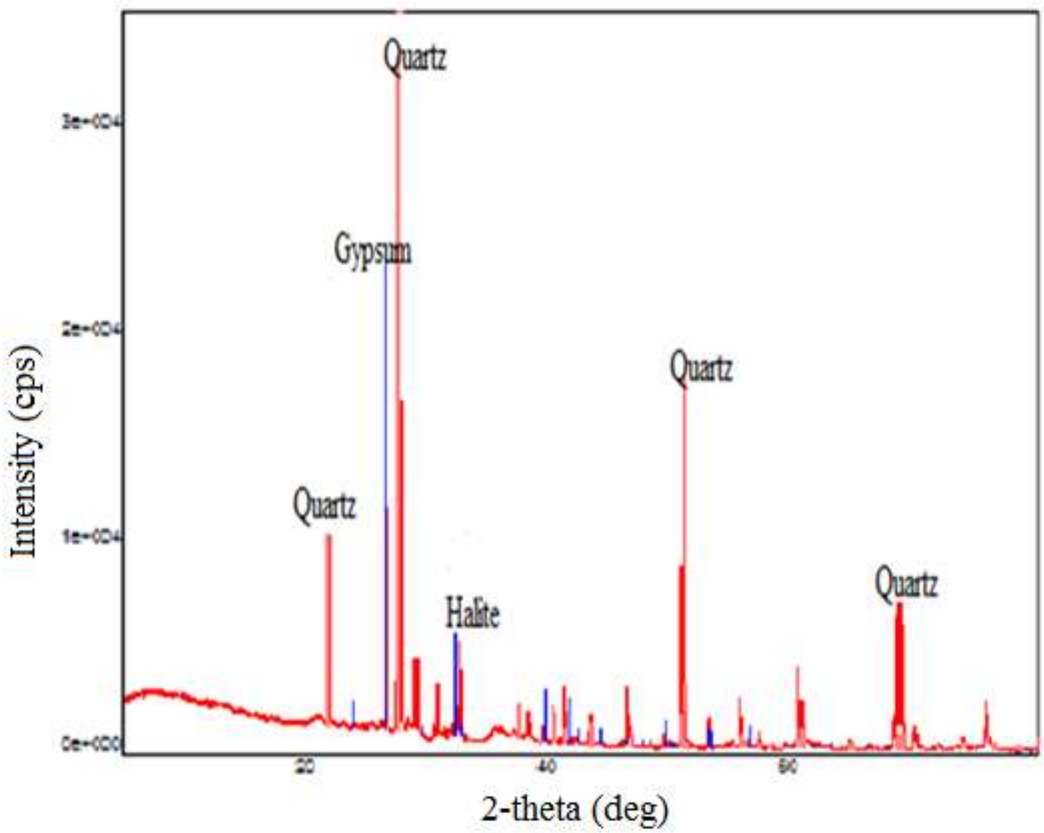


Figure 4-3: X-Ray Diffractogram for Sabkha

4.1.1.2 Chemical Composition of the Proposed Stabilizers

As stated earlier, ASTM C 150 Type I cement, CKD, EAFD and OFA were used as stabilizers. The chemical composition of these materials is summarized in Tables 4-1 through 4-3.

Table 4-1: Chemical Composition of the Used CKD

Constituent	**Weight %**
CaO	49.3
SiO_2	17.1
Al_2O_3	4.24
Fe_2O_3	2.89
K_2O	2.18
MgO	1.14
Na_2O	3.84
P_2O_5	0.12
Equivalent alkalis (Na_2O + $0.658K_2O$)	5.27
SO_3	3.56
Chloride	6.90
Loss on ignition, LOI	15.8
BaO (µg/g (ppm))	78.2
Cr_2O_3	0.011
CuO	0.029
NiO	0.012
SrO	0.37
TiO_2	0.34
V_2O_5	0.013
ZnO (µg/g (ppm))	65.8
ZrO_2	0.011

It is noticed from Table 4-1 that the used CKD contains 49% CaO, 17% SiO_2, 2.2% K_2O, 1.1% MgO and 3.6% SO_3 which constitute about 75, 80, 218, 1.14, 1.30 and 700%, respectively, of similar compounds in Type I Cement. Moreover; the LOI of the CKD is 15.8%, which can be considered very high compared with the ranges of the LOI value of the CKD, as shown in Table 2-2. A high loss on ignition (LOI) in the CKD implies that it contains a high amount of $CaCO_3$. When CKD is exposed to moisture, alkali sulfates quickly go into solutions. Free lime and some cementitious parts, if present, experience hydration. As a result, the availability of calcium ions is dictated by the equilibrium achieved through the solubility limit of $Ca(OH)_2$ and gypsum ($CaSO_4.2H_2O$) if present [Peethamparan et al., 2008]. Therefore, the high LOI in the current CKD probably indicates that it was exposed to moisture. It is well known that the lower the LOI is, the better will be the performance of CKD [Miller et al., 2003]. Furthermore, the current CKD contains 5.27% alkalis, which is about 4 times the alkalis in the Portland cement, as shown in Table 2-2. The data in Table 4-1 also show that the used CKD contains 6.9% chloride, which is more than in typical CKD.

Table 4-2 shows the chemical composition of the used EAFD. The most prevalent compounds are iron (Fe) about 34% and zinc (Zn) 10%. Furthermore, EAFD contains 9.4% of calcium (Ca) and 2.4% of silicon (Si) which are about 15 and 10% of similar compounds in Portland cement, respectively. Since lime and silicon are the main compounds that provide the cementitious compounds in Portland cement, the low content of these compounds indicates that EAFD may not provide adequate bonding. Therefore, 2% cement, by weight, was added to EAFD-soil mixtures. The increased quantity of cadmium (Cd), lead (Pb) and nickel (Ni) in the EAFD indicate that this stabilizer may contribute to heavy leaching of "hazardous" metals to the surrounding ground water.

Furthermore, the quantity of magnesium (Mg) is 2.3%, which is more than two times the quantity of this element in the ordinary Portland cement.

The data in Table 4-3 indicate that the LOI in the OFA is extremely high (61%) and the equivalent alkalis is very low compared to the ordinary Portland cement, as shown in Table 2-2. Similarly, the quantity of sulfur (S) in the OFA is almost six times that noted in the ordinary Portland cement.

Table 4-2: Chemical Composition of the Used EAFD

Constituent	Weight %	Constituent	Weight %
Aluminium	0.7	Nickel	0.01
Calcium	9.39	Lead	1.31
Cadmium	0.0004	Phosphorous	0.13
Copper	0.06	Silicon	2.38
Iron	33.6	Tin	0.03
Potassium	1.7	Sulphur	0.57
Magnesium	2.3	Titanium	0.09
Manganese	1.8	Zinc	10
Sodium	2.6	Oxygen	33.33

Furthermore, it is also noticed, from the data in Table 4-3, that OFA contains high quantities of magnesium (Mg) and sulfur (S). Moreover; it contains relatively high quantity of heavy metal, particularly vanadium (as V_2O_5). Typical fuel oils contain Fe, Ni, V, and Zn, in addition to aluminum (Al), calcium (Ca), magnesium (Mg), silicon (Si), and sodium (Na). Transition metals [iron (Fe), manganese (Mn), and cobalt (Co)] and alkaline-earth metals [barium (Ba), calcium (Ca), and magnesium (Mg)] may also be added for the suppression of soot or for corrosion control purposes [Bulewicz et al., 1974; Feldman, 1982, quoted by Abullah, 2009]. From the chemical analysis of OFA (Table 4-3) it is evident that it contains small quantities of calcium and silicon, required to produce cementing gel, C-S-H. Consequently, 2% cement was added to OFA-soil mixture to improve the cementing property of OFA.

Table 4-3: Physco Properties of the Used OFA

Constituent	Weight %
SiO_2	1.65
CaO	0.45
Al_2O_3	< 0.10
Fe_2O_3	0.47
MgO	17.48
K_2O	0.03
Na_2O	0.53
V_2O_5	2.65
SO_3	9.60
Equivalent alkalis ($Na_2O + 0.658K_2O$)	0.55
Loss on ignition (LOI)	60.60
Moisture content	5.90

4.1.2 Specific Gravity

Specific gravity of the investigated soils and industrial by-products is summarized in Table 4-4.

Table 4-4: Specific Gravity of the Investigated Soils and the Stabilizers

Material	Specific Gravity
Marl	2.69
Sand	2.63
Sabkha	2.71
Cement*	3.15
Cement Kiln Dust*	2.79
Electric Arc Furnace Dust	2.76
Oil Fuel Ash*	1.30

- As reported by the suppliers

The specific gravity of non-plastic marl soil is 2.69 which falls in the range of 2.64-2.92, as reported by Ahmed [1995]. Similarly; the specific gravity of sand is 2.63 which falls in the range of 2.62-2.70, as reported by Al-Guniayan [1998]. The specific gravity of the sabkha is 2.71, which is lower than the value of 2.73 reported by Al-Amoudi, [1994], and it falls in the range of 2.51-2.82, as reported by Amin [2004]. Generally; the specific gravity of the investigated soils falls in the range of eastern Saudi soils. The specific gravity of EAFD is 2.76 which falls in the range of 2.71-3.1, as reported by Yildirim and Prezzi [2009].

The specific gravity of CKD and OFA is 2.79 and 1.30, respectively.

4.1.3 Atterberg Limits of the Investigated Soils

It was not possible to get the required moisture contents for the 25 of blows for the liquid limit test for the investigated soils. Consequently, the liquid limit for the three soils was reported as "not defined". The three soils also could not be rolled to a thread of 1/8-in (3.18 mm). Therefore, the investigated soils were classified as "non-plastic".

4.1.4 Grain Size Distribution and Classification of the Investigated Soils

The classification of the investigated soils was based on the grain-size analysis and the plastic indices.

4.1.4.1 Grain Size Distribution and Classification of Marl

Figure 4-4 indicates that the grain-size curve obtained by wet sieving method was consistently above the one determined by dry sieving method. This is attributed to the fact that water tends to dissolve the salts between particles of the soil, thus, the proportion of wet materials passing a particular sieve is consistently more than that for dry sieving.

It can be seen from Figure 4-4 that the soil passing sieve ASTM #200 is 22 and 28%, respectively, when dry and wet sieving methods were used. The soil can be classified as SM or SC if the material passing #200 is more than 12%. However, since the investigated soil was non-plastic (i.e. PI is less than 4), the soil is classified as SM and A-3 according to the USCS and AASHTO soil systems, respectively, based on both dry and wet sieving methods.

4.1.4.2 Grain Size Distribution and Classification of Sand

The grain-size distribution curves for the sand are depicted in Figure 4-5. It can be seen that there is almost no variation between grain size distributions determined by both the dry and wet sieving methods. This is ascribed to the fact that sand is made up of quartz which is not affected much by washing. Since the material passing #200 for the dry and wet materials was less than 5%, it could be classified as SW or SP, according to the USCS. The coefficients of uniformity (C_u) determined by dry and wet sieving methods is almost the same, 3.1. Therefore, sand is classified as SP.

Moreover; since the sand is non-plastic in nature, it can be classified as A-3 according to the AASHTO system.

4.1.4.3 Grain Size Distribution and Classification of Sabkha

The grain-size distribution curves for the sabkha soil are depicted in Figure 4-6. It can be seen that there is a large variation between grain size distribution curves determined by the dry and wet sieving methods. The material passing #200 was 10.2% and 32.7% for dry and wet sieving methods, respectively. The difference in the grain size distribution curves may be ascribed to the fact that sabkha is made up of quartz and soluble minerals which are largely affected by washing. Water tends to dissolve the bonds and salts between particles of the soil; thus, the material passing by wet sieving is much more than that by dry sieving [Al-Amoudi, 1994].

Since the material passing sieve #200 is less than 50%, the investigated can be classified as SM or SC according to USCS system. Since the collected sabkha is non-plastic, PI < 4, therefore, it can be classified as SM according to the USCS system and since it is non-plastic, it can be classified as A-3 according to the AASHTO system for dry sieving.

The material passing sieve #200 by wet sieving is 32%, (greater than 12%). Therefore, the wet sabkha can be classified as SM or SC. But the collected sabkha is non-plastic, PI < 4, hence, the wet sabkha is classified SM according to the USCS system and A-3 according to the AASHTO system.

In summary; the three investigated soils were classified as A-3 according to AASHTO system since none of those soils could be rolled to a thread of 1/8-in (3.18 mm).

Furthermore, as long as the percent passing ASTM sieve #200 was less than 5% for wet and dry sand samples, there was no need for running hydrometer analysis.

Similarly; the percent passing ASTM sieve #200 was less than 50% and greater than 12% for both marl and sabkha. In addition, both marl and sabkha soils are proven to be non-plastic; hence there was no need to carry out hydrometer analyses, for these materials as well.

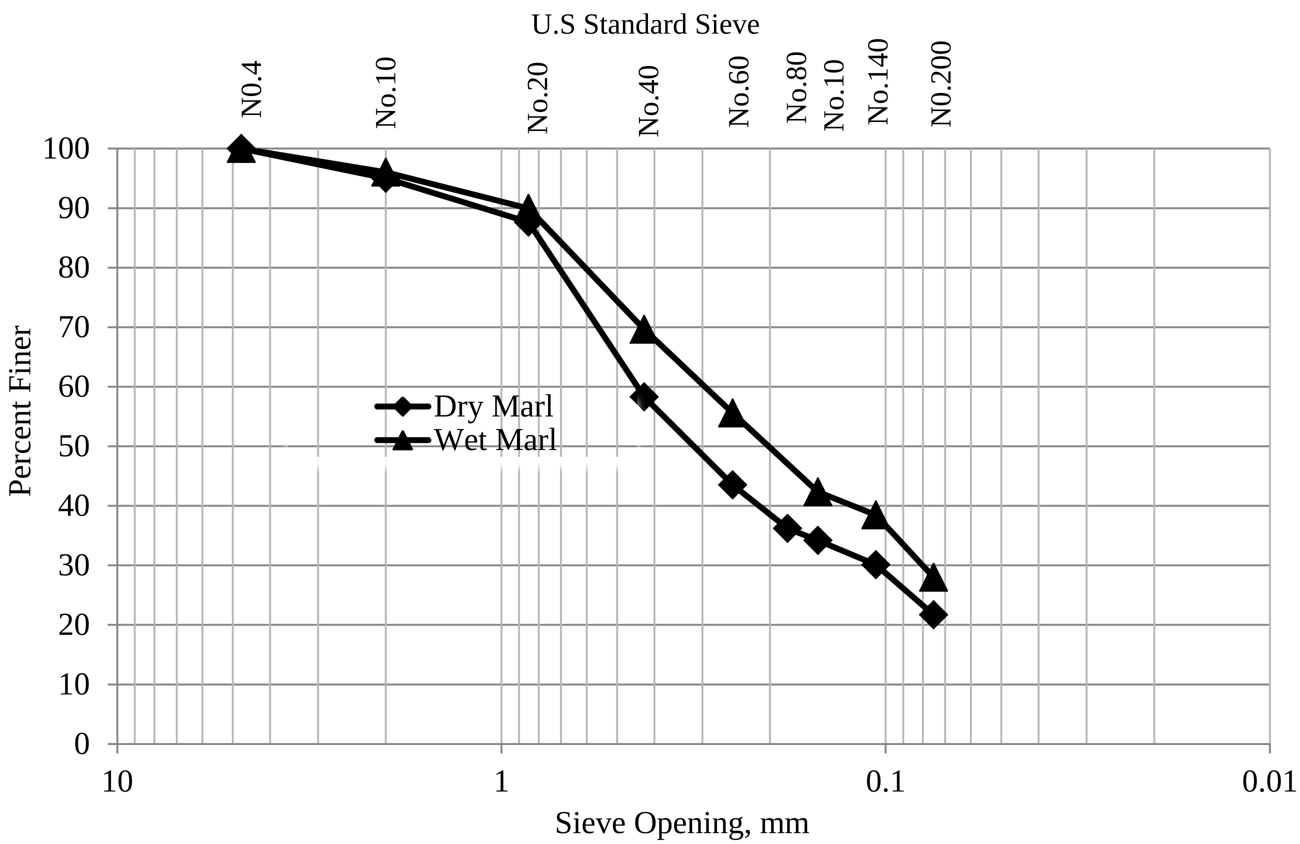


Figure 4-4: Grain Size Distribution of Marl

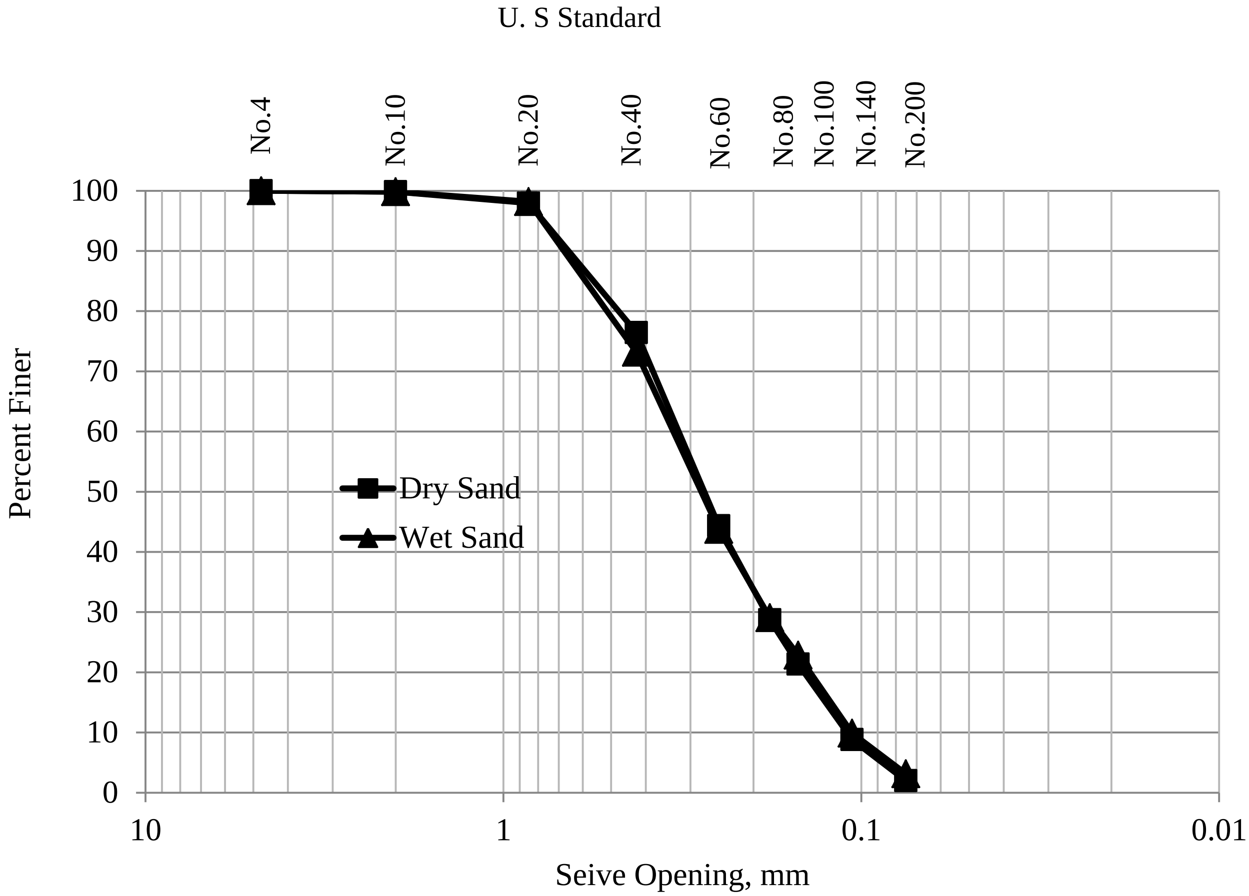


Figure 4-5: Grain Size Distribution of Sand

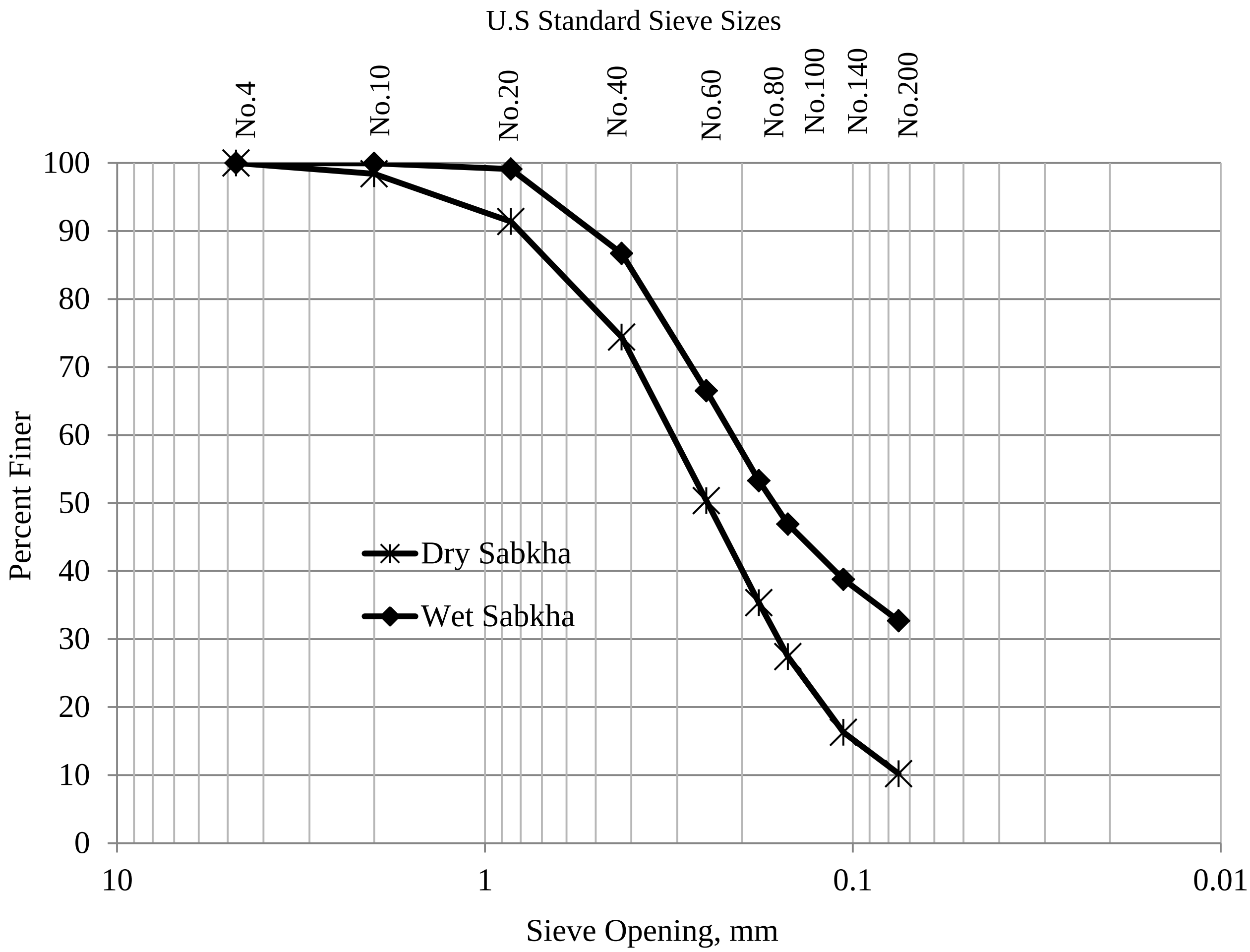


Figure 4-6: Grain Size Distribution of Sabkha

4.2 Stabilization of the Investigated Soils

In this research, cement (as a reference), CKD, EAFD and OFA were used as stabilizing agent agents. All of these additives are considered as waste materials and it is a noble task to use them in soil stabilization. Chemical stabilization technique is considered to be cost-effective and cheaper than many other techniques and requires less expertise and equipment [Kazemian and Barghchi, 2012]. Furthermore, the improvement in the unconfined compressive strength, soaked CBR and durability of the stabilized soils was the key factor. The environmental impact and the cost-effectiveness of the stabilizer(s) were considered as well.

4.3 General Mechanisms of Soil Stabilization

There are two basic mechanisms of stabilization which operate in stabilizing soils; the first is for sandy soils while the other is for clayey soils. Sandy materials, being volumetrically stable and less plastic, are strengthened (as measured by the unconfined compressive strength, bearing capacity, etc.) by direct cementitious effects of Portland cement. The main reaction in this case takes place between the C_3S and C_2S from cement with H_2O to form calcium silicate hydrate. The cementation is greatly increased with the concentration of available alkali in solution [Helmuth, 1987].

On the other hand; clayey soils having high volume instability, extreme sensitivity to moisture content, and high plasticity, undergo stabilization via ion-exchange mechanisms mediated by calcium-containing additives, such as lime, hydrated lime [$Ca(OH)_2$], and Portland cement. Such additions promote cation-exchange primarily by exchanging the sodium ions on the cleavage surfaces of the active clay minerals with calcium ions thereby causing flocculation/agglomeration of particles, resulting in granular materials of low plasticity, low sensitivity to moisture fluctuation with respect to volume change and bearing capacity, etc. Such a mechanism may be termed ion-exchange stabilization.

It might be noted, however, that such stabilization would be dependent upon the cation exchange capacity (CEC) of the clayey soil in question and the availability of calcium ions from the calcium-containing additive. The CEC of clay is dependent upon its composition. For instance, a clayey soil containing montmorillonite usually has a CEC ranging from 80 to 150 milliequivalent (meq) per 100 gram as compared with 3 to 15 meq for kaolinite and 10 to 40 meq for illite clays. One has to be aware, however, that the CEC of a clay may be affected by the interference of soluble alkalis (e.g. salts of K and Na), that can be readily released from the soils due to the presence of the stabilizers containing those elements. The amount and nature of the exchangeable ions in clay also affect the properties of soils. For instance, calcium-saturated clays are usually more friable than sodium-saturated clays. Consequently, the workability of soils can be improved by replacing the sodium ions with calcium ions [Christensen, 1969, quoted by Abdullah, 2009].

Stabilization of soils with cement means mixing soil, cement and water. The mixture is compacted. The mixture developed is of a new building material that resists water, thermal and frost effects. Stabilized soils are adaptable as road pavements, building foundations, canal lining, etc.

Cement is a heterogeneous material composed of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) (according to the nomenclature used in cement chemistry; C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3, H = H_2O, $\hat{S}$ = SO_3) [Wang, 2002]. The reactions between cement and water can be described as follows:

$$C_3S + C_2S + H_2O = C\text{-}S\text{-}H + Ca(OH)_2$$

Where:

C-S-H is calcium silicate hydrate with C/S = 0.5-2 and S/H = 1-2.

With regard to soil stabilization, the two calcium silicate phases (C_3S and C_2S) are the most important ones. These two phases contribute to the formation of provide calcium silicate hydrate, (C-S-H), which acts as a gluing agent in the soil matrix. Upon hydration, those phases produce calcium hydroxide which provides available calcium for cation exchange, flocculation and agglomeration, and stabilizes the clayey soil [Wang, 2002].

Wherever soil is used for pavements, it is placed in a loose state and then compacted by rolling or vibrating until the desired degree of compaction is achieved. Field moisture-density tests provide a means by which compaction of the soil is controlled on the site. The moisture-density test is designed specifically to aid in the field compaction of the soil. The assumption is that the stability of a given soil increases with increasing dry density.

4.4 Compaction Test Results

The maximum dry density and the optimum moisture content of the proposed mixtures were determined using modified Proctor compaction tests. The effect of the additives on these two parameters for each of the investigated soils is discussed in the following sub-sections. The Compaction test results were also useful in determining the optimum moisture content for preparing specimens to determine other properties.

4.4.1 Compaction Test Results of Cement-Stabilized Soils

4.4.1.1 Compaction Test Results of Cement-Stabilized Marl

Compaction tests were conducted on plain (0% additive) marl as well as with stabilized cement (2, 5 and 7%). The moisture content-dry density relationship is depicted in Figure 4-7. The data in Figure 4-7 indicate that the maximum dry density increases due to the addition of cement. Further, the optimum moisture content in marl mixed with cement was less than that without cement. This tendency is similar to the trend reported by Al-Amoudi et al., [2010]. The maximum dry density was 1.89, 1.90, 1.94 and 1.98 g/cm^3 for the cement addition of 0, 2, 5 and 7%, respectively. The increase in the density of marl with cement may be attributed to the higher specific gravity of cement (3.15) as compared with the parent marl (2.69).

Moreover; the data in Figure 4-7 show that the optimum moisture content is 10.4, 7.6, 8.4 and 9.0% for marl with cement contents of 0, 2, 5 and 7%, respectively. The decrease was probably due to the high content of fine materials in the marl, which filled up the voids reducing the amount of water required for lubrication.

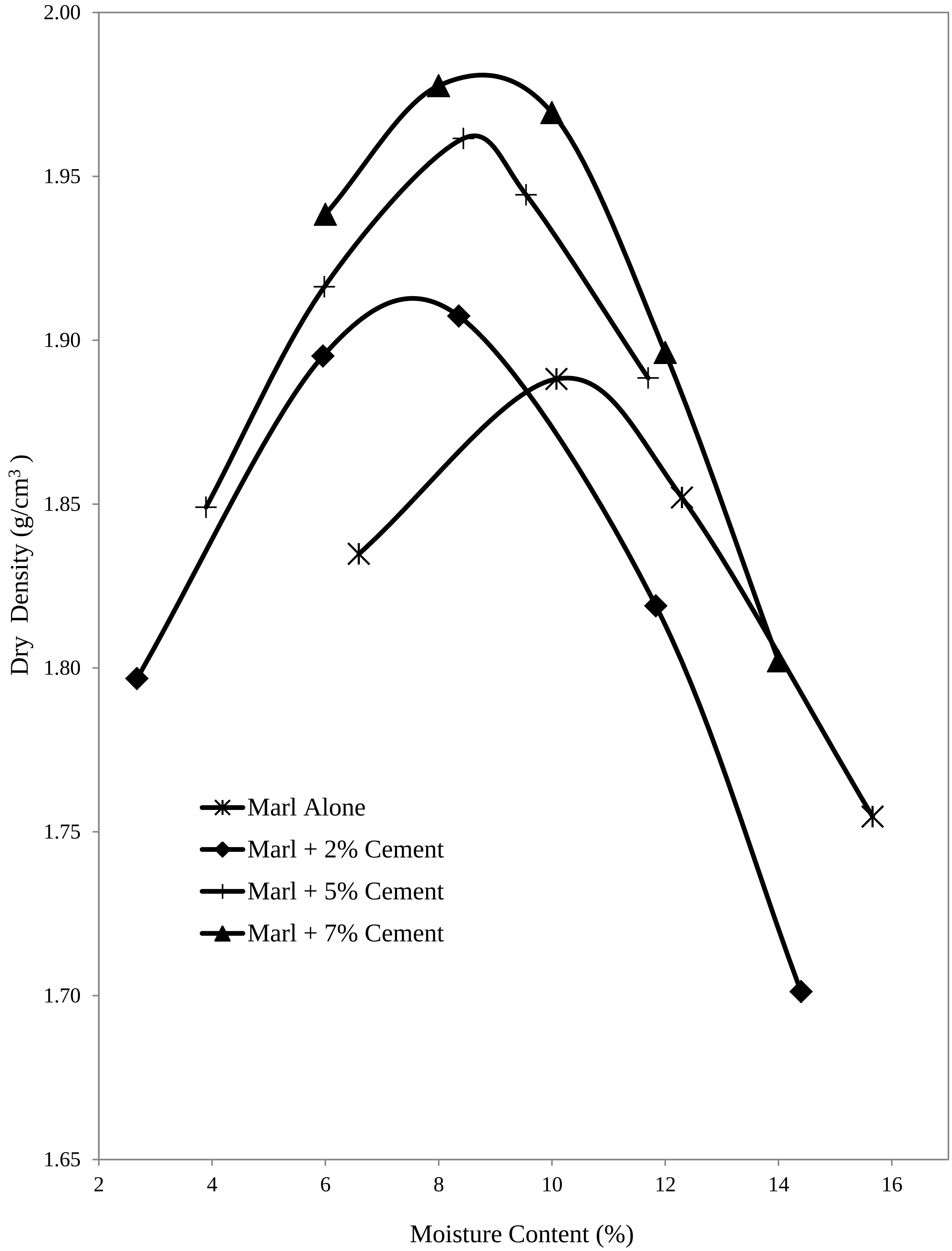


Figure 4-7: Moisture-Dry Density Relationship for Marl Stabilized with Cement

4.4.1.2 Compaction Test Results of Cement-Stabilized Sand

In order to study the effect of cement content on the optimum moisture content and maximum dry density of sand, compaction tests were conducted on sand–cement mixtures with additive contents in the range of 2 to 7%. The results of the moisture content and dry unit-weight are presented in Figure 4-8.

The data in Figure 4-8 reveal that the maximum dry density and the optimum moisture content of the sand-cement mixtures increase with an increase in the cement content increases. The maximum dry density was 1.78, 1.83 and 1.87 g/cm^3 for mixtures with cement content of 2, 5 and 7%, respectively.

Furthermore, the optimum moisture content of sand-cement mixture increases with anin crease in the cement content. The increase in the maximum dry density was due to the higher specific gravity of cement (3.15) than that of sand (2.63). In addition, sand is of poor gradation and the added cement filled up the voids within the sand.

The increase in the optimum moisture content may be attributed to the fact that cement is a very fine material; Consequently, the water requirement increases with increasing quantity of cement.

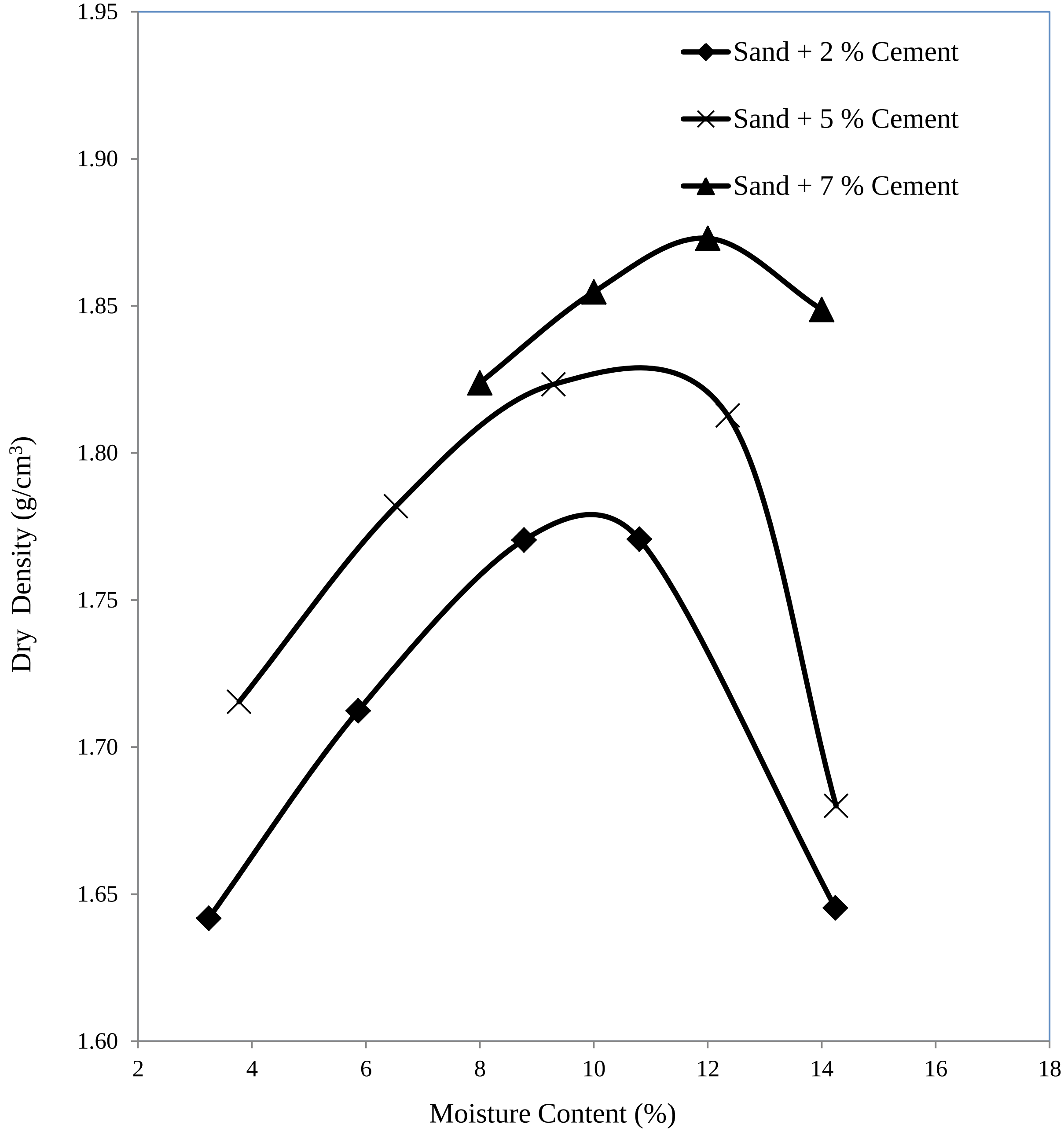


Figure 4-8: Moisture-Dry Density Relationship for Sand Stabilized with Cement

4.4.1.3 Compaction Test Results of Cement-Stabilized Sabkha

For studying the effect of the cement content on the maximum dry density-moisture content relationship, modified Proctor compaction tests were carried out on sabkha soil with and without cement. The cement content utilized was 2, 3, and 7%. The results of the dry density and moisture content for sabkha stabilized with cement are depicted in Figure 4-9.

A consistent increase in the maximum dry density was noted, in Figure 4-9, with an increase in the cement content in sabkha. A similar trend was reported by Al-Amoudi [1994]. The maximum dry density of the plain sabkha was 1.95 g/cm^3 while it was 1.96, 1.98 and 1.99 g/cm^3 for sabkha stabilized with 2, 5 and 7 % cement, respectively. The increase in the maximum dry density may be ascribed to the higher specific gravity of cement (3.15) as compared to sabkha (2.71).

The data in Figure 4-9 also indicate that the optimum moisture content decreases marginally with an increase in the cement content. The optimum moisture content of the plain sabkha was 10.80% while it was 10.40, 10.00 and 9.70% for sabkha with 2, 5 and 7% cement, respectively. The decrease in the optimum moisture content indicates that cement acts as a lubricant in addition to its role of filler.

In summary, data in Table 4-5 indicate that when the cement content increases in the soils, the maximum dry density increases and that was probably due to the higher specific gravity of the cement compared with that of the soils. Furthermore, the cement works as a filler. Therefore, the increase in the cement content in the investigated soils caused variation in the optimum moisture content due to the different gradation of the investigated soils.

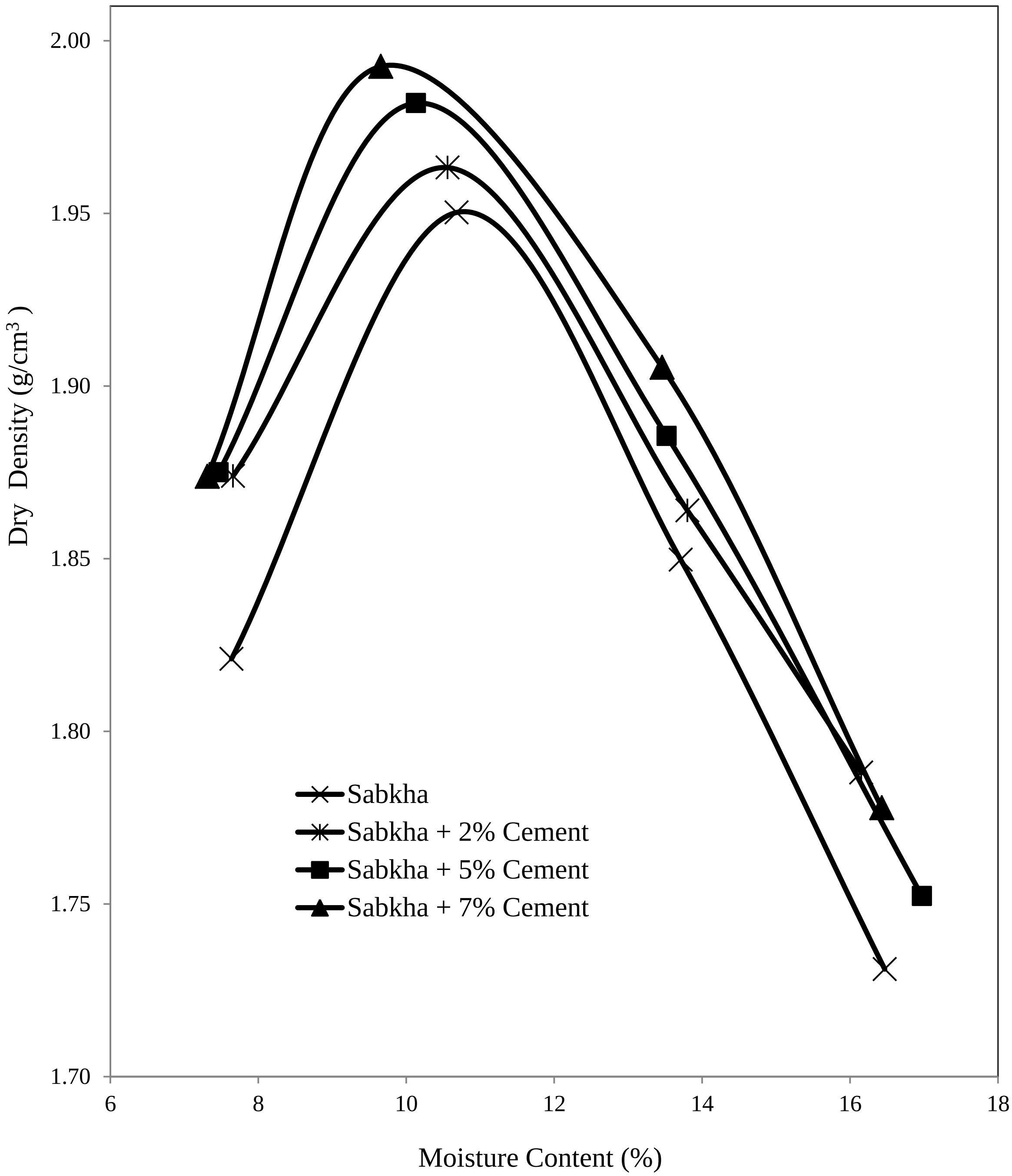


Figure 4-9 Moisture-Dry Density Relationship for Sabkha Stabilized with Cement

4.4.2 Compaction Test Results of CKD-Stabilized Soils

4.4.2.1 Compaction Test Results of CKD-Stabilized Marl

Compaction tests were carried out on marl stabilized with 0, 10, 20 and 30% CKD. The results are presented in Figure 4-10.

From the data in Figure 4-10, it is evident that there is, generally, an increase in the maximum dry density of marl with an increase in CKD content. Furthermore, maximum dry density of marl stabilized with 0, 10, 20 and 30% CKD was 1.89, 1.93, 1.96 and 1.91 g/cm^3, respectively. The increase in the maximum dry density indicates that CKD fills up the pores in the marl and makes it dense in addition to the higher specific gravity of the CKD (2.79) than that of marl (2.69). Nevertheless; the maximum dry density of marl with 30% CKD was less than of marl with 20% CKD. This may be attributed to the formation of macro-pores when 30% CKD was added which resulted in a decrease in the maximum dry density. Similar phenomenon was reported by Al-Gunaiyan [1998] when he studied the effect of cement added to marl.

The data in Figure 4-10 also indicate that the CKD addition to marl resulted in a decrease in the optimum moisture content. The optimum moisture content was 10.4, 8.0, 7.8 and 7.7%, respectively, for 0, 10, 20 and 30% CKD addition.

The decrease in the water content was almost the same for all the CKD dosages. That can be interpreted by the fact that CKD is a very fine material and its paste works as a lubricant. The decrease in the water content was almost the same for all the CKD dosages. That can be interpreted by the fact that CKD is a very fine material and its paste works as a lubricant.

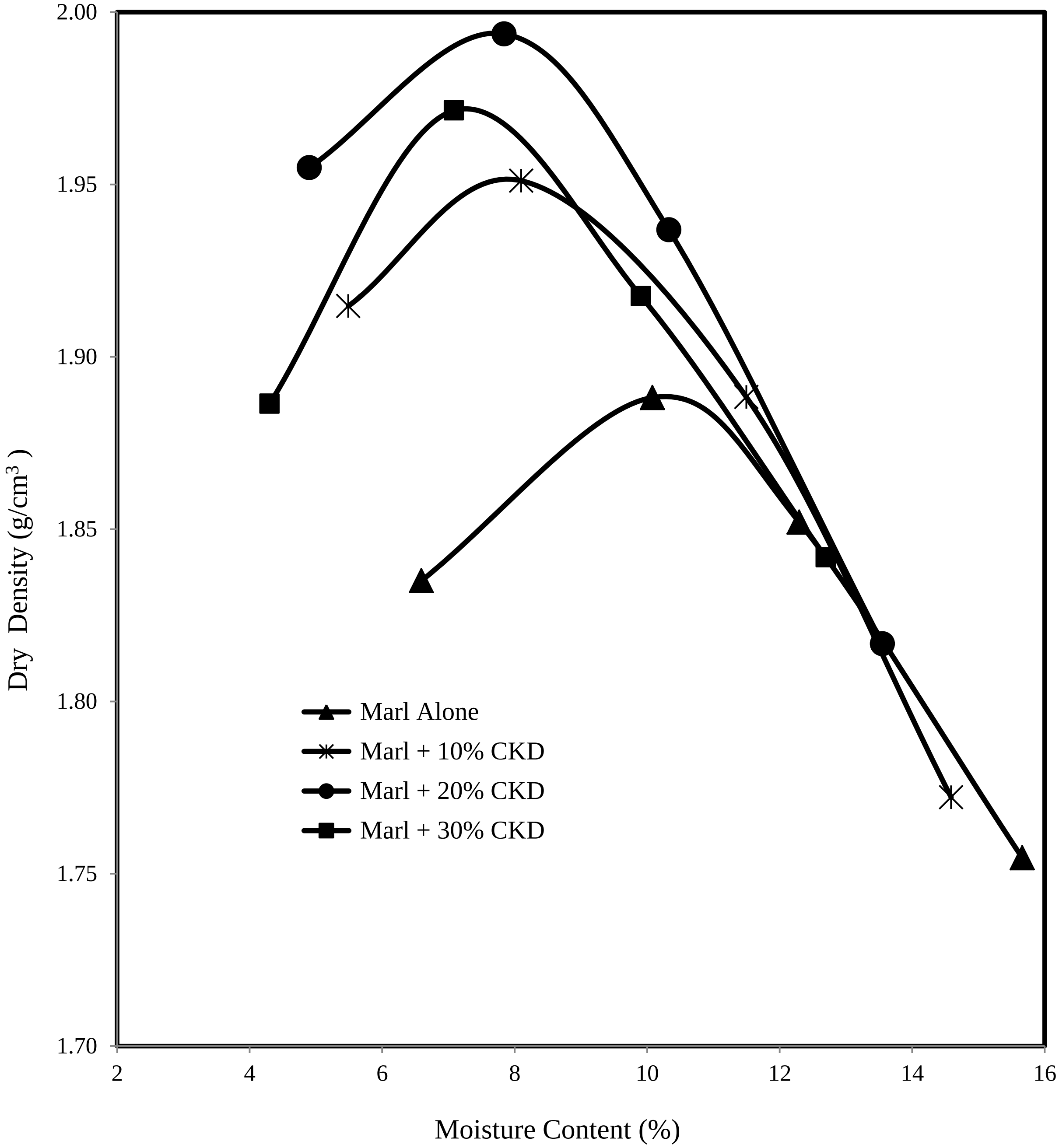


Figure 4-10: Moisture-Dry Density Relationship for Marl Stabilized with CKD

4.4.2.2 Compaction Test Results of CKD-Stabilized Sand

Compaction tests were conducted on sand stabilized with 0, 10, 20 and 30% CKD. The results of moisture content versus dry unit weight for sand stabilized with CKD are presented in Figure 4-11.

The data in Figure 4-11 show that as the CKD content increases, the maximum dry density of the sand increases. The maximum dry density was 1.91, 1.96 and 1.99 g/cm^3 for sand with 10, 20 and 30% CKD, respectively. The increase in the maximum dry density may be attributed to that fact that the specific gravity of CKD (2.79) is more than that of sand (2.63). The increase in the density may also be attributed to the fact that CKD either acts as a cementing material or as a filler. Further, when the CKD content increases, the optimum moisture content of the stabilized sand marginally decreases. The reduction in the optimum moisture content of the sand-CKD mixtures was due to the fact that sand is of poor gradation (SP) and adding CKD has filled up the voids between sand particles which reduced the amount of water required for lubrication. This trend is similar to what was reported by Abdullah [2009].

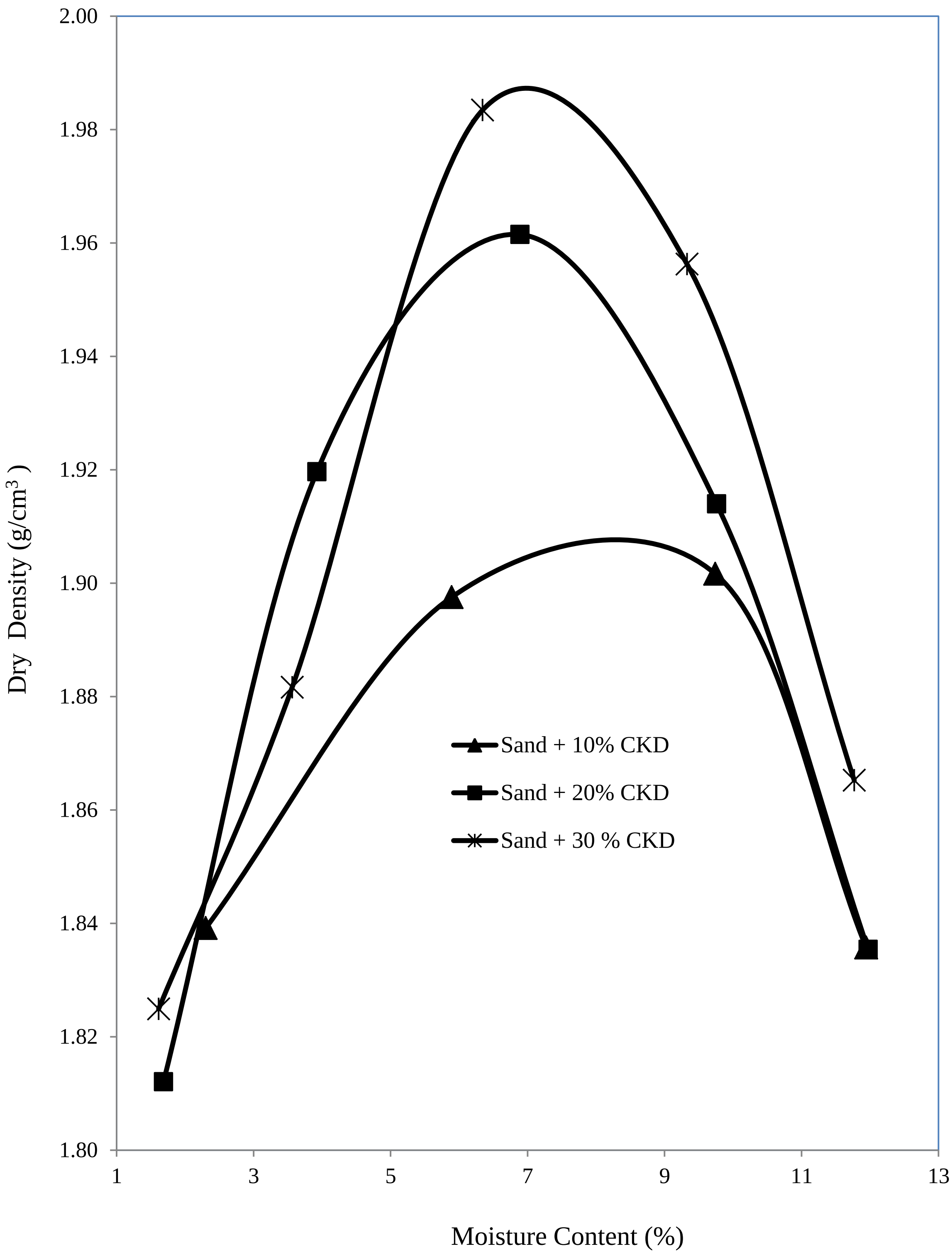


Figure 4-11: Moisture-Dry Density Relationship for Sand Stabilized with CKD

4.4.2.3 Compaction Test Results of CKD-Stabilized Sabkha

Modified Proctor compaction tests were conducted on plain (0% additive) sabkha soil as well as on sabkha stabilized with 10, 20 and 30% CKD. Plain sabkha was used as a reference. The results, presented as a plot of moisture content versus dry density, are reported in Figure 4-12.

The data in Figure 4-12 reveal that the addition of CKD to sabkha decreases its maximum dry density. This trend is similar to that reported by Shabel [2006]. The maximum dry density of sabkha alone is 1.95 g/cm^3 while that with 10, 20 and 30% CKD it was 1.93, 1.89 and 1.88 g/cm^3, respectively. It was expected that the CKD addition would increase the maximum dry density of the sabkha since the specific gravity of CKD (2.79) is more than that of the sabkha (2.71). However, the decrease in the maximum dry density with the addition of CKD was probably due to the fact that CKD, is very fine material, dislocates the granular structure of the sabkha causing the particles of the investigated sabkha to float in the CKD and thus reduce the maximum dry density. Such a phenomenon was also reported earlier [Abudllah, 2009; and Ahmed, 1995].

Furthermore, the data in Figure 4-12 show that as the CKD content in the investigated sabkha increases, the optimum moisture content also increases. The optimum moisture content was 10.80, 11.20, 12.50 and 12.80% for sabkha with 0, 10, 20 and 30% CKD, respectively. The increase in the optimum moisture content may be attributed to the fact that CKD is a very fine material, thus the water content increases.

In summary; adding CKD to the investigated soils caused variation in the maximum dry density. As CKD content increases in the investigated marl, the maximum dry density increases. The increase in the maximum dry density was probably due to the higher specific gravity of the CKD than that of the marl. However, the increase in the maximum dry density of marl with 30% CKD was less than that of marl with 20% CKD, which was ascribed to the fact that the CKD is a very fine material and more CKD cause the marl particles to float in the CKD which resulted in a decrease in maximum dry density.

The CKD in sand caused an increase in the maximum dry density of sand-CKD mixture. That was probably due to the fact that sand is poorly graded and CKD is very fine material, which filled up the voids and CKD has higher specific gravity of sand.

On the other hand; the CKD content in sabkha caused a decrease in maximum dry density. That was ascribed to the fact that more fine material caused the sabkha particles to float in the CKD which, in turn, resulted in a decrease of the maximum dry density

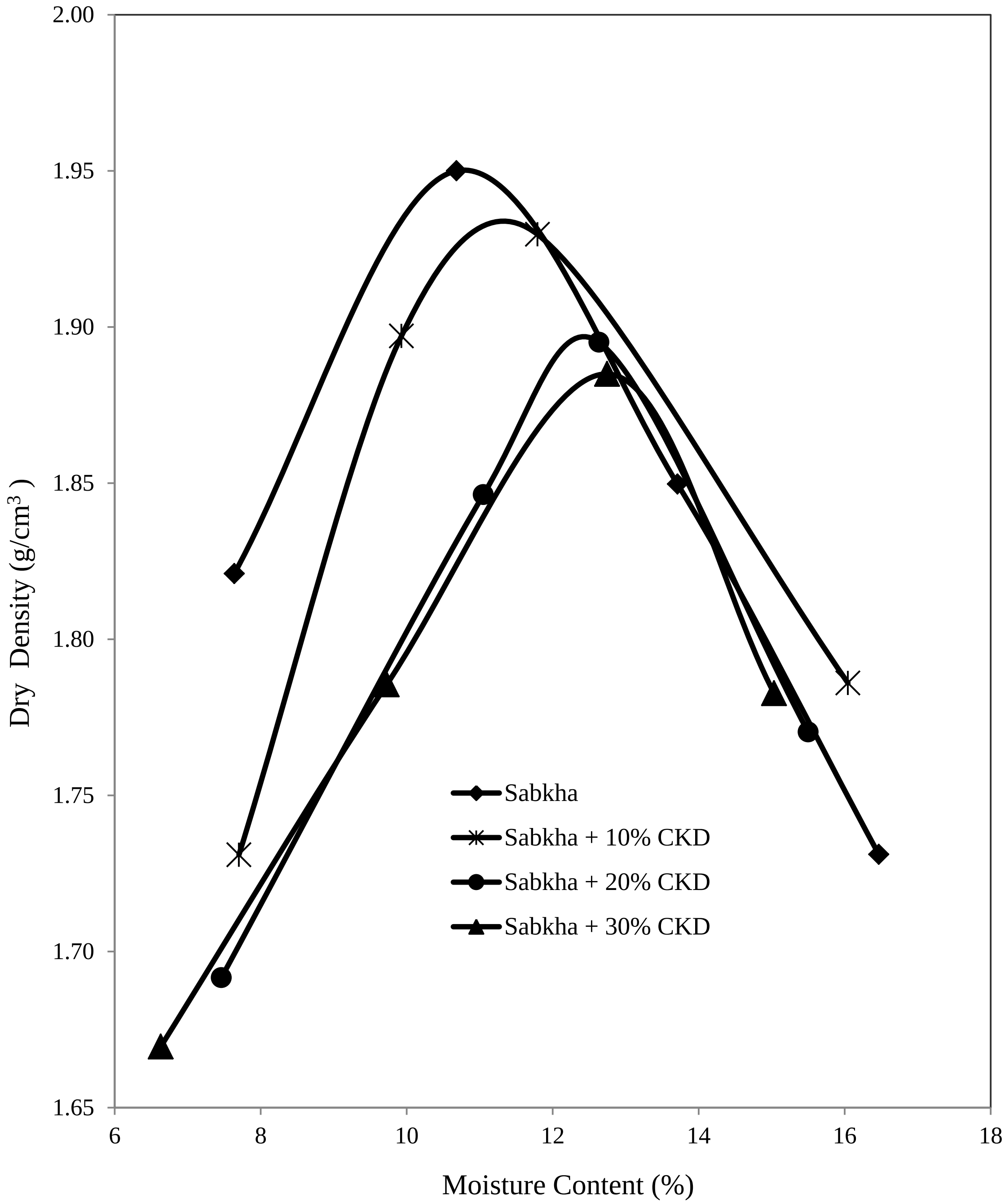


Figure 4-12: Moisture-Dry Density Relationship for Sabkha Stabilized with CKD

4.4.3 Compaction Test Results of 2% Cement plus CKD -Stabilized Soils

4.4.3.1 Compaction Test Results of 2% Cement plus CKD - Stabilized Marl

Compaction tests were conducted on marl with 2% cement and with the addition of cement and CKD. The CKD addition was in the range of 10 to 30%. The results are presented as moisture content versus dry density in Figure 4-13.

From the data in Figure 4-13, it can be noticed that the addition of CKD to non-plastic marl plus 2% cement resulted in an increase in the maximum dry density. The maximum dry density of the marl-stabilized with 2% cement plus 10, 20 and 30% CKD was 1.98, 1.98 and 1.95 g/cm^3, respectively. The maximum dry density of marl with 2% cement was 1.90 g/cm^3. This increase was due to the fact that the specific gravity of CKD (2.79) is higher than the specific gravity of non-plastic marl (2.69). The addition of 10 and 20% CKD has caused same increment in the maximum dry density. While the 30% of CKD has caused less increment in the maximum dry density less than the 10 and 20% CKD had. That was probably due to the fact that 30% CKD has damaged the gradation of the marl which reduced the maximum dry density [Abdullah, 2009].

Furthermore, CKD addition has caused a marginal increase in the optimum moisture content in the marl-cement-CKD mixtures. The optimum moisture content in 0, 10, 20 and 30% CKD with 2% cement was 7.6, 8.4, 8.4 and 10.0%, respectively. While the optimum moisture content in the 0, 10 and 20% CKD mixture was almost similar, it was significantly increased in the 30% CKD mixture. This has probably decreased the unit weight of the 30% CKD mixture.

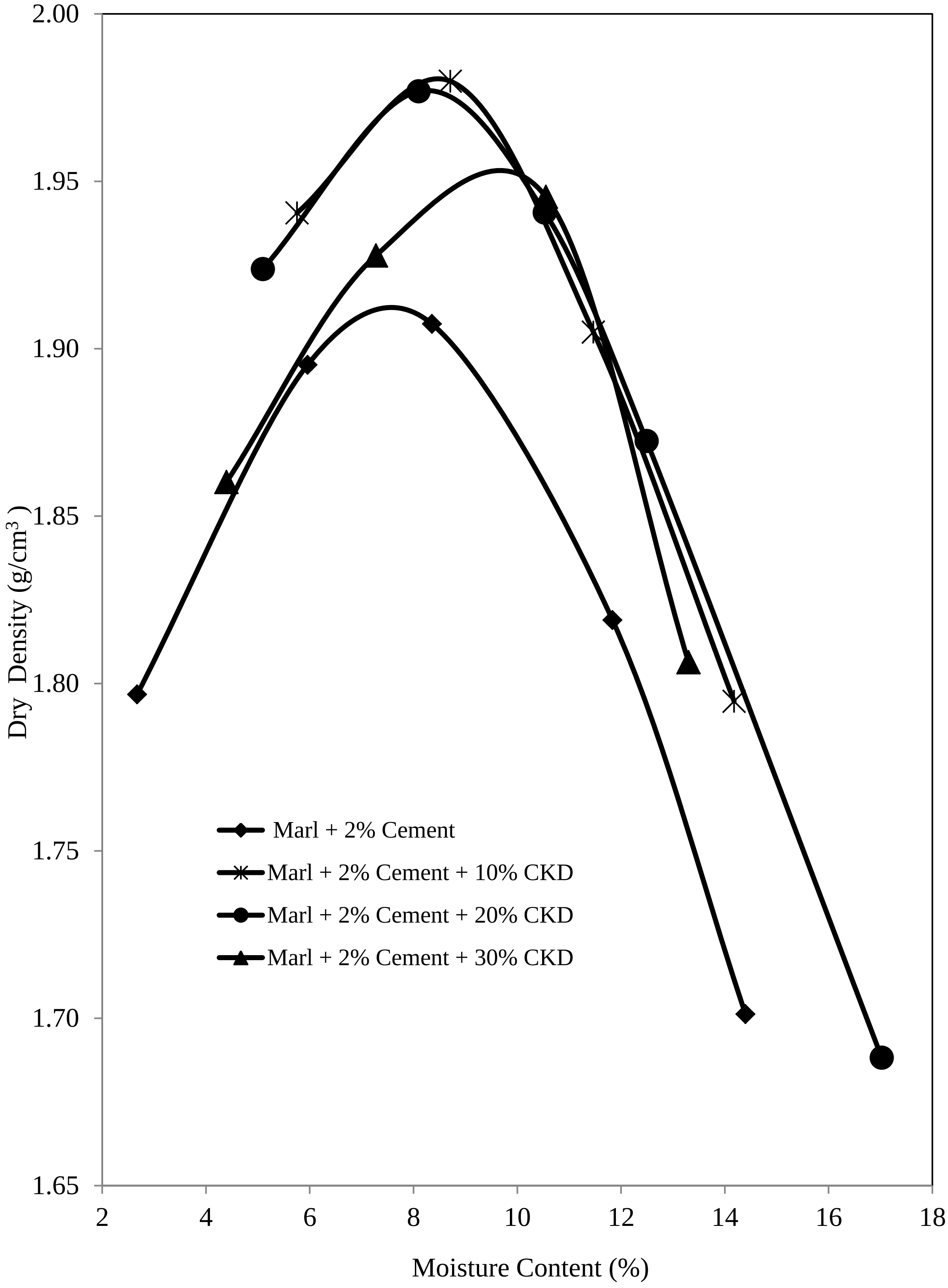


Figure 4-13: Moisture-Dry Density Relationship for Marl Stabilized with 2% Cement and Varying Quantity of CKD

4.4.3.2 Compaction Test Results of 2% Cement plus CKD - Stabilized Sand

To study the influence of CKD content with 2% cement on the dry density of sand, compaction tests were conducted on sand with 2% cement as well as on sand–CKD addition with 2% cement. The CKD contents were in the range of 10 to 30%. The results of moisture content versus dry density are depicted in Figure 4-14.

The data in Figure 4-14 show that the addition of CKD to sand with 2% cement has increased the maximum dry density of the sand compared to sand stabilized with only 2% cement. The maximum dry density of the sand-stabilized with 2% cement plus 0, 10, 20 and 30% CKD was 1.79, 1.92, 1.96 and 1.97 g/cm^3, respectively. The increase in the density may be attributed to the filler effect of CKD in addition to the higher specific gravity of CKD (2.79) than that of sand (2.63).

Moreover; the data in Figure 4-14 also show that the optimum moisture content decreases with increasing the quantity of CKD. The decrease in the optimum moisture content was probably due to the fact that CKD is a very fine material, which fills the voids between sand particles thus reducing the void volume. Consequently, the amount of water needed for lubrication decreases.

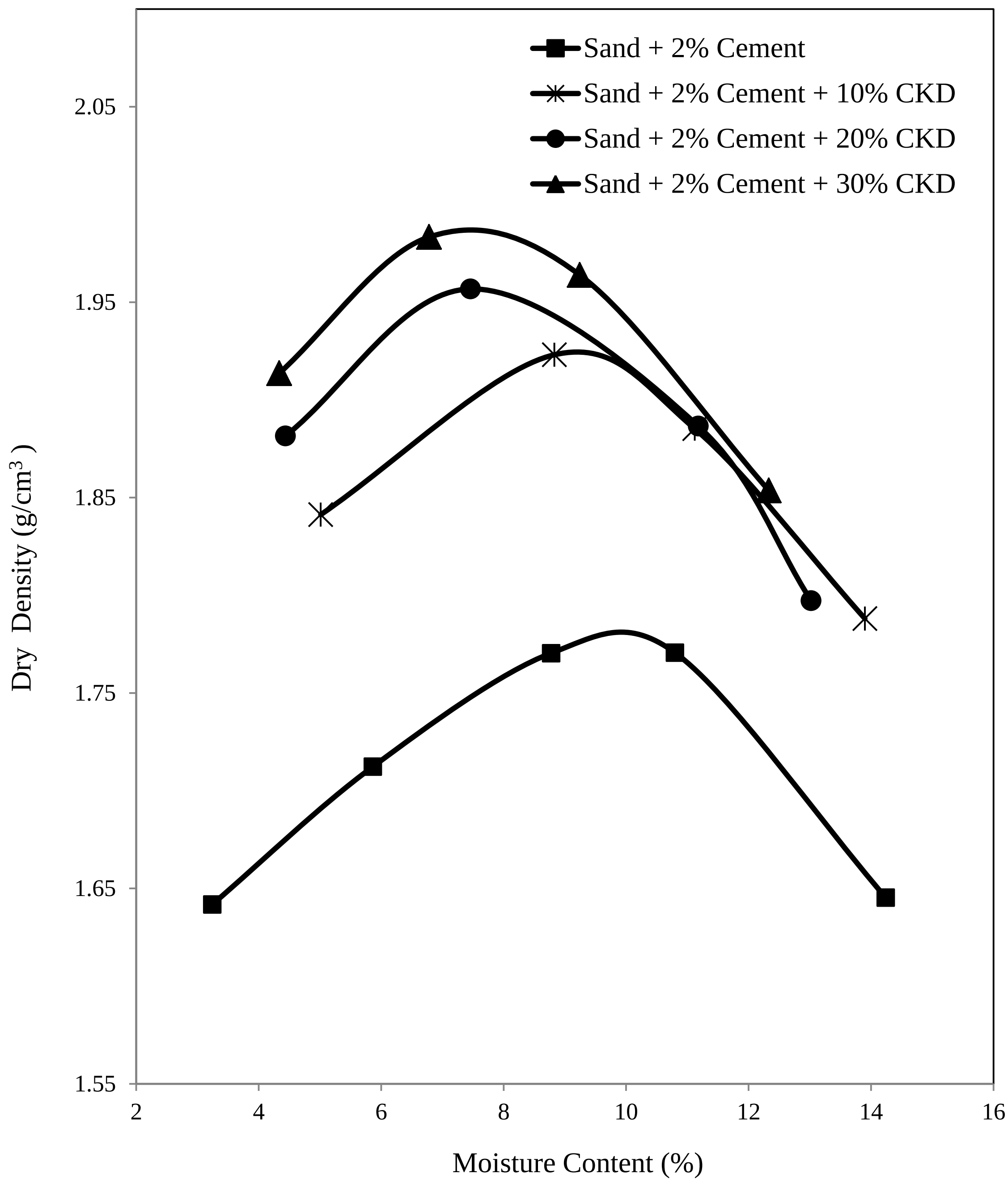


Figure 4-14: Moisture-Dry Density Relationship for Sand Stabilized with 2% Cement and Varying Quantity of CKD

4.4.3.3 Compaction Test Results of 2% Cement plus CKD -Stabilized Sabkha

Modified compaction tests were conducted on sabkha mixed with 2% cement and 0, 10, 20 and 30% CKD. Sabkha stabilized with 2% cement was used as a reference to compare the effect of CKD on the compaction characteristics. The results are presented in Figure 4-15.

The data in Figure 4-15 indicate that the maximum dry density decreases with an increase in the quantity of CKD. The maximum dry density of sabkha-2% cement mixture with 0, 10, 20 and 30% CKD was 1.96, 1.93, 1.84 and 1.85 g/cm^3, respectively. A similar trend was reported by Shabel [2006]. The decrease in density was probably due to the formation of macro-pores which tend to reduce the density. Further increase in the CKD content disrupts the granular structure of the sabkha, causing the particles to float in the CKD and thus reduce the maximum dry density [Abdullah, 2009; Ahmed, 1995].

Another point to note from the data in Figure 4-15 is that the addition of CKD caused a marginal variation in the optimum moisture content.

In summary; addition CKD to the investigated marl and sand soils with 2% cement caused an increase in the maximum dry density while it caused a decrease in the maximum dry density of sabkhsa with 2% cement mixture.

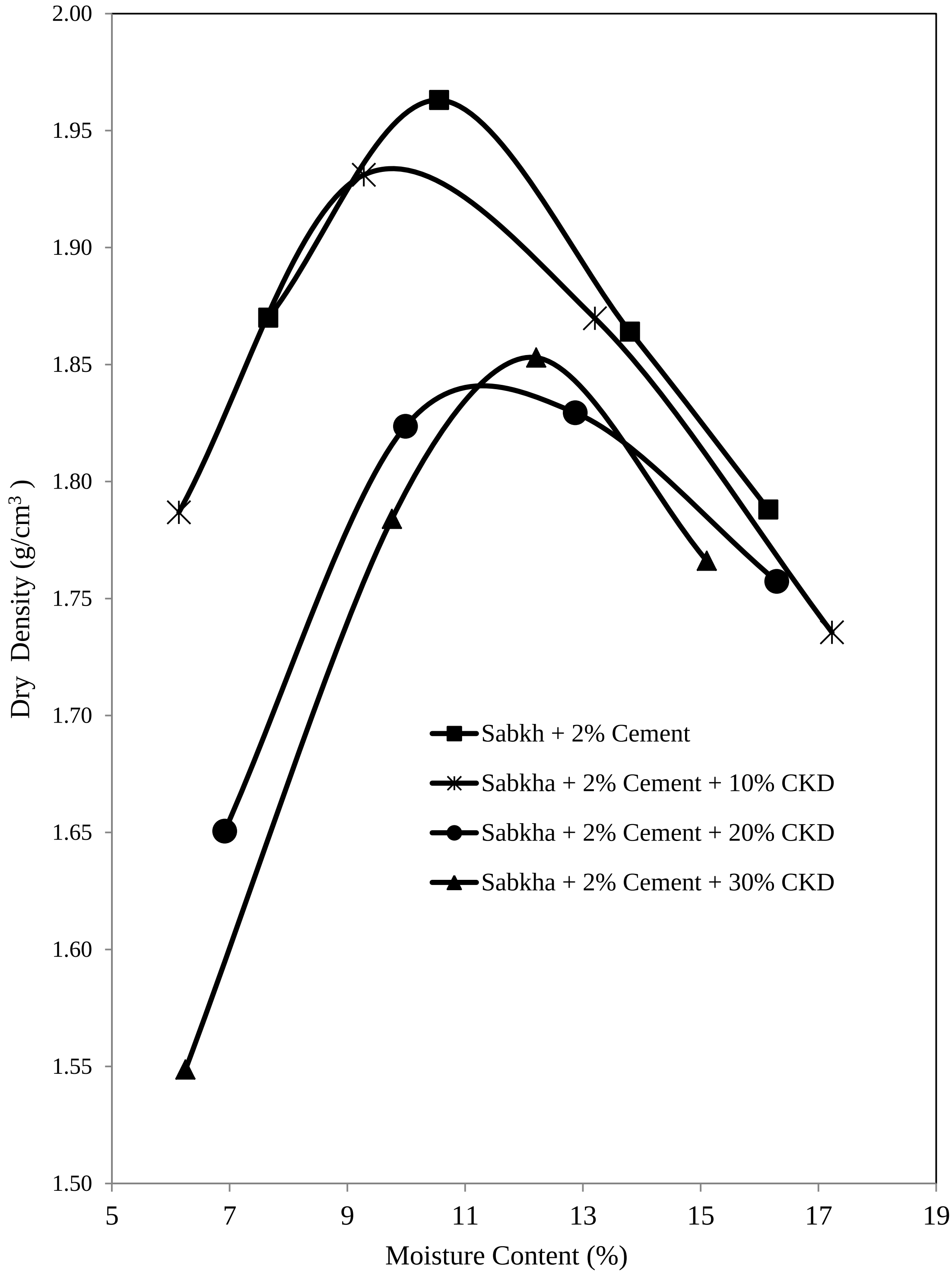


Figure 4-15: Moisture-Dry Density Relationship for Sabkha Stabilized with 2% Cement and Varying Quantity of CKD

4.4.4 Compaction Test Results of 2% Cement plus EAFD -Stabilized Soils

4.4.4.1 Compaction Test Results of 2% Cement plus EAFD -Stabilized Marl

Compaction tests were conducted on marl mixed with 2% cement and with 0, 5, 10, 20 and 30% EAFD. The results of the moisture content versus the dry density are reported in Figure 4-16.

From the data in Figure 4-16, it can be seen that the addition of EAFD increased the maximum dry density of the marl-2% cement mixtures. The maximum dry density of 0, 5, 10, 20 and the 30% EAFD was 1.90, 2.0, 2.04, 2.10 and 2.23 g/cm^3, respectively. The increase in the maximum dry density of marl-2% cement mixtures may be ascribed to the higher specific gravity of EAFD (2.76), which is more than the specific gravity of the investigated non-plastic marl soil (2.69). Also, EAFD, being very fine material, effectively fills up the voids in the marl-2% cement mixtures.

The data in Figure 4-16 also indicate that the addition of EAFD to non-plastic marl-2% cement mixtures has caused a variation in the optimum moisture content. The optimum moisture content was 7.6, 9.2, 9, 8.8 and 8.0% for the EAFD contents of 0, 5, 10, 20 and 30%, respectively. The increase in the water requirement may be attributed to the fact that EAFD powder is a very fine material and, as such, the increase in the quantity of this material requires additional water for lubrication.

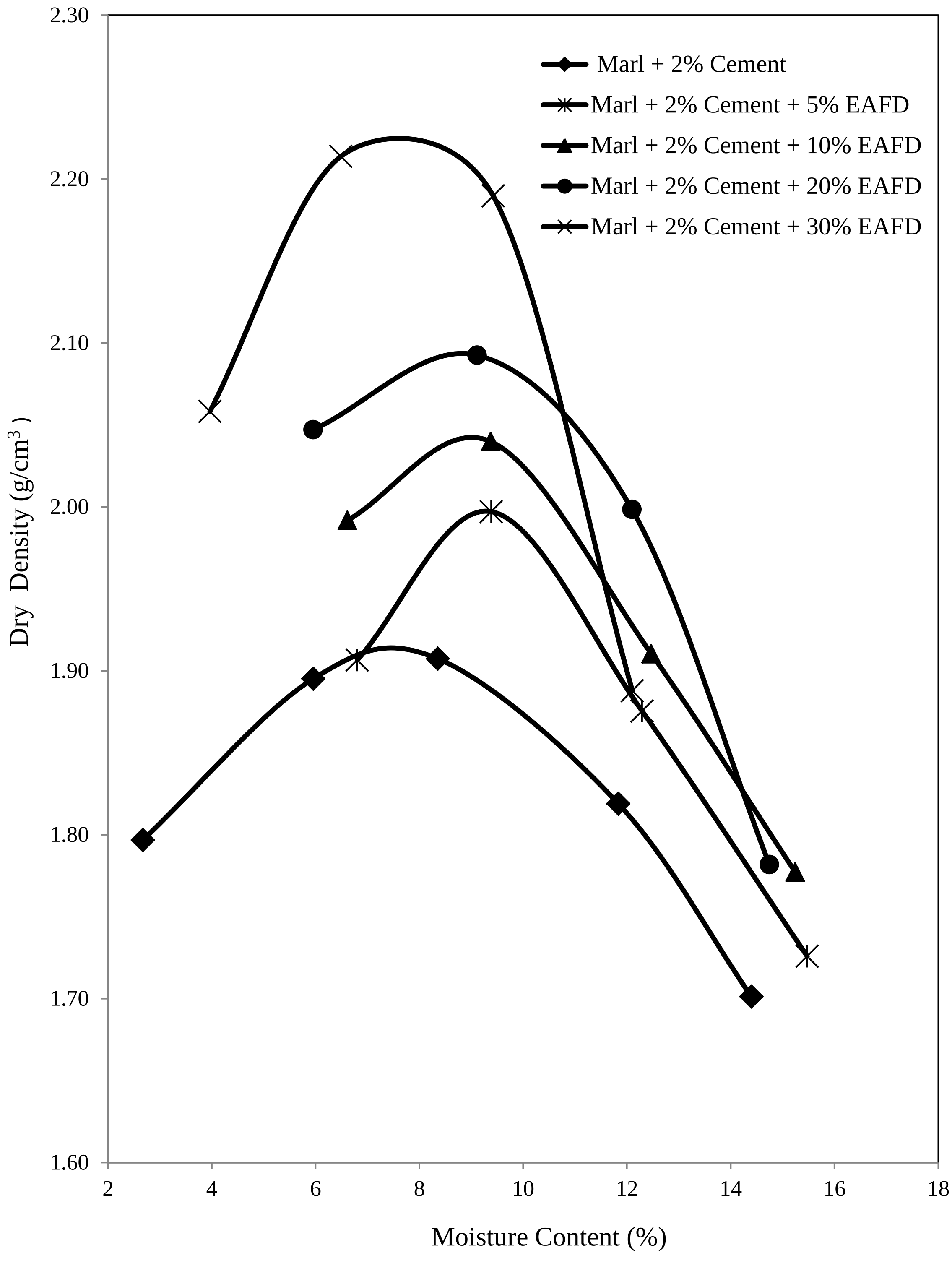


Figure 4-16: Moisture-Dry Density Relationship for Marl Stabilized with 2% Cement and Varying Quantity of EAFD

4.4.4.2 Compaction Test Results of 2% Cement plus EAFD -Stabilized Sand

The effect of EAFD content on the dry density–moisture content relationship of sand with 2% cement was carried out using the modified compaction tests. The tests were conducted on sand with 2% cement as well as on sand with 2% cement and EAFD. The EAFD additions were in the range of 5 to 30%. The results of moisture content versus dry density are reported in Figure 4-17.

The data in Figure 4-17 indicate that as the quantity of EAFD in the sand-2% cement mixture increases, the maximum dry density increases. The maximum dry density of the investigated sand plus 2% cement mixtures increased from 1.78 g/cm^3 to 1.90, 1.93, 2.08 and 2.19 g/cm^3, respectively, due to the addition of 5, 10, 20 and 30% EAFD. That was expected since the EAFD has higher specific gravity (2.76) than that of the sand (2.63).

The data in Figure 4-17 also indicate that as EAFD content increases the optimum moisture content marginally decreases. The optimum moisture contents of sand with 2 % cement was 10.0 9.0, 9.2, 9.4 and 7.8% for EAFD contents 0, 5, 10, 20 and 30%, respectively. This was probably due to the fact that the investigated sand is of poor gradation, SP, and the EAFD powder is very fine material which fills up the voids within the sand particles thereby leading to a reduction in the volume of water needed for the lubrication.

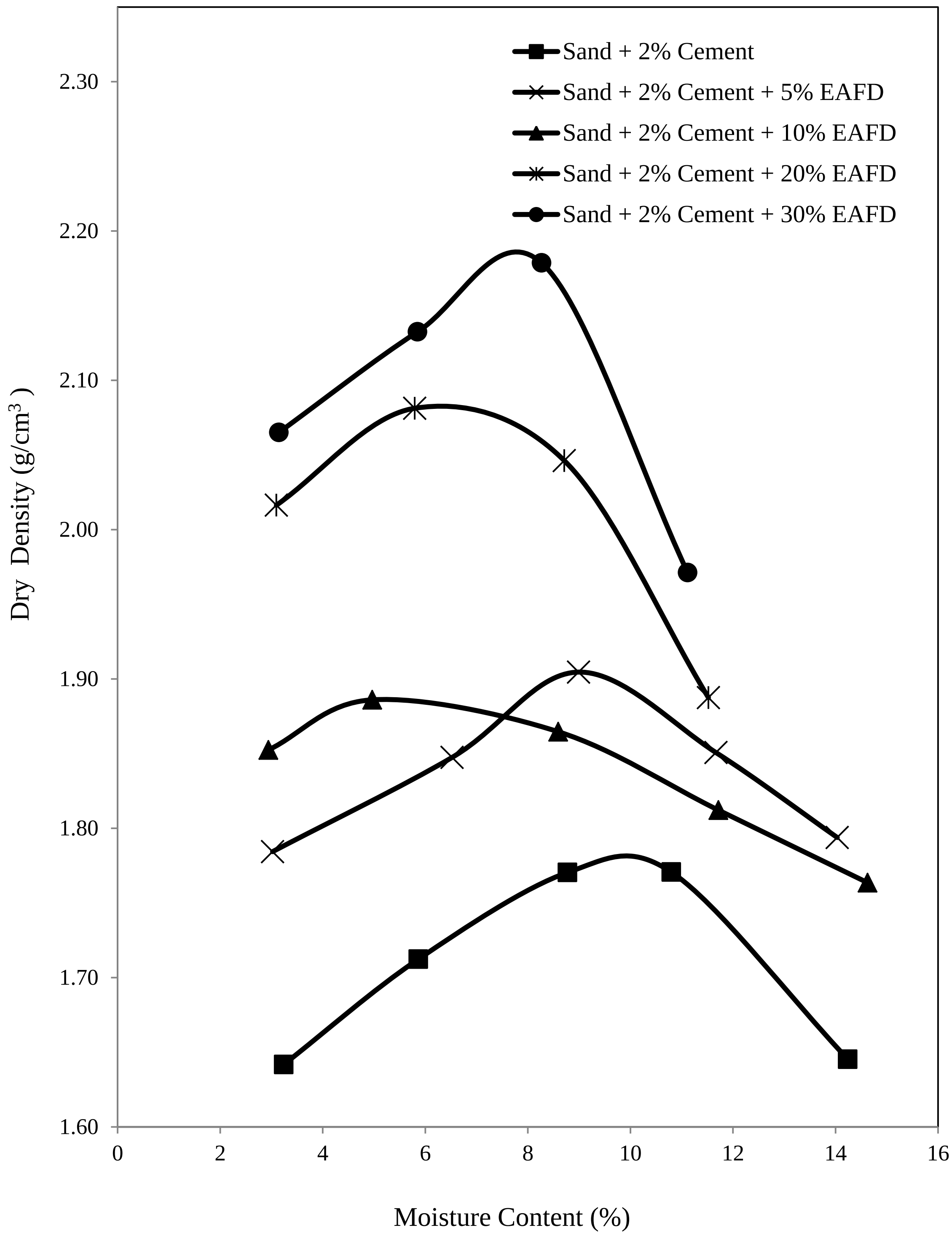


Figure 4-17: Moisture-Dry Density Relationship for Sand Stabilized with 2% Cement and Varying Quantity of EAFD

4.4.4.3 Compaction Test Results of 2% Cement plus EAFD -Stabilized Sabkha

Compaction tests were conducted on sabkha stabilized with EAFD content in the range of 5 to 30% plus 2% cement. The moisture content versus the dry density relationship is reported in Figure 4-18.

The data Figure 4-18 indicate that the maximum dry density of sabkha with 2% cement increases with the quantity of EAFD. The increase in the maximum dry density was probably due to the higher specific gravity of EAFD (2.76) compared to that of the sabkha soil (2.71). The maximum dry unit weight of 5% EAFD was not that different from that of sabkha without EAFD since the difference in the specific gravity is not significant and the amount of the EAFD addition is small. However, a significant improvement in the maximum dry density was noted with the addition of 10% or more of EAFD.

It can also be noted from the data in Figure 4-18 that the optimum moisture content increases with increasing EAFD content. Mixes with up to 10% EAFD did not show any effect on the optimum moisture content. Moreover; the 20 and 30% EAFD sabkha mixtures showed the same effect on the optimum moisture content. These dosages increased the optimum moisture content from 10.6 to 11.2%. However, the 10% EAFD increased the optimum moisture content from 10.6 to 10.8%. This increase may be attributed to the fact EAFD powder is very fine and increasing its quantity tends to increase the volume of water for lubrication.

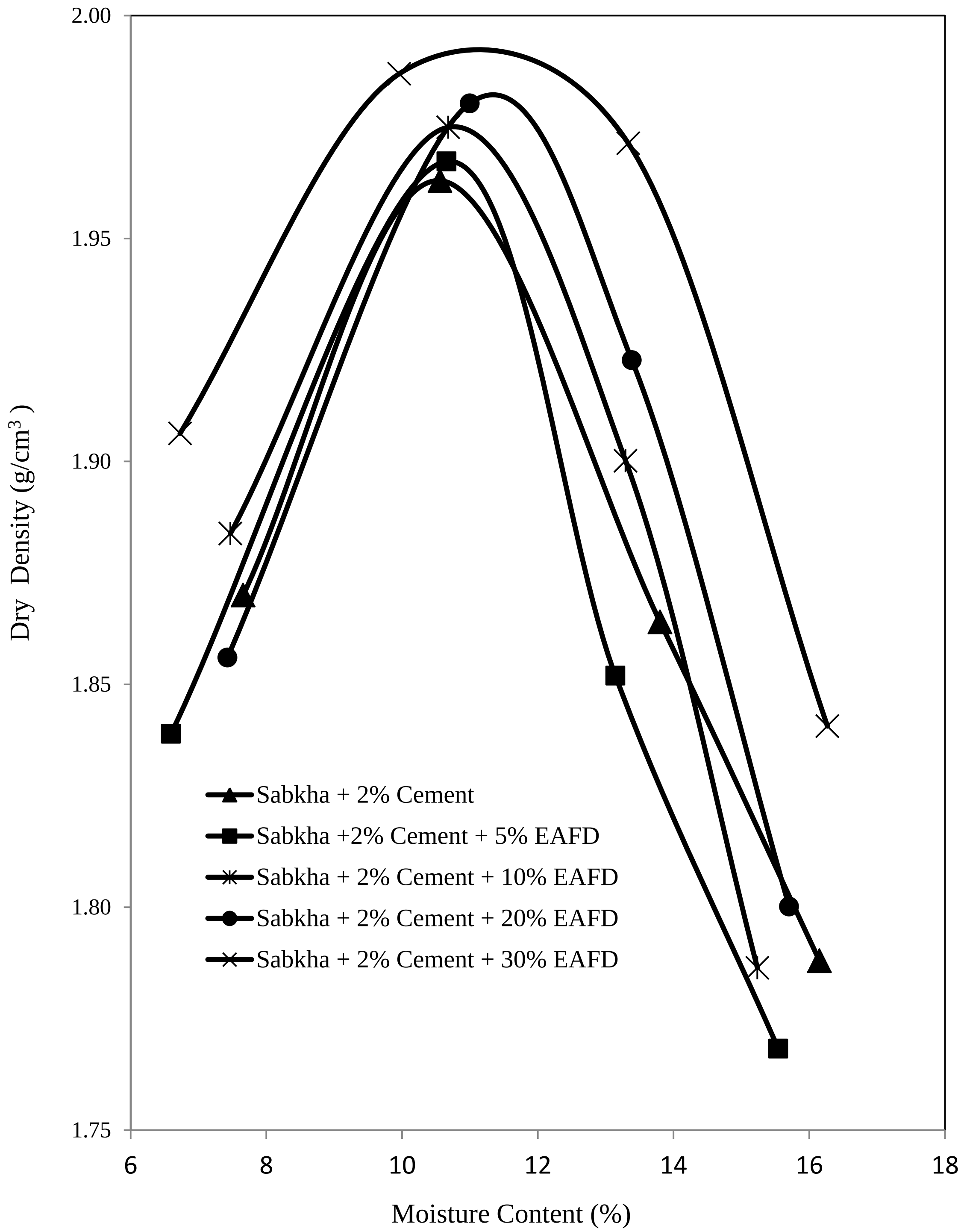


Figure 4-18: Moisture-Dry Density Relationship for Sabkha Stabilized with 2% Cement and Varying Quantity of EAFD

In summary; the addition of EAFD to the investigated soils with 2% cement increased the maximum dry density which can be attributed to the higher specific gravity of the EAFD compared to the specific gravity of the investigated soils and also it may be due to the filler effect.

4.4.5 Compaction Test Results of 2% Cement plus OFA-Stabilized Soils

4.4.5.1 Compaction Test Results of 2% Cement plus OFA-Stabilized Marl

The effect of OFA addition with 2% cement on the dry density–moisture content relationship of marl was studied using compaction tests. Marl with 2% cement and marl-2% cement and OFA was tested and the results of dry density and moisture content are reported in Figure 4-19.

The data in Figure 4-19 show that the maximum dry density decreased and the optimum moisture content increased with an increase in the quantity of OFA. The maximum dry density of the investigated marl plus 2% cement mixtures with 0, 5, 10 and the 15% OFA was 1.90, 1.88, 1.80 and 1.72 g/cm^3, respectively. The decrease in the maximum dry density may be attributed to the fact that OFA is of lower specific gravity (1.30) than that of the marl (2.69). The increase in the optimum moisture content may be attributed to the fact that the OFA is very fine material and it needs more moisture for lubrication.

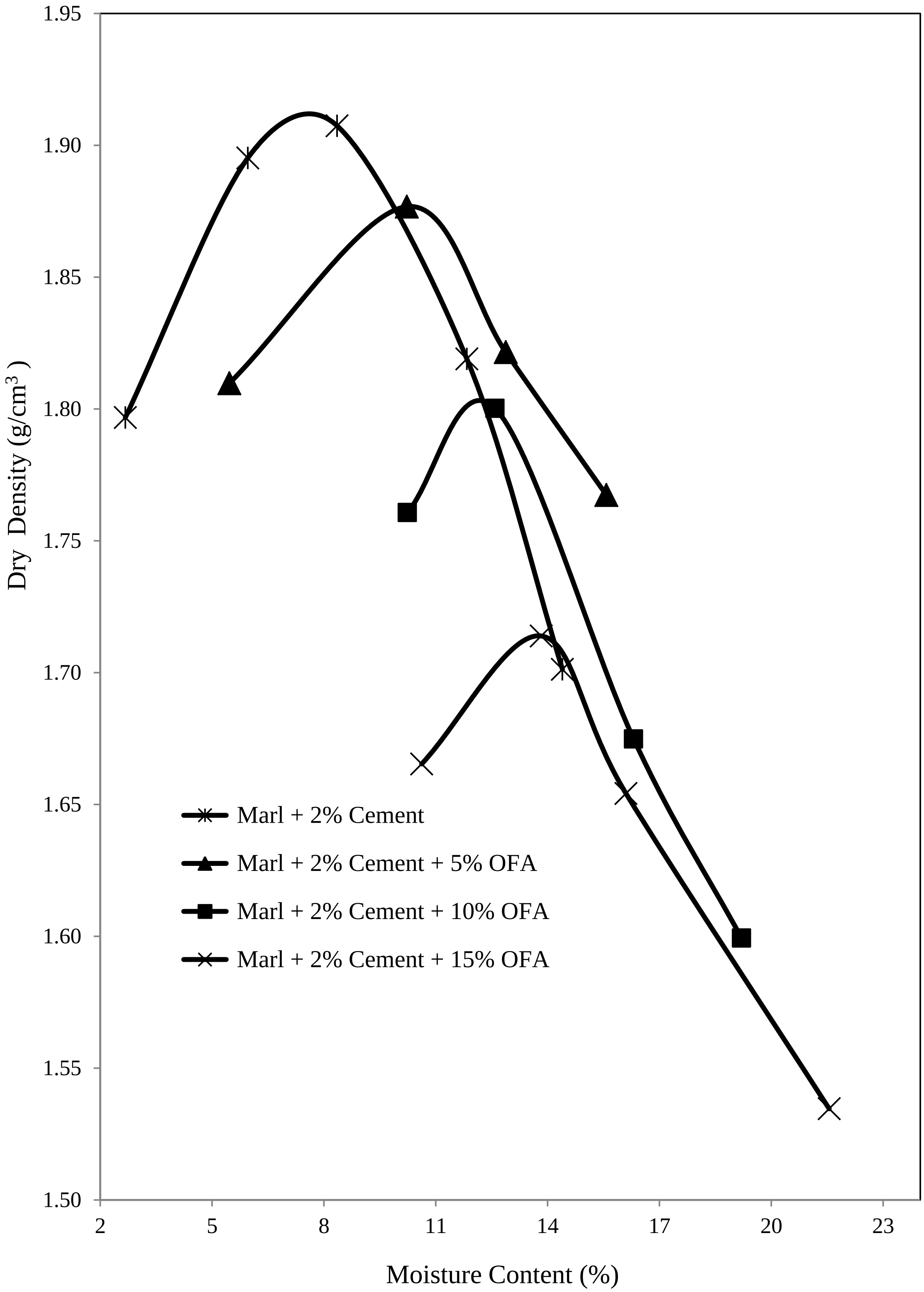


Figure 4-19: Moisture-Dry Density Relationship for Marl Stabilized with 2% Cement and Varying Quantity of OFA

4.4.5.2 Compaction Test Results of 2% Cement plus OFA-Stabilized Sand

The density-moisture relationship for sand stabilized with 2% cement and 5 to 15% OFA is depicted in Figure 4-20.

The data in Figure 4-20 indicate that the unit weight of sand with 2% cement increases with increasing quantity of OFA. The increase in the maximum dry density was not expected since the specific gravity of the OFA (1.3) is less than that of sand (2.63). The maximum dry density was 1.78, 1.79, 1.80 and 1.82 g/cm^3 for mixtures with 0, 5, 10 and 15% OFA, respectively. This increase was probably due to the fact that the OFA powder is very fine and the sand is of poor gradation, SP. Consequently, the OFA fills up voids within the mixture thereby increasing the unit weight of the composite mixture.

The data in Figure 4-20 depict that increasing OFA content caused a marginal increase in the optimum moisture content. The marginal increase in the optimum moisture content is attributed to the fact that the OFA is a very fine material, thus more water is required for its lubrication.

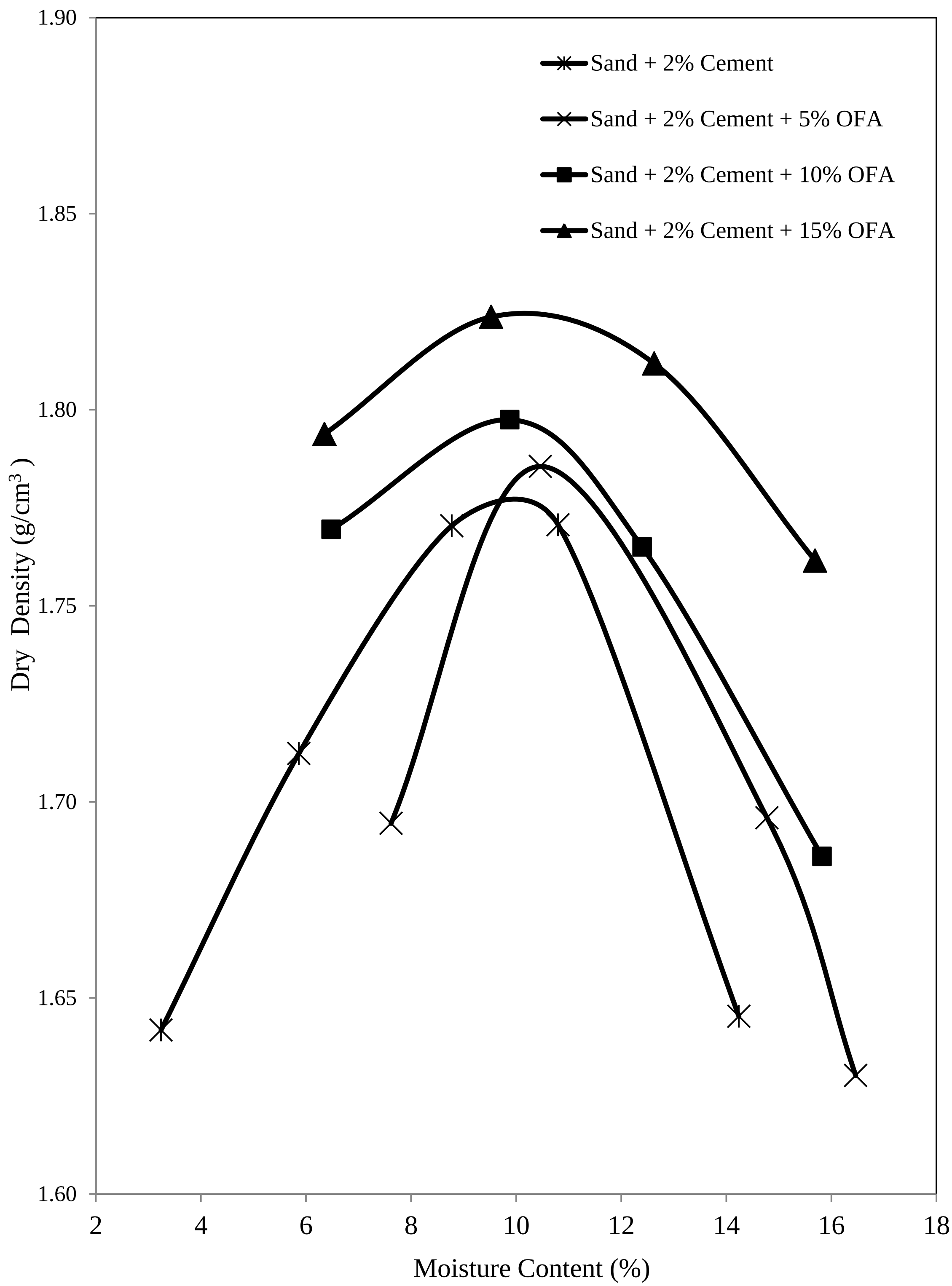


Figure 4-20: Moisture-Dry Density Relationship for Sand Stabilized with 2% Cement and Varying Quantity of OFA

4.4.5.3 Compaction Test Results of 2% Cement plus OFA-Stabilized Sabkha

Compaction tests were performed on sabkha stabilized with 2% cement plus 5 to 15% OFA. The results are reported in Figure 4-21. The data in Figure 4-21 indicate a decrease in the maximum dry density and an increase in the optimum moisture content with increasing quantity of OFA. The maximum dry density of sabkha with 2% cement plus 0, 5, 10 and 15% OFA was 1.96, 1.88, 1.77 and 1.75 g/cm^3, respectively. The decrease in the maximum dry density may be attributed to fact that the specific gravity of OFA (1.30) is less than that of sabkha (2.71).

It is also to be noted that the optimum moisture content of sabkha with 2% cement plus sabkha with 2% cement plus 0, 5, 10 and 15% OFA was 10.8, 11.4, 14.4 and 15.6%, respectively. The increase in the optimum moisture content may be attributed to the fact that OFA is a very fine material and, Consequently, it requires more water for lubrication.

In summary; the addition of OFA to the investigated soils with 2% cement caused variation in the maximum dry density. It decreased the maximum dry density of marl and sabkha with 2% cement which is ascribed to the lower specific gravity of the OFA compared to that of the marl and sabkha. However, OFA addition to the 2% cement-sand mixture increased the maximum dry density which was attributed to the fact that sand is of poor gradation, SP, and the OFA addition contributed to rearrangement of the sand particles which, in turn, increased the maximum dry density. Further, the addition of OFA to soils increased the optimum moisture content which may be attributed to the fact that OFA is very fine and more amount of water is required for lubrication.

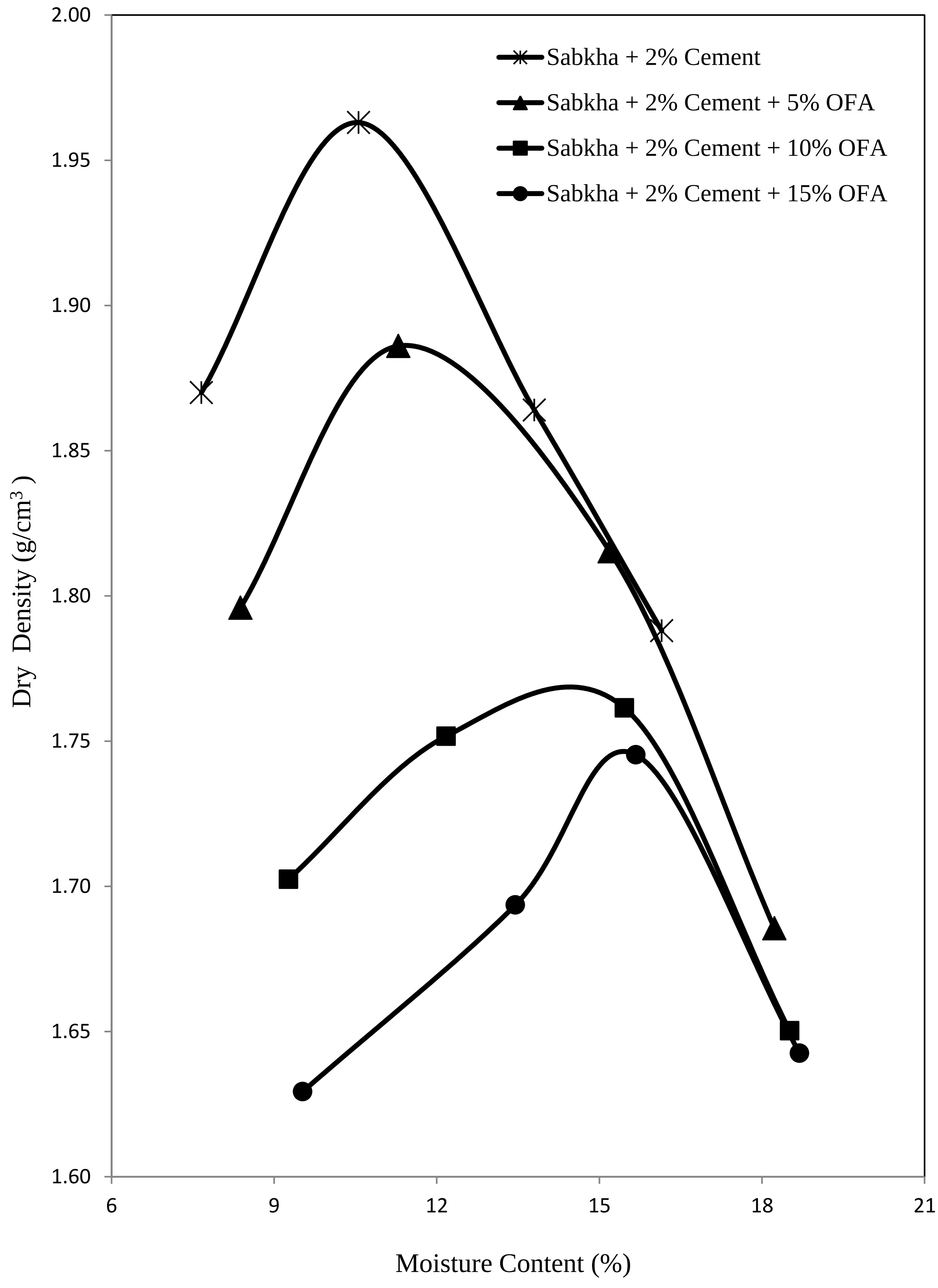


Figure 4-21: Moisture-Dry Density Relationship for Sabkha Stabilized with 2% Cement and 5-15% OFA

Table 4-5 summarize the optimum moisture content and the corresponding maximum dry density for the three investigated soils stabilized with the proposed stabilizers.

Table 4-5: Summary of the Compaction Results of the Investigated Soils

Additive Type and Content	**Marl**		**Sand**		**Sabkha**	
	γ_d (g/cm^3)	w_{opt} (%)	γ_d (g/cm^3)	w_{opt} (%)	γ_d (g/cm^3)	w_{opt} (%)
Plain (No Additive)	1.89	10.4	**	**	1.95	10.8
2% Cement	1.90	7.6	1.78	10.0	1.96	10.6
5% Cement	1.94	8.4	1.83	11.2	1.98	10.0
7% Cement	1.98	9.0	1.87	12.0	1.99	9.7
10% CKD	1.93	8.0	1.91	9.0	1.93	11.2
20% CKD	1.96	7.8	1.96	7.0	1.89	12.5
30% CKD	1.91	7.7	1.99	6.6	1.88	12.8
2% Cement + 10% CKD	1.98	8.4	1.92	9.2	1.93	9.8
2% Cement + 20% CKD	1.98	8.4	1.96	7.6	1.84	11.2
2% Cement + 30% CKD	1.95	10.0	1.97	7.4	1.85	12.2
2% Cement + 5% EAFD	2.00	9.2	1.90	9.0	1.97	10.6
2% Cement + 10% EAFD	2.04	9.0	1.93	9.2	1.97	10.8
2% Cement + 20% EAFD	2.10	8.8	2.08	6.4	1.98	11.2
2% Cement + 30% EAFD	2.23	8.0	2.19	7.8	1.99	11.2
2% Cement + 5% OFA	1.88	10.2	1.79	10.0	1.88	11.4
2% Cement + 10% OFA	1.80	12.2	1.80	10.1	1.77	14.4
2% Cement + 15% OFA	1.72	14.0	1.82	10.4	1.75	15.6

** Not conducted

4.5 Evaluating the Treatment of Marl Soil

The improvement in the properties of marl due to the use of selected stabilizers was evaluated by determining the unconfined compressive strength (UCS), soaked CBR and weight loss using the standard durability test. The environmental impact of the stabilizers that contain toxic metals was also studied. In addition, scanning electron microscopy was utilized to qualitatively interpret the mechanisms behind the improvement in the strength of the stabilized marl. The effects of different additives on the properties of the investigated marl are discussed in the following sub-sections.

4.5.1 Results of the Unconfined Compression Tests of Non-Plastic Marl

The unconfined compression tests were carried out on prepared specimens of plain and stabilized marl with varying amounts of each type of the proposed stabilizers. It is to be reported that all the UCS specimens were prepared at the optimum moisture content and maximum dry density of each mixture, as had been stated in Sections 4.4.1.1 through 4.4.5.1. The results of these tests are discussed in following sub-sections.

4.5.1.1 UCS of Marl Stabilized with Cement

The UCS of untreated marl as well of that treated with cement was measured. The cement contents were 2, 5 and 7% by weight of the dry soil. The results are reported in Figure 4-22.

It could be noted from the data in Figure 4-22 that as the cement content increases, the UCS of marl increases linearly. The average UCS for marl was 61, 644, 2,333 and 3,953

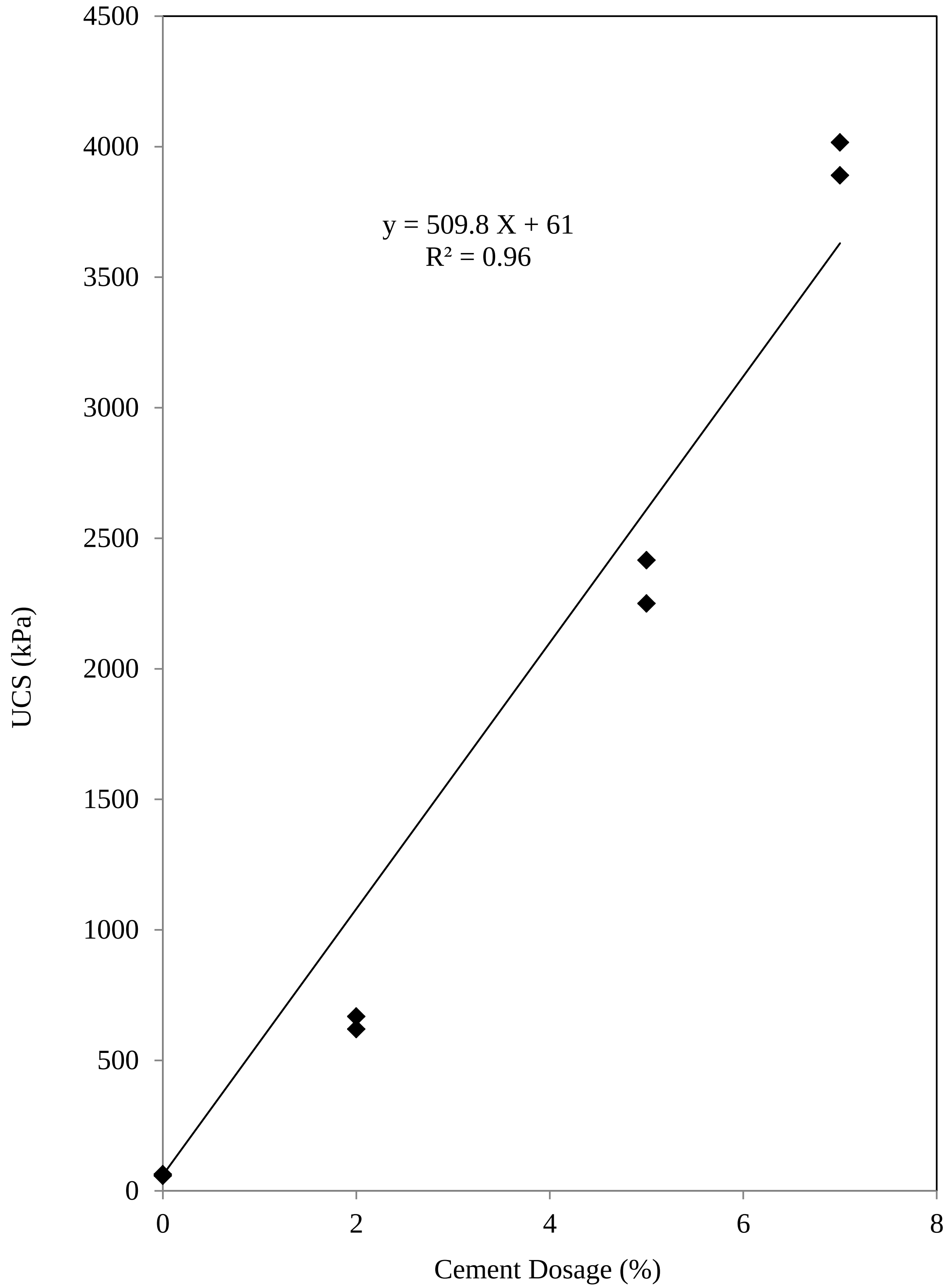


Figure 4-22: Effect of Cement Dosage on the UCS of Marl (7-Day Sealed Curing)

kPa for cement contents of 0, 2, 5 and 7%, respectively. Abdullah [2009] reported that the UCS for marl was 270, 548 and 964 kPa at cement contents of 0, 2, and 5%, respectively, corresponding to optimum moisture contents of 13, 14 and 14.2%, respectively. The variation between the results reported by Abdullah [2009] and those achieved in this study is expected due to the difference in the quality of the investigated marl. Further, Al-Amoudi et al. [2010] reported that the UCS after 90 days of sealed curing for non-plastic marl from Dhahran was about 7,510 and 8,174 kPa for cement contents of 5 and 7%, respectively. The high UCS reported by Al-Amoudi et al. [2010] may be attributed to longer curing period, i. e. 90 days, compared with only seven days in the present study.

The improvement in the UCS due to cement addition may be ascribed to the fact that when cement is added to soil in the presence of enough moisture, cement reacts with water to produce C-S-H which binds the soil particles together. It is well known that cement is the best candidate stabilizer for non-plastic soils as reported in the literature (Section 2.2).

The relationship between the cement dosage and the UCS of the investigated marl can be expressed by the following equation:

$$UCS = 509.8 * X + 61 \qquad R^2 = 0.96 \tag{4.1}$$

Where:

UCS = Unconfined compressive strength of cement-stabilized marl; 7-day sealed curing, kPa.

X = Cement dosage (%).

R^2 = Correlation coefficient.

ACI [1990] specifies a minimum UCS of 1,380 and 3,450 kPa for sub-base and base course, respectively, for rigid pavements. Similarly, it specifies minimum UCS of 1,725 and 5,175 kPa for sub-base and base course, respectively, for flexible pavements (Table 3-2). From the data in Figure 4-22, it is evident that marl with 2% cement is not suitable for either rigid or flexible pavements. This may be attributed to the fact that the amount of the cementing paste, produced by 2% cement, was not enough to provide the necessary binding between the marl particles. Further, the data in Figure 4-22 indicated that marl stabilized with 5% cement developed an UCS of 2,333 kPa, which is suitable for sub-base in rigid and flexible pavements while marl stabilized with 7% cement developed an UCS of 3,953 kPa and, hence, it is suitable for base construction in rigid pavements. Further, The dosage of cement required to be added to marl to be used as a base-course in flexible pavements, as estimated by extrapolation from Eq. 4.1, is 10.5%.

The improvement in the UCS of non-plastic marl stabilized with cement may be attributed to the fact that the selected non-plastic marl contains high quantity of solid fine-grained particles that minimized the volume of voids and decreased the volume of water required for lubrication and the water/cement ratio. The decrease in water/cement produces thick C-S-H gel that produces a strong bond between the marl particles [Matschei, et al., 2007].

The effect of cement addition on the UCS of non-plastic marl can be explained using the SEM technique. Typical BEI and SEM with EDX micrographs, presented in Figure 4-23 (a through d), show the morphology of marl stabilized with 2 and 7% cement.

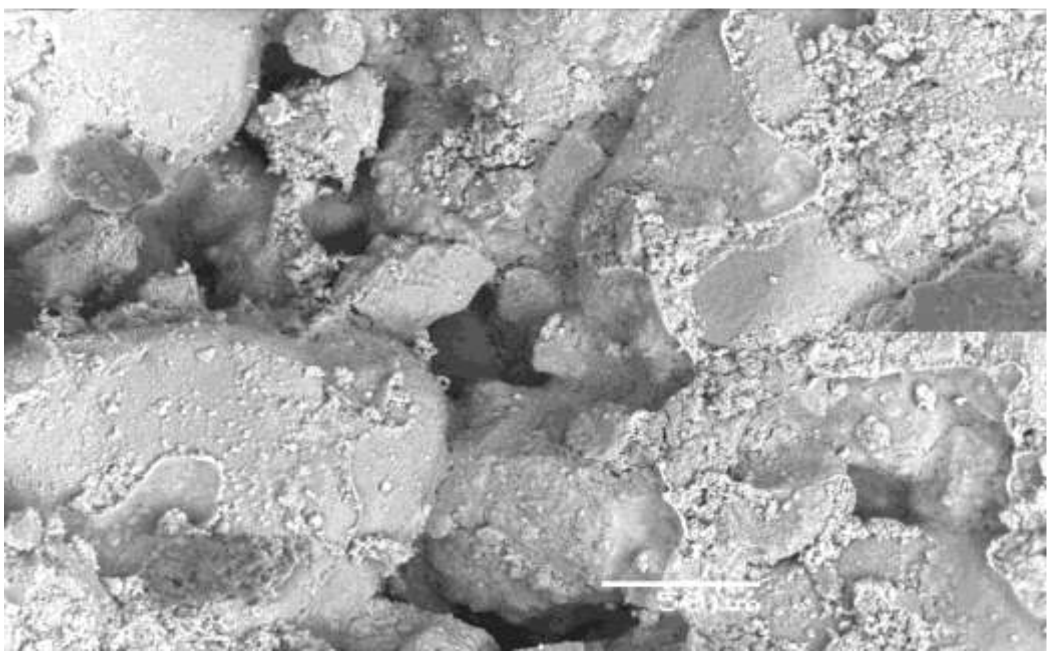
Figure 4-23(a) shows the BEI of marl stabilized with 2% cement. A porous microstructure with voids could be seen in the micrograph. Similarly, Figure 4-23(b) shows the BEI of marl stabilized with 7% cement. The volume of the voids is reduced and the pore spaces are filled with C-S-H gel. The good bond noted in this BEI is probably responsible for the increase in the UCS of marl with 7% cement.

Figure 4-23(c) shows the SEM of marl with 2% cement. The SEM micrograph indicates a porous morphology and lack of cementing gel thereby indicating the need for additional cement to make the marl denser. The EDX, Figure 4-23(d), indicated the presence of Ca, Si, Mg, Al, K and Fe with about 20.6, 11, 7.1, 2.7, 1.9 and 1.2 %, respectively. These are mainly contributed by the marl soil and cement. The presence of Ca and Mg was brought from the cement and dolomite in marl soil, respectively.

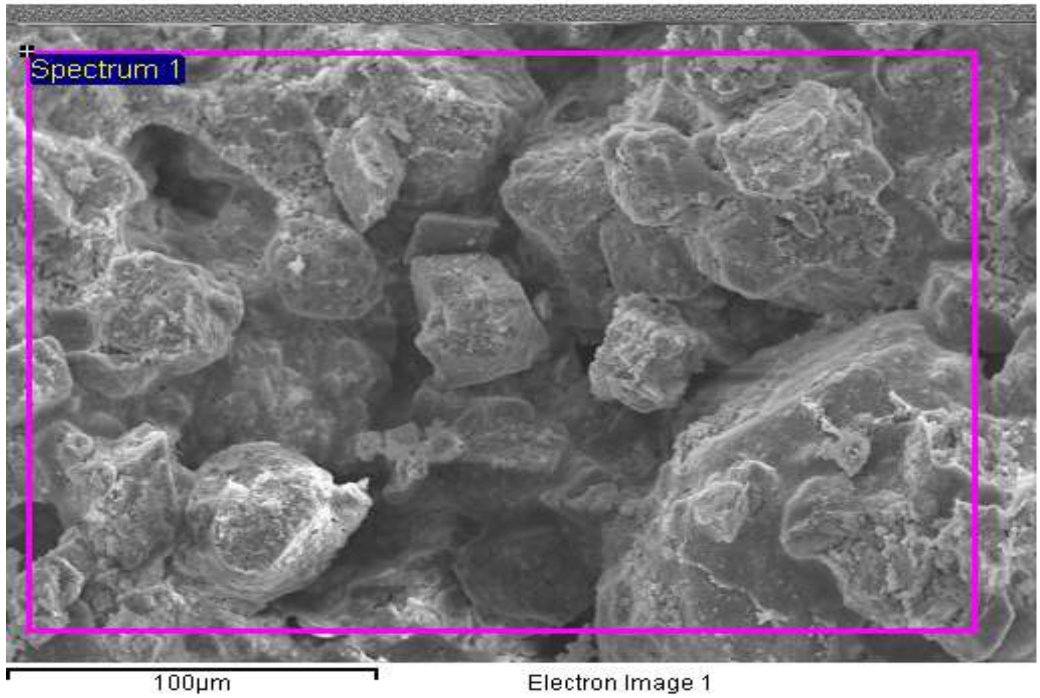
Figure 4-23(e) shows the SEM of marl stabilized with 7% cement. A dense morphology is indicated in this specimen. The marl particles are covered by C-S-H gel. The EDX, Figure 4-23 (f), shows that Ca, Si, S, Mg, Al, K and Fe elements form 16.7, 13.6, 1.0, 3.8, 3.9, 3.2 and 0.9%, respectively.

The dense structure of this specimen is responsible for the highest strength developed by 7% cement.

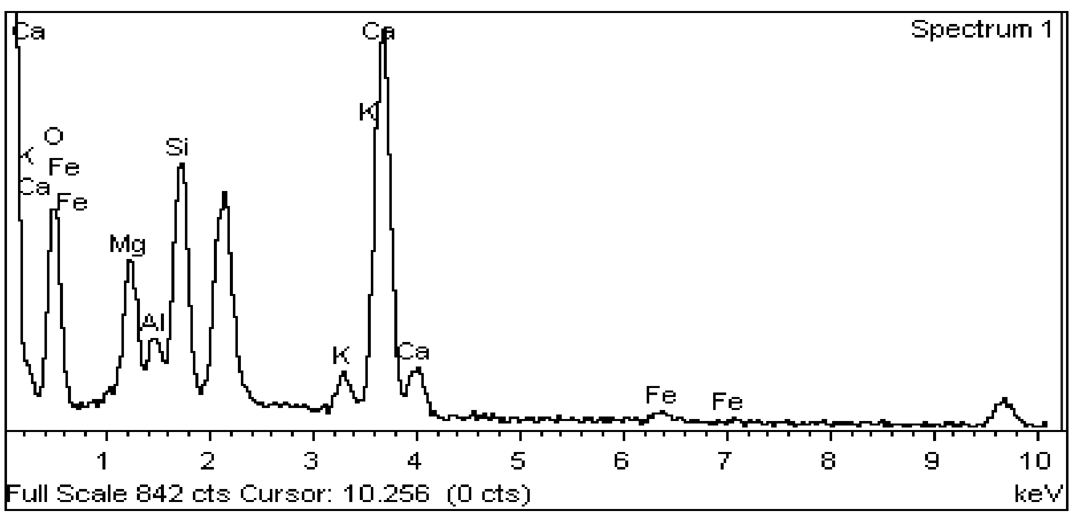
a) BEI of marl stabilized with 2% cement (X400)



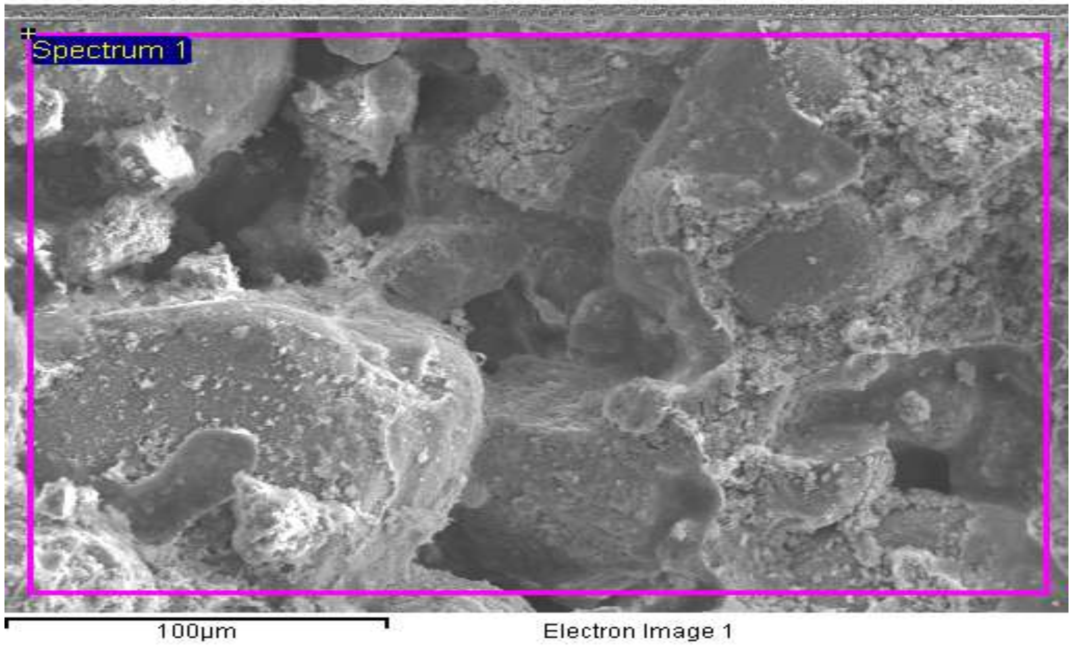
b) BEI of marl stabilized with 7% cement (X400)



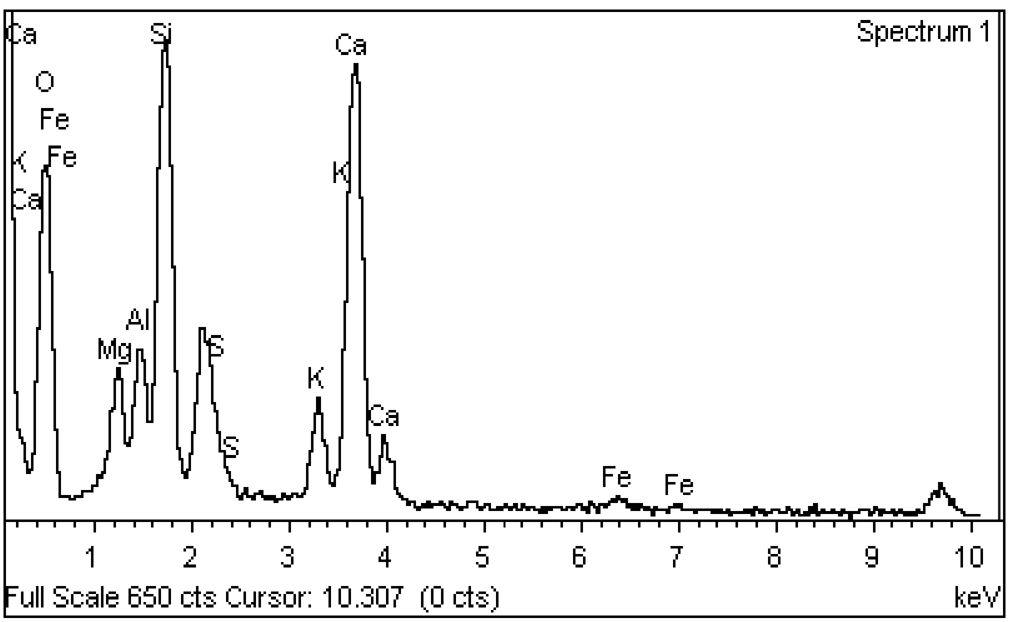
c) SEM of marl stabilized with 2% cement (X400)



d) EDX of marl stabilized with 2% cement



e) SEM of marl stabilized with 7% cement (X400)



f) EDX of marl stabilized with 7% cement

Figure 4-23: BEI, SEM and EDX of Marl Stabilized with 2 or 7% Cement

4.5.1.2 UCS of Marl Stabilized with CKD

Unconfined compression tests were conducted on plain marl and marl treated with CKD additions in the range from 10 to 30%. The results are plotted in Figure 4-24.

From the data in Figure 4-24, it is clear that the UCS of marl with 0, 10, 20 and 30% CKD by weight of dry soil is 61, 367, 800 and 1050 kPa, respectively. This is in agreement with the findings reported by Abdullah [2009] that the addition of CKD in the range of 0 to 30% improved the 7-day UCS of non-plastic marl from 270 to 1235 kPa. Further, Rahman et al. [2006] reported that the addition of CKD content from 0 to 50% improved the 14-day UCS of non-plastic marl from 357 to 4709 kPa. The significant improvement in the UCS for the marl stabilized with CKD reported by Rahman et al. [2006] was due to the long period of curing time (i.e. 14 days as compared with 7 days in this study).

From the data in Figure 4-24, a linear relationship between the UCS and the CKD content for non-plastic marl was noticed. The following model best fits the data:

$$UCS = 34 * X + 59.5 \qquad R^2 = 0.98 \qquad (4.2)$$

Where:

UCS = Unconfined compressive strength of CKD-stabilized marl, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

It is to be noted that the marl stabilized with CKD did not meet the ACI Committee [1990] minimum strength requirement (1,380 kPa) that qualifies a soil to be used as a construction material for sub-base course in rigid and flexible pavements.

In spite of the fact that CKD contains high amount of calcium and silicon required for producing C-S-H gel, the improvement in the UCS was not very significant (i.e. as compared with cement). That was probably due to the high loss on ignition (LOI) and the high alkalis of the CKD, as shown in Table 4-1. The high alkalis delay the formation of C-S-H gel and weaken the strength of the produced hydrated cement pastes [Cuisinier et al., 2011].

Furthermore, the chloride and magnesium in the CKD could have reacted and produced magnesium chloride, that causes severe deterioration to the cementing gel more than NaCl or $CaCl_2$, which reacts with the cementitious C–S–H in the cement paste formed by CKD to produce non-cementitious magnesium–silicate–hydrate (M–S–H) and $CaCl_2$ as proposed by the following reaction [Mussato et al. (2004)]:

$MgCl_2$ + C-S-H $\rightarrow$ M-S-H + $CaCl_2$.

Further, the formation of soluble $CaCl_2$ leads to initial strength loss [Reddy et al., 2011].

.

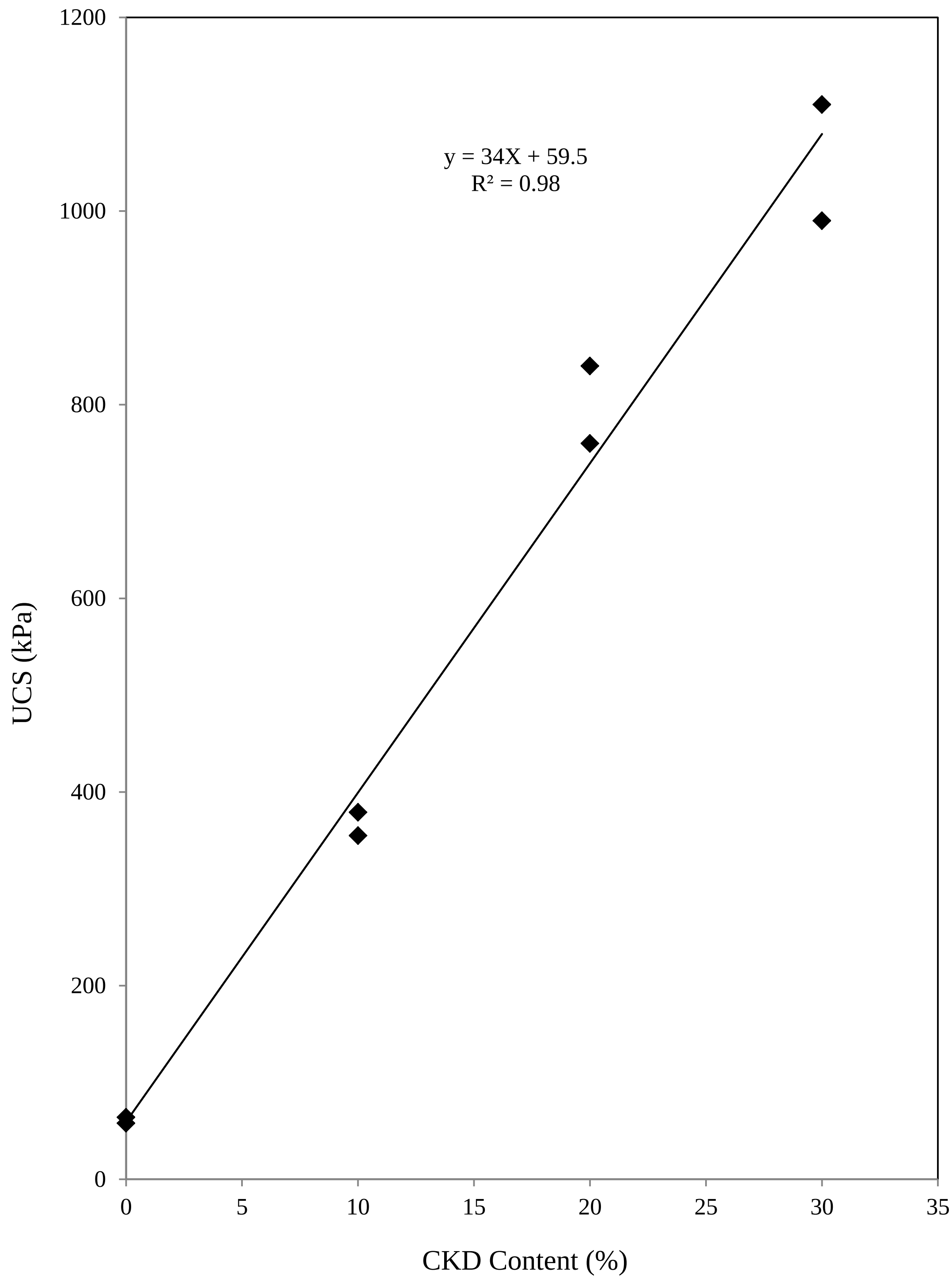


Figure 4-24: Effect of CKD Content on the UCS of Marl (7-Day Sealed Curing)

4.5.1.3 UCS of Marl Stabilized with 2% Cement plus CKD

Unconfined compression tests were conducted on non-plastic marl with 2% cement as well as on non-plastic marl treated with CKD additions of 10 to 30% with 2% cement. The results of the UCS in terms of the CKD content are plotted in Figure 4-25.

The data in Figure 4-25 illustrate that the UCS of non-plastic marl + 2% cement increases exponentially with the quantity of CKD. It could be noted from the data in this figure that 30% CKD addition has improved significantly the UCS of the non-plastic marl with 2% cement (from 644 to 1,780 kPa) to satisfy the minimum strength (1,725 kPa) specified by ACI [1990] for the stabilized soil to be used as a construction material for sub-base in flexible pavements. Therefore, the 30% CKD plus 2% cement is a suitable stabilizer for the investigated marl to be used as sub-base course in rigid and flexible pavements.

Though 10 and 20% CKD additions have improved the UCS of the non-plastic marl with 2% cement (from 644 to 960 and 1,290 kPa, respectively); none of those contents improved the UCS of marl with 2% cement to meet the minimum strength (1,380 kPa) specified by the ACI [1990] for sub-base course in rigid pavements. However, Abdullah [2009] reported that 20% CKD plus 2% cement improved the UCS of the non-plastic marl from 270 to 1,520 kPa even with the usage of optimum moisture content of 13% while the same dosage in this study with the optimum moisture content of 8.4% failed to improve the UCS to 1,380 kPa. The improvement in the strength reported by Abdullah [2009] could be attributed to the good quality of the marl he studied. Therefore, the quality of the soil significantly affects the level of strength improvement.

The relationship between the UCS and CKD content in marl with a constant dosage of 2% cement could be expressed by the following best fit statistical model.

$$UCS = 657.76 * e^{0.034X} \qquad R^2 = 0.99 \qquad (4.3)$$

Where:

UCS = Unconfined compressive strength of marl stabilized with 2% cement and varying quantity of CKD, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

The improvement in UCS was probably due to the fact that addition of 2% cement to marl plus 30% CKD enhanced the cementing effect of CKD.

Figure 4-26 (a) shows BEI of marl stabilized with 2% cement plus 30% CKD. A relatively dense and compacted structure could be depicted in BEI. The bonding between marl particles can be noted. Also, the volume of voids, compared to Figure 4-23 (a), is minimized due to the addition of 30% CKD. However, few voids are noted which hinder the full strength gain of marl with 30% CKD plus 2% cement.

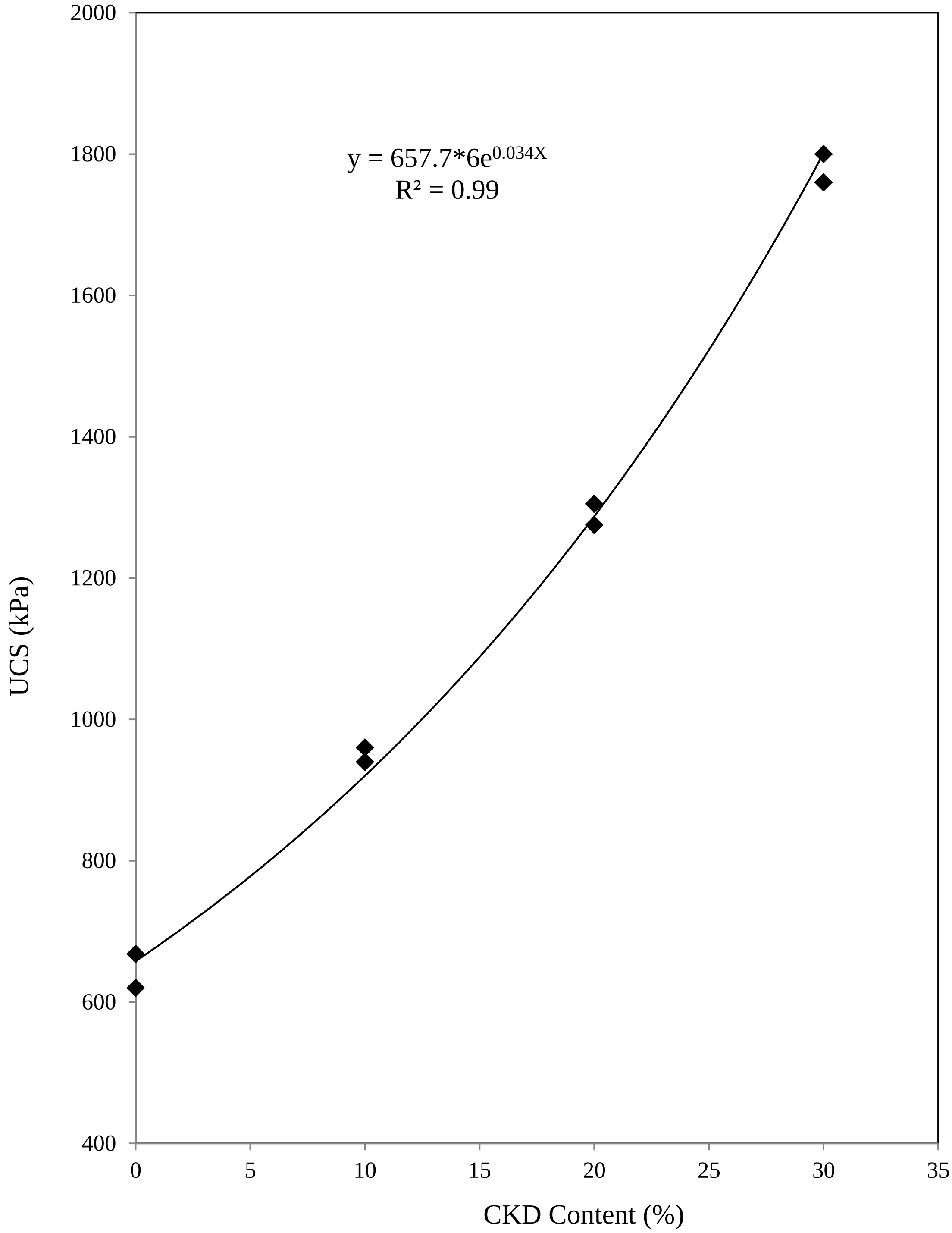
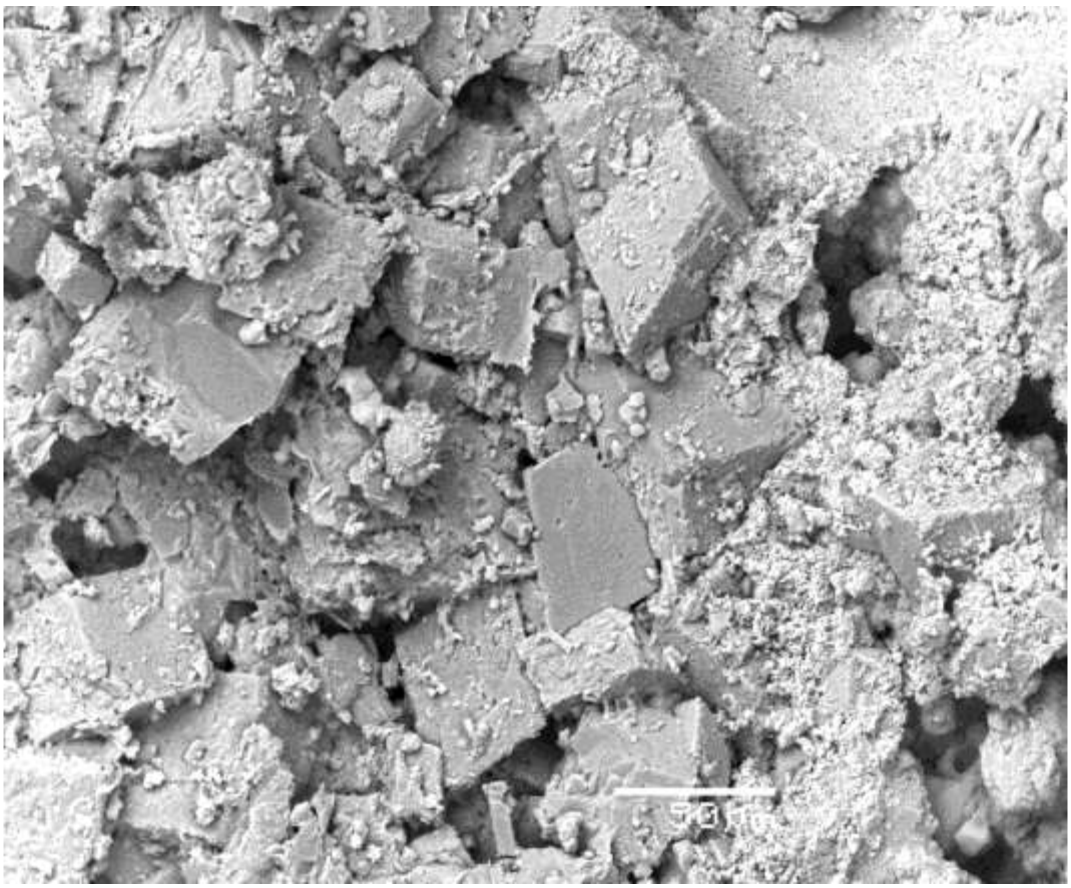


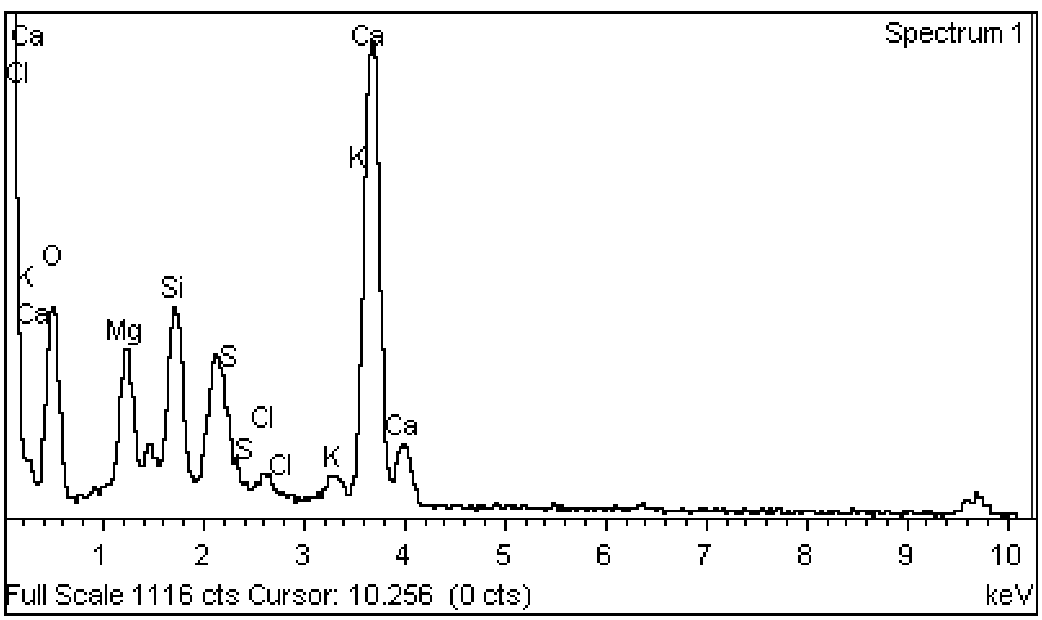
Figure 4-25: Effect CKD on the UCS of Marl with 2% Cement (7-Day Sealed Curing)

The SEM in Figure 4-26 (b) shows morphology similar to that indicated in the BEI. Dense structure with isolated voids is shown. The EDX, Figure 4-26 (c), indicates mainly the presence of Ca, Mg, Si, S, Cl, and K contents with about 25.5, 6.6, 7.9, 1.6, 1.3 and 1.3%, respectively. It is also noticed that there is a significant increase in calcium, silicone, chloride and potassium contents compared with marl stabilized with only 2% cement.



a) BEI of marl stabilized with 2% cement plus 30% CKD (X400)

b) SEM of marl stabilized with 2% cement plus 30% CKD (X400)



c) EDX of marl stabilized with 2% cement plus 30% CKD

Figure 4-26: BEI, SEM and EDX of Marl Stabilized with 30% CKD plus 2% Cement (7-Day Sealed Curing)

4.5.1.4 UCS of Marl Stabilized with 2% Cement plus EAFD

Unconfined compression tests were conducted on marl with 2% cement plus 0, 5, 10, 20 and 30% EAFD. The results of UCS against EAFD content are reported in Figure 4-27.

An exponential increase in the UCS could be noted with an increase in the quantity of EAFD. The UCS of marl plus 2% cement with 0, 5, 10, 20 and 30% EAFD was 644, 676, 876, 1,427 and 2,430 kPa, respectively. This indicates that 30% EAFD has increased the UCS of marl plus 2% cement by almost four times.

The relationship between the EAFD content and the UCS of non-plastic marl plus 2% cement could be expressed by the following equation:

$$UCS = 523.32*e^{0.051X} \qquad R^2 = 1 \qquad (4.4)$$

Where:

UCS = Unconfined compressive strength of marl stabilized with 2% cement and varying quantity of EAFD, 7-day sealed curing, kPa.

X = EAFD content (%).

R^2 = Correlation coefficient.

It is to be noted that the UCS of non-plastic marl with 20% EAFD plus 2% cement (1,405 kPa) satisfies the minimum strength (1,380 kPa) requirement specified by ACI [1990] for the stabilized soil material to be used as a sub-base course in rigid pavements. Similarly; marl with 30% EAFD plus 2% cement satisfies the minimum strength (1,725 kPa) requirement of ACI [1990] for the marl soil to be used as a sub-base course in flexible pavements. Further, the BEI, SEM micrographs and schematic illustration of interaction (Figure 4-28) provide qualitative evidence of the strength improvement due to the addition of EAFD. Comparison of BEI in Figure 4-28 (a) with that in Figure 4-23 (a) indicates that the microstructure of marl gets denser with the addition of EAFD. This may be attributed to the filler effect of the EAFD.

Figure 4-28 (b) shows SEM of marl stabilized with 2% cement and 30% EAFD. A dense morphology is indicated in this micrograph. The EDXA, Figure 4-28(c), indicates the presence of Mg, Si, Ca, Fe and Zn with the weight percentage of about 5.7, 6.8, 13.7, 22.0 and 6.7, respectively. The high amount of iron and zinc is due to the high concentration of these elements in EAFD. The presence of Zn retards the setting of cement. However, this affect is noticeable only in the initial period of 2 to 3 days [Najamuddin, 2011].

The XRD of marl stabilized with 2% cement and 30% EAFD, Figure 4-28(d), indicated the presence of Wustite [FeO], 20.4%, Ankerite [$CaFe^{2+}_{0.6}\ Mg_{0.3}Mn^{2+}_{0.1}(CO_3)_2$], 56.6%, Quartz [$SiO_2$], 16.1%, and Calcite [$CaCO_3$], 6.9%.

Figure 4-28(e) presents the molecular illustration for wustite in marl stabilized with 2% cement plus 30% EAFD. This mechanism based on the XRD results, electronegativity of the elements and the exothermic of cement hydration. The XRD patterns indicated the formation of wustite and ankerite products in high percentages. Furthermore, it is well known that the hydration of cement is exothermic reaction which, in turn, warms the surface area of quartz particles, Si, to react with Ca and Fe. Interestingly, the electronegativity of Fe, Ca and Si is 1.8, 1.0 and 1.9 Pauling, respectively. The moderate electronegativity of Ca facilitates the enhanced stability of the bonding interaction between Fe, Ca and Si elements in the structure of the developed mixture [Weinhold and Landis, 2005].

Similarly, Figure 4-28(f) shows the molecular illustration for ankerite [$CaFe^{2+}_{0.6}$ $Mg_{0.3}Mn^{2+}_{0.1}$ $(CO_3)_2$] product shown by XRD (Figure 4-28(d)). It is noted that the presence of Mn^{2+} in the mixture is trivial. Thus, the other elements in structure were considered in the mechanism. The proposed interaction between EAFD, cement and dolomite, present in the marl, is supported by the electronegativity differences of Mg, Ca and Fe is 1.3, 1.0 and 1.8 Pauling, respectively. The moderate electronegativity of Ca facilitates the stability of bonding interactions between Mg, Ca and Fe elements in the developed mixture [Weinhold and Landis, 2005].

Therefore, the improvement in the strength of the marl stabilized with 2% cement plus 30% EAFD could be attributed to the binding effect in addition to the marginal filler effect. Hence, the improvement in the microstructure is due to the incorporation of EAFD in the presence of cement.

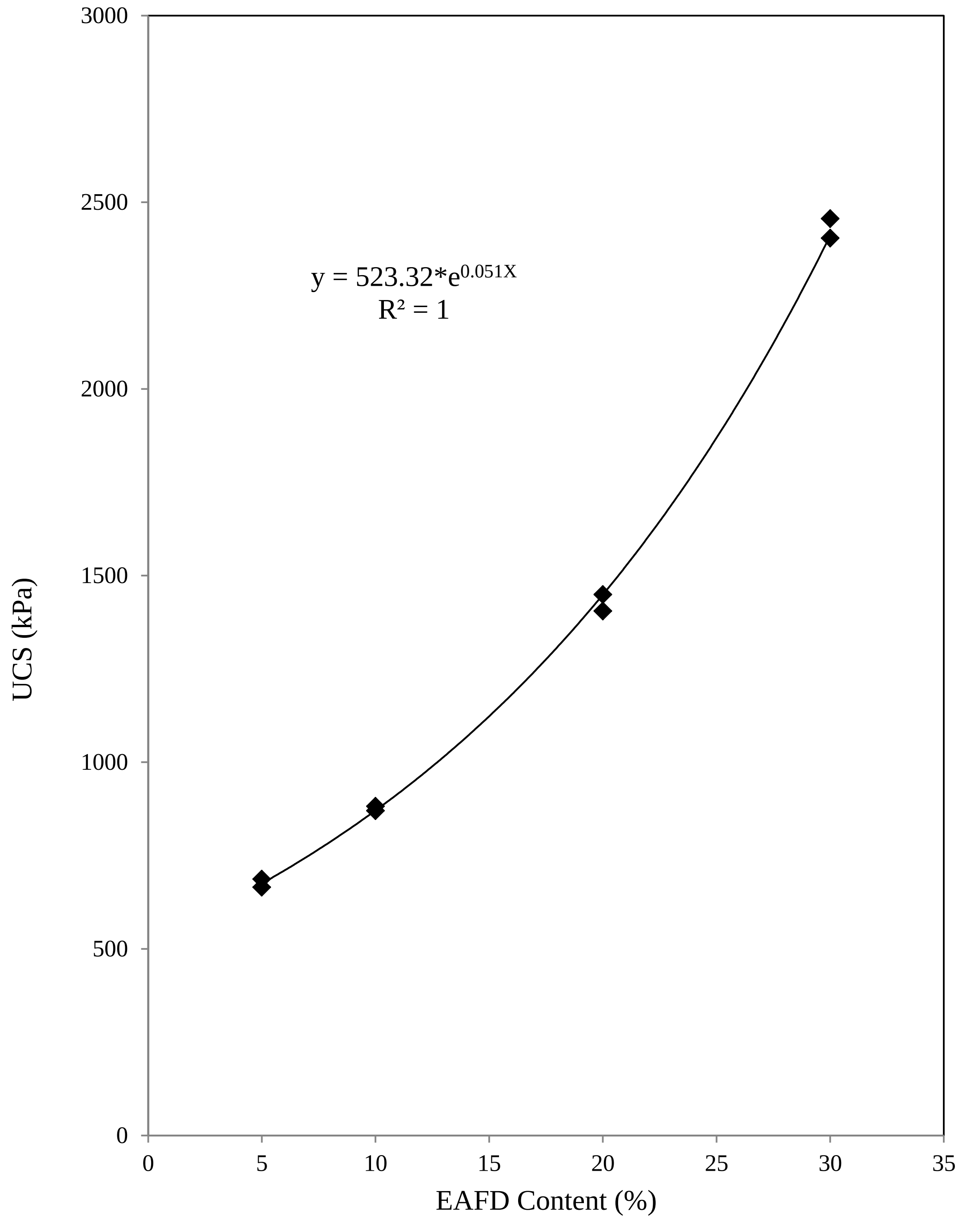
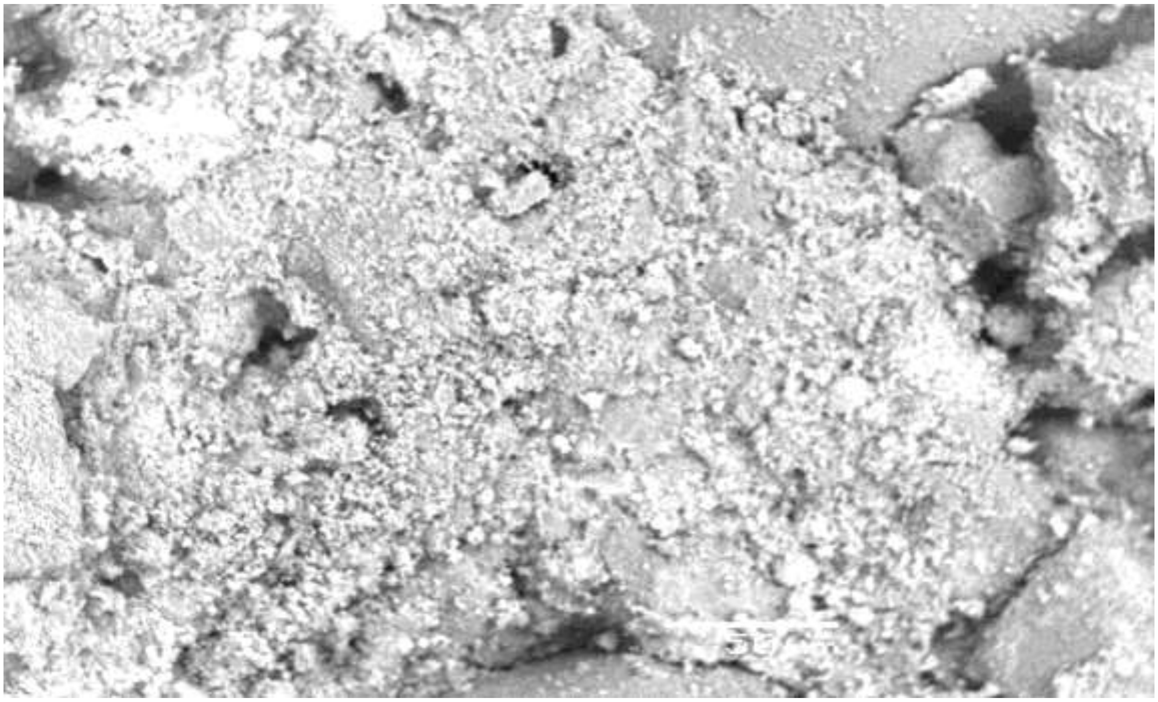
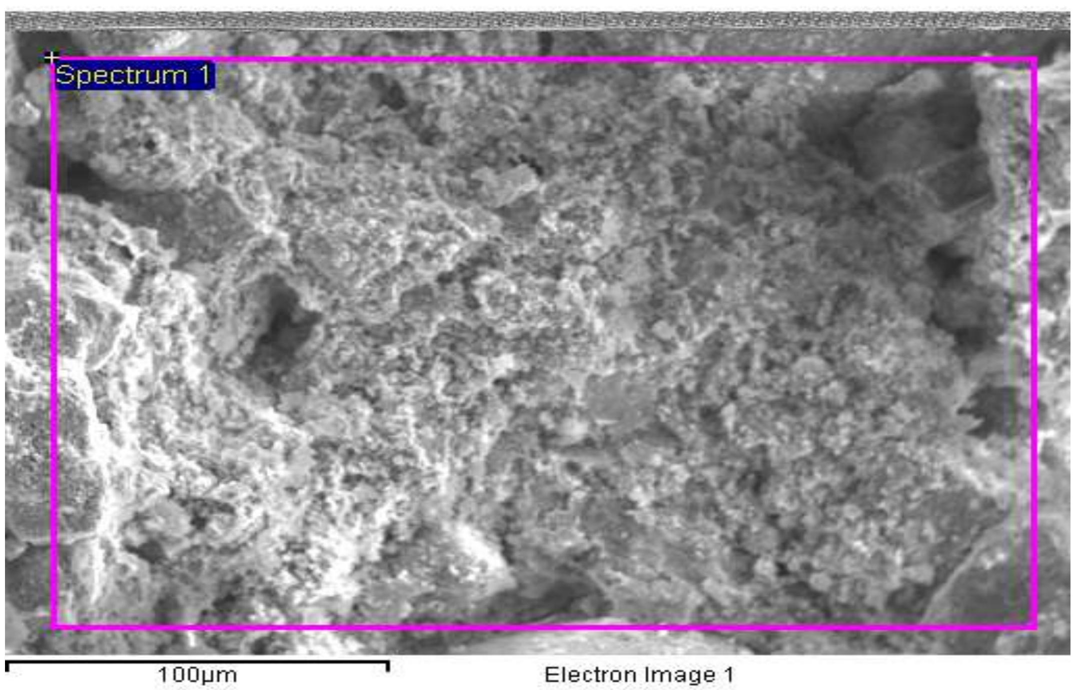


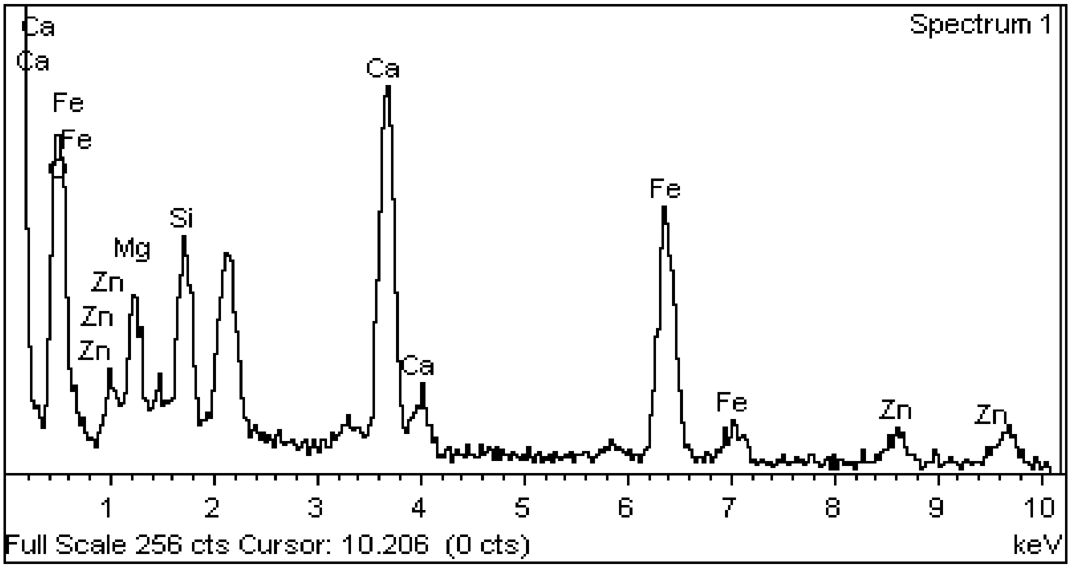
Figure 4-27: Effect of EAFD Content on the UCS of Marl with 2% Cement (7-Day Sealed Curing)



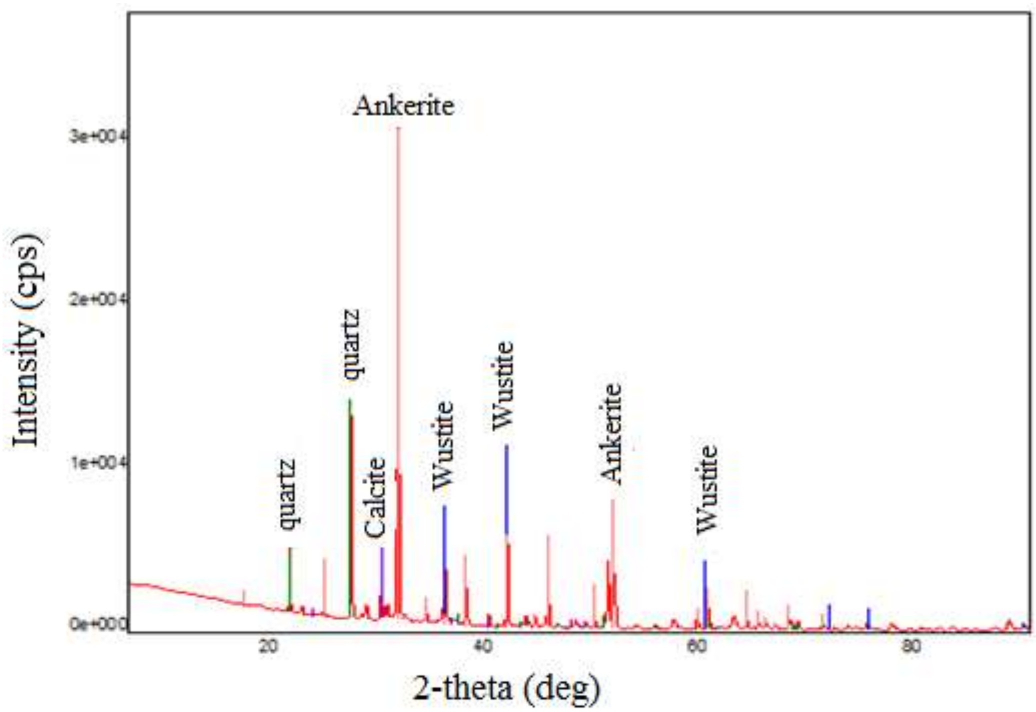
a) BEI of marl stabilized with 2% cement plus 30 % EAFD (X400)



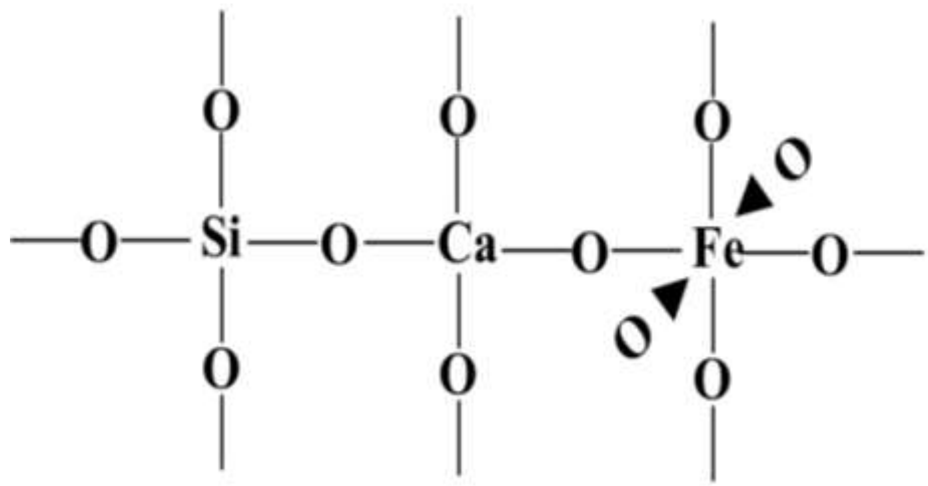
b) SEM of marl stabilized with 30% EAFD plus 2% cement (X400)



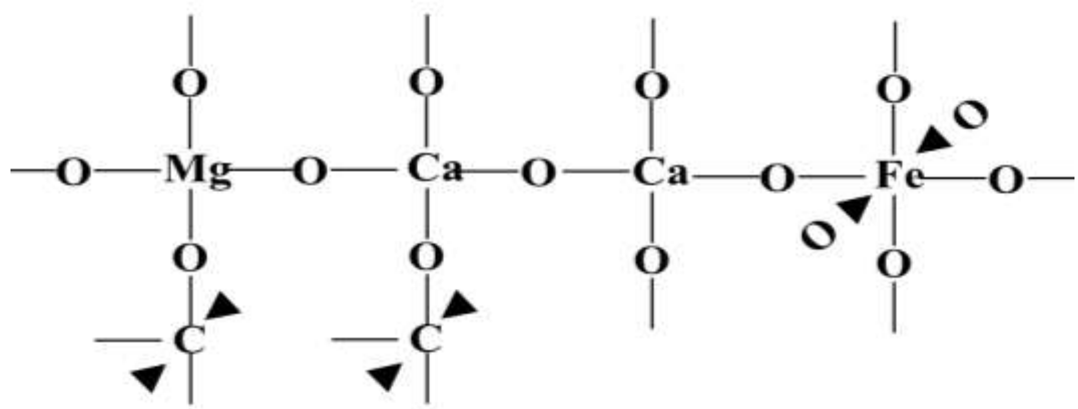
c) EDX of marl stabilized with 30% EAFD plus 2% cement



d) X-ray diffractogram of marl stabilized with 30% EAFD plus 2% cement



e) Molecular illustration for wustite in marl stabilized with 2% cement plus 30% EAFD



f) Molecular illustration for ankerite in marl stabilized with 2% cement plus 30%EAFD

Figure 4-28: BEI, SEM, EDX, XRD and Molecular Interaction of Marl Stabilized with 30% EAFD and 2% Cement (7-Day Sealed Curing)

4.5.1.5 UCS of Marl Stabilized with 2% Cement plus OFA

Unconfined compression tests were conducted on marl stabilized with 2% cement and on that treated with 2% cement plus OFA contents of 5, 10 or 15%. The results are reported in Figure 4-29.

The data in Figure 4-29 indicated that the UCS of marl with 2% cement plus 5 or 10% OFA decreases from 644 to 262 and 232 kPa, respectively. A similar decrease was reported by Abdullah [2009]. On the other hand, the UCS of marl with 2% cement plus 15% OFA increased to 802 kPa. However, this strength is much less than the minimum strength (1,380 kPa) specified by ACI [1990] for the soil to be used as sub-base course in rigid pavements.

The best fit model for the relationship between OFA content and UCS of the non-plastic marl plus 2% cement could be expressed by the equation.

$$UCS = 9.52X^2 - 133.92X + 656.4 \qquad R^2 = 0.99 \qquad (4.5)$$

Where:

UCS = Unconfined compressive strength of marl stabilized with 2% cement and varying quantity of OFA, 7-day sealed curing, kPa.

X = OFA content (%).

R^2 = Correlation coefficient.

The reduction in the UCS of the non-plastic marl with 2% cement caused by the addition of 5 and 10% OFA was probably due to the fact that the OFA has very high LOI and low alkalis, as shown in Table 4-3, which, in turn, retarded the reaction of the 2% cement. However, the more amount of OFA the more water needed for lubrication, allows the hydration which activated the reaction of the 2% cement and of the trivial amount of the calcium and silicon amount in the OFA [Kolay et al., 2011; and Edil et al., 2006]. This resulted in recovery of the UCS of soil with 15% OFA plus 2% cement. However, the more amount of the OFA content in stabilized soils, the lower was the soaked CBR [Edil et al., 2006].

The developed UCS of marl stabilized with 2% cement and varying quantity of OFA did not meet the minimum strength requirement (1,380 kPa) specified by ACI [1990]. Therefore, OFA addition with 2% cement is not suitable to be used as a stabilizer for non-plastic marl.

In a statistical models, the relation between the variables is considered reliable if the correlation coefficient (R^2) is greater than 0.80 [Montgomery, 2009]. Hence, the relations reported in Equations 4.1 through 4.5 can be considered reliable since the value of the correlation coefficient (R^2) is 0.96, 0.98, 0.99, 1 and 0.99, respectively. The developed relations are useful for estimating the required amount of the various stabilizers used in the present investigation, namely cement, CKD, CKD plus 2% cement, EAFD plus 2% cement and OFA plus 2% cement to attain the required 7-day sealed curing strength.

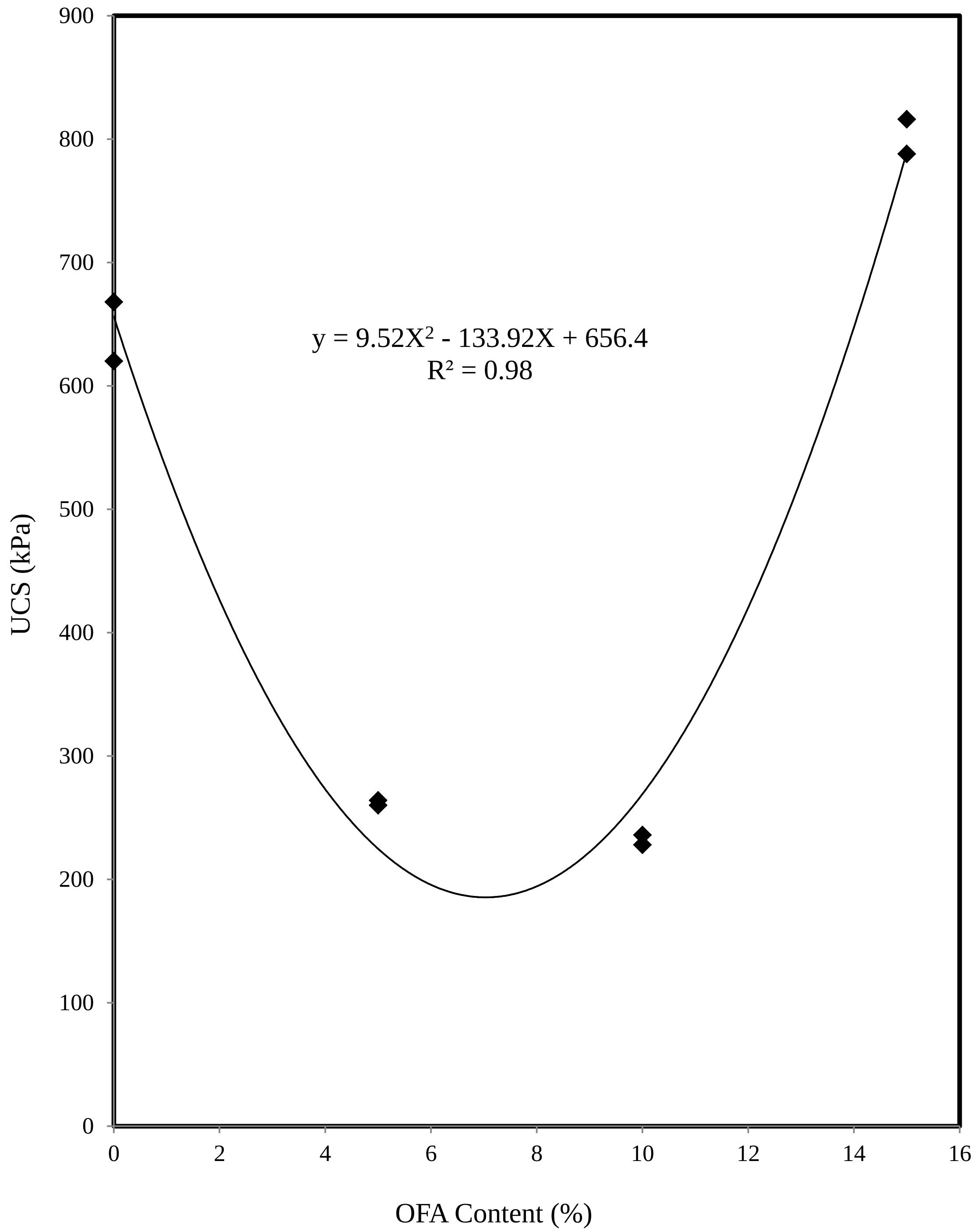


Figure 4-29: Effect of OFA Content on the UCS of Marl with 2% Cement (7-Day Sealed Curing)

The results of the UCS for untreated and treated non-plastic marl are summarized in Table 4-6. The data in Table 4-6 indicate that plain non-plastic marl shows very low UCS and it should be stabilized prior to be used as a construction material for pavements.

From the data in Table 4-6, the stabilizers and dosages that satisfied the minimum UCS requirements specified by ACI [1990], mentioned in Table 3-2, are summarized in Table 4-7. From this table, it is evident that 5 and 7% cement, 2% cement plus 30% CKD, 2% cement plus 29% EAFD and 2% cement plus 30% EAFD were useful in improving the UCS of selected marl to meet the ACI strength requirements. As reported in Section 3.1, only theses mixtures will be tested for soaked CBR.

4.5.2 Results of Soaked CBR Tests on Non-Plastic Marl

Specimens of marl treated with cement alone or with 2% cement plus stabilizer that fulfilled the minimum strength requirements specified by the ACI [1990], as well as of plain marl (as reference), were subjected to soaked CBR tests. Specimens were prepared and tested according to ASTM D 1883. The specimens were sealed and cured for seven days at laboratory condition (22 ± 3^oC). Then, they were soaked in tap water for 96 hours before testing. The effect of each stabilizer on the soaked CBR of non-plastic marl is discussed in the following sub-sections.

Table 4-6: UCS of Marl with Cement and/or Cement plus Stabilizer (7-Days Sealed Curing)

Additive Type and Content	**UCS (kPa)**		
	Specimen #1	Specimen #2	Average
Plain Marl (No Additive)	58	64	61
2% Cement	620	668	644
5% Cement	2,250	2,416	2,333
7% Cement	3,890	4,016	3,953
10% CKD	355	379	367
20% CKD	760	840	800
30% CKD	990	1,110	1,050
2% Cement + 10% CKD	940	960	950
2% Cement + 20% CKD	1,275	1,305	1,290
2% Cement + 30% CKD	1,760	1,800	1,780
2% Cement + 5% EAFD	665	687	676
2% Cement + 10% EAFD	870	882	876
2% Cement + 20% EAFD	1,405	1,449	1,427
2% Cement + 30% EAFD	2,404	2,456	2,430
2% Cement + 5% OFA	260	264	262
2% Cement + 10% OFA	228	236	232
2% Cement + 15% OFA	788	816	802

Table 4-7: Additives Satisfying the ACI [1990] Requirement for Marl

Additive Type and Content	UCS (kPa)
5% Cement	2,333
7% Cement	3,953
2% Cement + 30% CKD	1,780
2% Cement + 20% EAFD	1,427
2% Cement + 30% EAFD	2,430

4.5.2.1 CBR Results of Marl Stabilized with Cement

For studying the effect of cement content on the soaked CBR of non-plastic marl, CBR tests were conducted on specimens treated with cement additions. The cement additions were 2, 5 and 7%. The results are reported in Figure 4-30.

It is noticed, from the data in Figure 4-30 that the soaked CBR of untreated non-plastic marl was very poor (10%), which is not suitable for soil layers in pavements. When cement was added, the soaked CBR of the marl increased. This CBR increment confirms the findings reported in the literature [Abdullah, 2009; and Ahmed, 1995] except that in this study, soaked not unsoaked CBR tests were used. It is well known that non-plastic marl is somewhat sensitive to water as it was reported by many researchers [Abdullah, 2009; and Ahmed, 1995,], whereby complete loss in the bearing capacity of marl occurs upon inundation. For instance, Abdullah [2009] found that the unsoaked CBR of the plain non-plastic marl was 47%, while in this study the soaked CBR of the plain marl is 10%. However, the soaked CBR of non-plastic marl was significantly improved (from 10 to

590%) due to the addition of 7% cement. The soaked CBR of the non-plastic marl with 0, 2, 5 and 7% cement was 10, 60, 250 and 590%, respectively. Generally; the addition of cement improved the soaked CBR of the investigated marl making it an excellent candidate for base-course in pavements.

Further, there was an exponential relationship between the soaked CBR and the cement content. The correlation can be expressed by the following equation:

$$\text{Soaked CBR (\%)} = 13.12e^{0.569X} \qquad R^2 = 0.97 \qquad (4.6)$$

Where:

X = Cement content (%).

R^2 = Correlation coefficient.

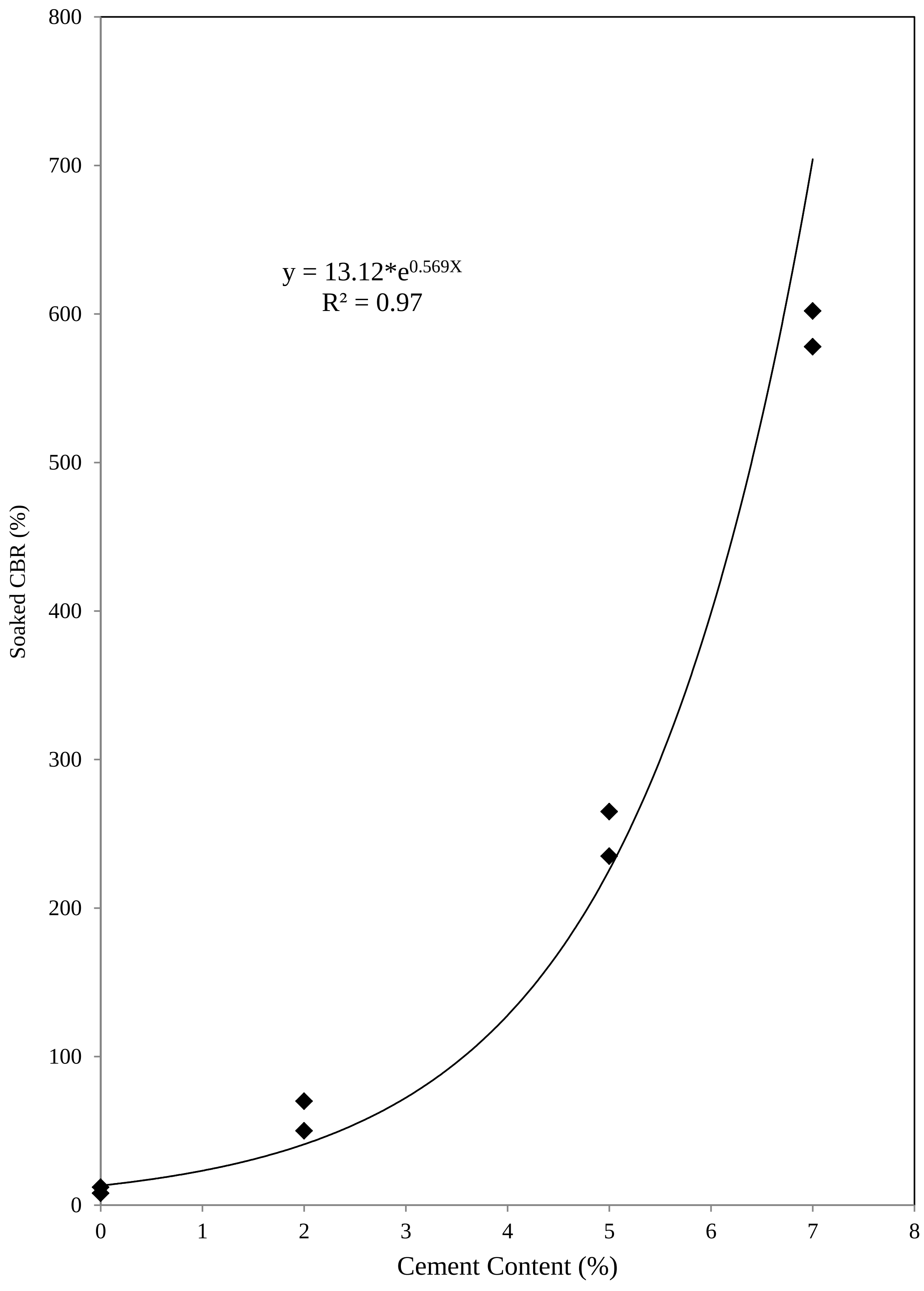


Figure 4-30: Effect of Cement Content on Soaked CBR of Marl (7-Day Sealed Curing)

4.5.2.2 CBR Results of Marl Stabilized with 2% Cement plus CKD

For studying the effect of CKD additions on the soaked CBR of marl with 2% cement, soaked CBR tests were carried out. The results of the soaked CBR are plotted against CKD content in Figure 4-31.

The data in Figure 4-31 indicate that the soaked CBR of 2% cement-stabilized marl increases exponentially with an increase in the CKD content. The soaked CBR for the 2% cement-stabilized marl was 60, 95, 140 and 285% for the CKD contents of 0, 10, 20 and 30%, respectively. The findings in this study are similar to those reported by Abdullah [2009] except that the findings here are of lower value due to the soaking conditions that were used in this study.

An exponential relationship was noted between the soaked CBR and the CKD content. The relation can be expressed by the following equation:

$$\text{Soaked CBR (\%)} = 56.88 * e^{0.051X} \quad R^2 = 0.96 \tag{4.7}$$

Where:

CBR = California bearing ratio of non-plastic marl stabilized with 2% cement and varying quantity of CKD, 7-day sealed curing, (%).

X = CKD content (%).

R^2 = Correlation coefficient.

Generally; all CKD additions in association with 2% cement improved the soaked CBR of non-plastic marl to be an excellent material for use as a base-course in pavements (i. e. CBR > 50 %), as shown in Table 3-3.

4.5.2.3 CBR Results of Marl Stabilized with 2% Cement plus EAFD

The effect of EAFD additions on the soaked CBR of 2% cement-stabilized marl was studied. Soaked CBR tests were carried out on marl stabilized with 2% cement and varying quantity of EAFD. The results of the soaked CBR are plotted against the EAFD in Figure 4-32. The data in Figure 4-32 indicate that the soaked CBR of marl with 2% cement increased with the quantity of EAFD. Moreover; the soaked CBR of marl stabilized with 2% cement and 0, 5, 10, 20 or 30% EAFD was 60, 153, 186, 297 and 304%, respectively.

The data from Figure 4-32 indicate that there was small improvement in the soaked CBR achieved by the 30% EAFD plus 2% cement compared to the improvement of the soaked CBR developed by the 20% EAFD. That was probably due to the fact that the EAFD turned to be prevailing. Furthermore, marl stabilized with EAFD alone turned to sludge when it was soaked.

A linear relationship was noted between the soaked CBR and EAFD contents of non-plastic marl stabilized with EAFD plus 2% cement. The best fit model is as follow:

$$\text{Soaked CBR (\%)} = = 8.08X + 95 \qquad R^2 = 0.89 \tag{4.8}$$

Where:

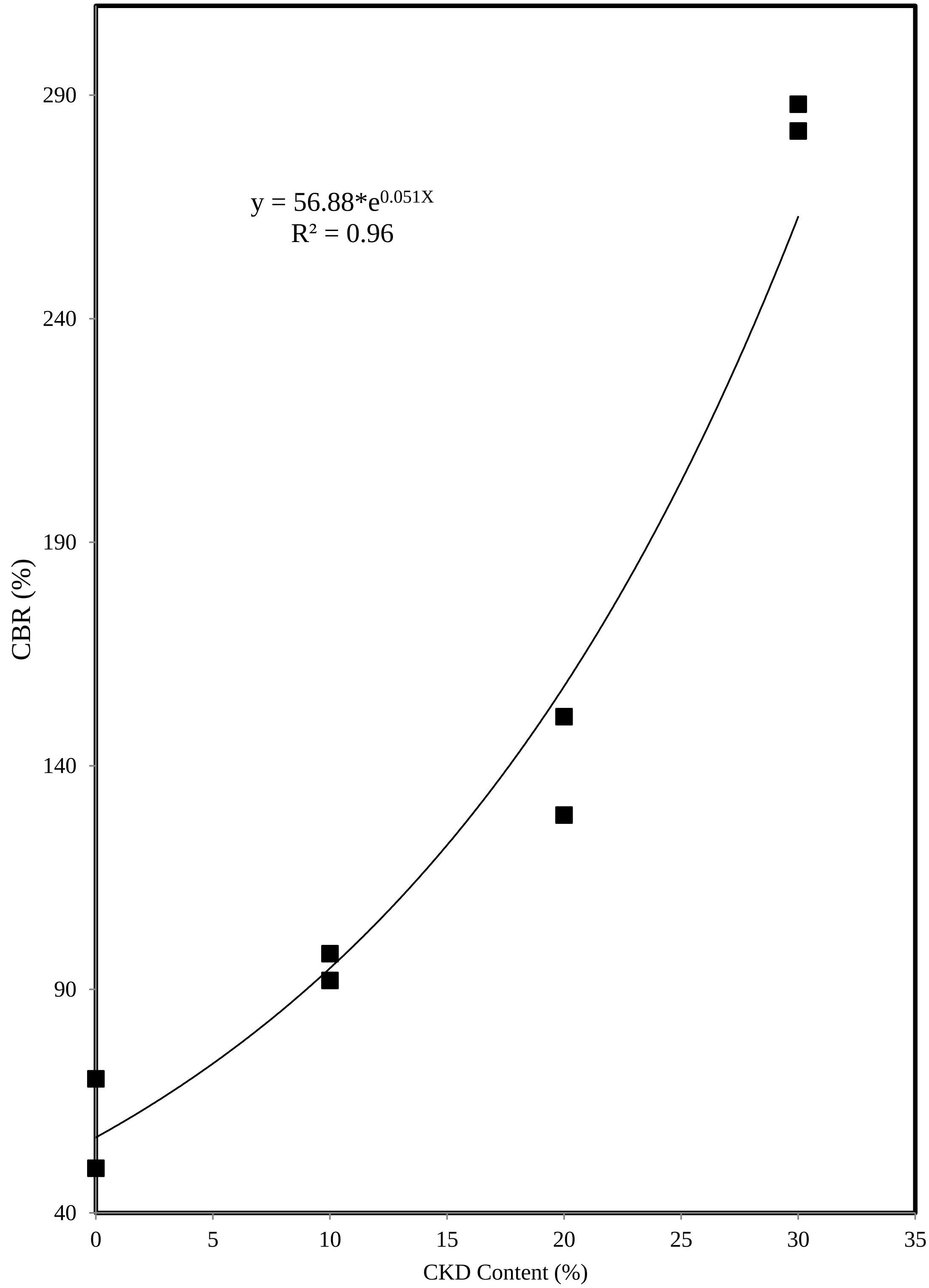


Figure 4-31: Effect of CKD Content on Soaked CBR of Marl with 2% Cement (7-Day Sealed Curing)

CBR = California bearing ratio of non-plastic marl stabilized 2% cement and varying quantity of EAFD, 7-day sealed curing, (%).

X = EAFD content (%)

R^2 = Correlation coefficient.

However, all EAFD additions plus 2% cement have improved the soaked CBR of non-plastic marl to meet the requirements to be excellent materials, with soaked CBR greater than 50%, to be used as base course in pavements, as shown in Table 3-3.

In summary; the relations presented in Equations 4.6 through 4.8 can be considered reliable, as the value of correlation coefficient (R^2) is 0.97, 0.96 and 0.89, respectively, is significantly greater than 0.8. The developed relations are useful for estimating the required amounts of the stabilizers cement, CKD plus 2% cement and EAFD plus 2% cement for non-plastic marl soils to attain the desired soaked CBR at 7-day sealed curing.

The results of the soaked CBR tests on stabilized marl are summarized in Table 4-8. It is noticed from the data in Table 4-8 that the soaked CBR of plain non-plastic marl, 10%, was very low, less than the 20% required for use in sub-base course in pavements, as shown in Table 3-3.

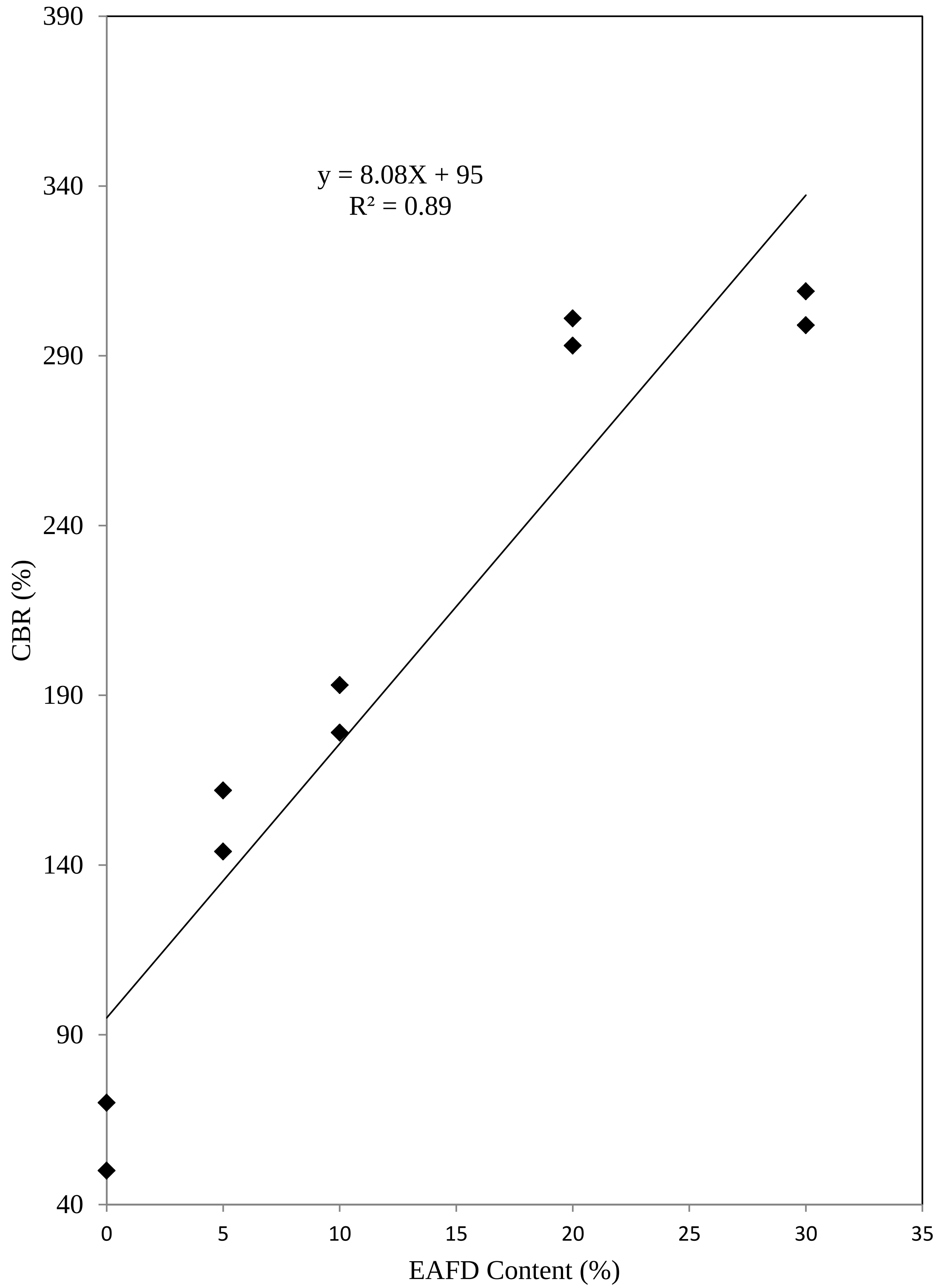


Figure 4-32: Effect of EAFD Content on Soaked CBR of Marl with 2% Cement (7-Day Sealed Curing)

Table 4-8: CBR of Marl with Cement and/or Cement plus Stabilizer

Additive Type and Content	**UCS (kPa)**	**Soaked CBR (%)**		
		Specimen # 1	Specimen # 2	Average
Plain Marl (No Additive)	61	8	12	10
2% Cement	644	50	70	60
5% Cement	2,333	235	265	250
7% Cement	3,953	578	602	590
2% Cement + 10% CKD	950	92	98	95
2% Cement + 20% CKD	1,290	151	129	140
2% Cement + 30% CKD	1,780	282	288	285
2% Cement + 5% EAFD	676	144	162	153
2% Cement + 10% EAFD	876	179	193	186
2% Cement + 20% EAFD	1,427	293	301	297
2% Cement + 30% EAFD	2,430	299	309	304

A significant improvement in the soaked CBR (60, 250 and 590%) was noted in the marl with 2, 5 and 7% cement addition, respectively. Similarly; the soaked CBR improvement was very good (95, 140 and 285%) in marl stabilized with 2% cement plus 10, 20 or 30% CDK, respectively. Furthermore, the soaked CBR of 2% cement plus 5, 10, 20 or 30% EAFD was 153, 186, 297 and 304% respectively.

4.5.3 Results of the Durability Tests on Stabilized Non-Plastic Marl

ASTM D 559 durability tests were conducted on the investigated marl that had satisfied the minimum strength requirements of ACI [1990]. The data in Table 4-9 summarize the weight loss in the various stabilized non-plastic marl mixtures. From the data in this Table, it is clear that as the cement content increases, the weight loss decreases significantly. The same trend is noticed for the EAFD content plus 2% cement. The highest weight loss, 8.9%, occurred for non-plastic marl stabilized with 20% EAFD plus 2% cement. The lowest weight loss was noted for marl stabilized with 7% cement. The weight losses are 0.4 and 2.7% for the cement contents of 5 and 7%, respectively, which are almost equal to what were reported by Ahmed [1995]. However, Al-Amoudi et al. [2010] reported that the weight loss was 2 and 4.8% for the cement content of 7 and 5%, respectively. The reported high weight loss in this investigation was probably due to the inferior quality of the investigated marl.

All the measured weight losses shown in Table 4-9 are below the maximum allowable weight loss of 14% according to the Portland Cement Association (PCA) and of 11% according to USA Corps of Engineers (USACE) for soils classified as SP and soils having, plasticity index, PI < 10, respectively [ACI, 1990]. Therefore, the mentioned stabilizers and dosages in Table 4-9 are appropriate not only from strength point of view but also from durability perspective.

Table 4-9: Weight loss of Stabilized Marl

Additive Type and Content	Weight Loss (%)
5% Cement	2.7
7% Cement	0.4
2% Cement + 30% CKD	8.2
2% Cement + 20% EAFD	8.9
2% Cement + 30% EAFD	7.8

4.5.4 Results of TCLP Tests on the Stabilized Non-Plastic Marl

EAFD contains some toxic elements, such as cadmium, lead and nickel, as shown in Table 4-2. The dosages of 20 and 30% of this stabilizer mixed with 2% cement improved the strength and durability of the non-plastic marl so as to satisfy the strength and durability requirements. Therefore, toxicity characteristics leaching procedures (TCLP) were carried out to study the environmental impact of using this stabilizer. The maximum allowable and measured concentrations of the toxic elements in the investigated marl stabilized with the EAFD contents of 20 and 30% plus 2% cement, are summarized in Table 4-10.

The data in Table 4-10 show that the measured concentrations of the cadmium and lead for the non-plastic marl stabilized with 20% EAFD plus 2% cement are 0.58 and 0.12 mg/l, respectively. The measured concentration of these elements in marl stabilized with 30% EAFD plus 2% cement is 0.67 and 0.17, respectively. Therefore, the measured concentrations of the cadmium and lead are far below the maximum allowable concentrations (EPA limits) of 1 and 5 mg/l, respectively, as shown in Table 4-10.

Furthermore, increasing the EAFD content from 20 to 30% in the marl with 2% cement increased the measured concentration of the cadmium element by about 12%. Based on that, from interpolation of results in Table 4-10, if we use 50% EAFD in marl plus 2% cement would increase to about 0.9 (mg/l), which is still below the maximum allowable value.

In summary; the 20 and 30% EAFD plus 2% cement dosages are not only appropriate stabilizers for non-plastic marl from strength and durability aspects, but also from environmental point of view.

Table 4-10: TCLP for Marl Stabilized with 2% Cement + EAFD

Metal		EPA Limits	Measured Value	
			20 % EAFD	30 % EAFD
Name	Symbol	(mg/l)	(mg/l)	(mg/l)
Silver	Ag	5	0.007	0.012
Arsenic	As	5	0000	0000
Barium	Ba	100	1.008	1.043
Cadmium	Cd	1	0.575	0.669
Chromium	Cr	5	0.002	0.003
Mercury	Hg	0.2	0.014	0.017
Lead	Pb	5	0.119	0.174
Selenium	Se	1	0.094	0.101
Nickel	Ni	NR	0.038	0.043
Vanadium	V	NR	0000	0000

NR: Not regulated by EPA

4.6 Evaluating the Treatment of the Investigated Sand

The improvement of the properties of dune sand due to the use of selected stabilizer types and contents was assessed utilizing the evaluation techniques mentioned in Chapter 3. The effects of different additives on the properties of investigated sand are discussed in detail in the following sub-sections.

4.6.1 Results of the Unconfined Compression Tests of Sand

Since the investigated sand is pure quartz and a non-cohesive material, it does not alone have any unconfined compressive strength. Therefore, sand with 2% cement was considered as the reference for relative comparison. Prepared specimens of sand stabilized with the proposed stabilizer types and content were sealed cured for 7-days at laboratory condition (22 ± 3 ^{0}C) before testing.

4.6.1.1 UCS of Sand Stabilized with Cement

For studying the correlation between the cement content and the UCS of sand, unconfined compression tests were carried out on sand-cement mixtures. Cement additions of 2, 5 and 7% were used. Results of the UCS against the cement content are plotted in Figure 4-33.

The data in Figure 4-33 indicate that as the cement content increases, the UCS of the sand-cement mixture increases linearly. The UCS of sand with 2, 5 and 7% cement was 369, 1,050 and 1,719 kPa, respectively. Furthermore, the data in Figure 4-33 indicate that there is a linear correlation between the UCS of stabilized sand and the cement content which could be expressed by the following best-fit model:

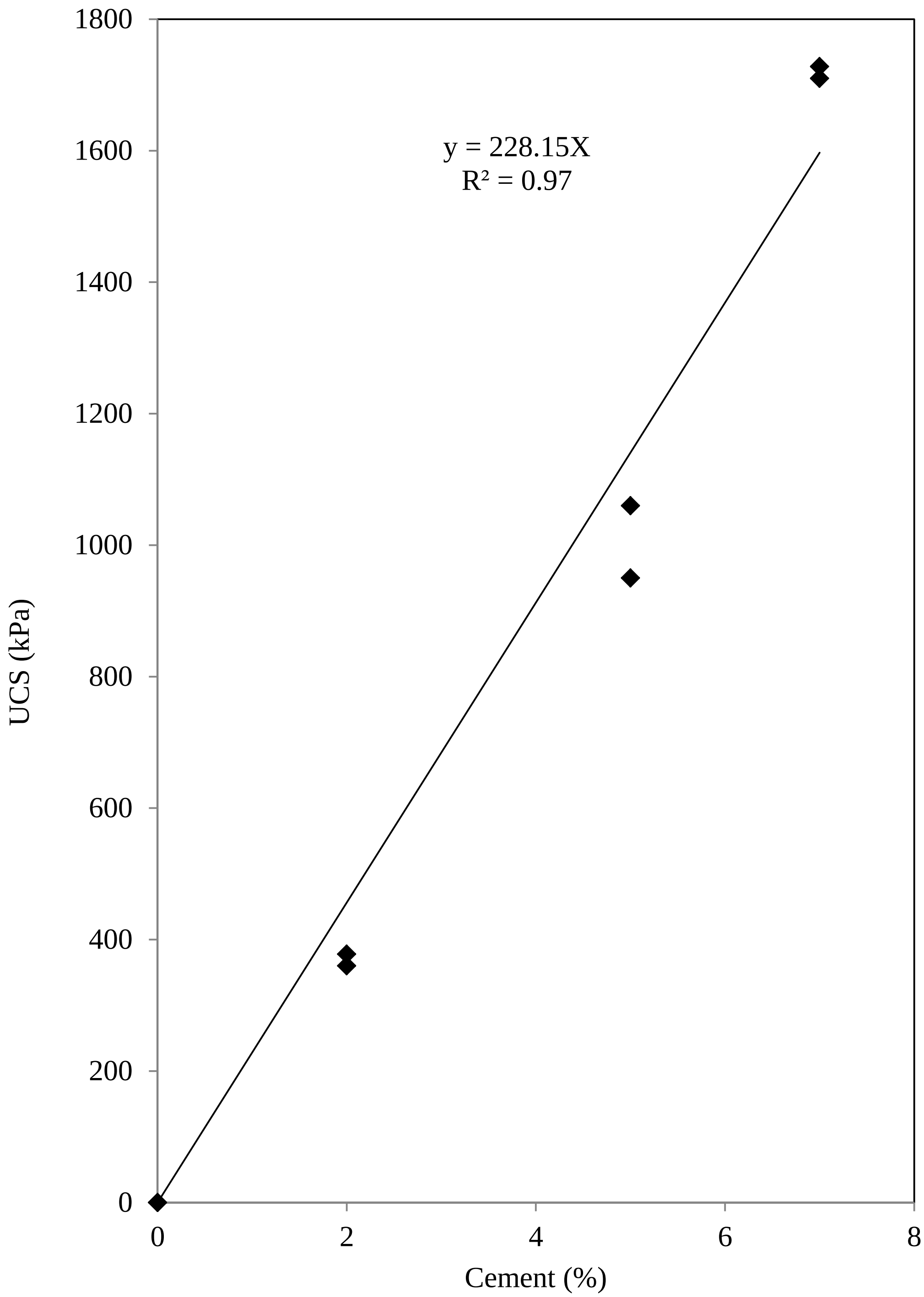


Figure 4-33: Effect of Cement Content on the UCS of Sand (7-Day Sealed Curing)

$$UCS = 228.15*X \qquad R^2 = 0.97 \qquad (4.9)$$

Where:

UCS = Unconfined compressive strength of cement- stabilized sand, 7-day sealed curing, kPa.

X = Cement content (%).

R^2 = Correlation coefficient.

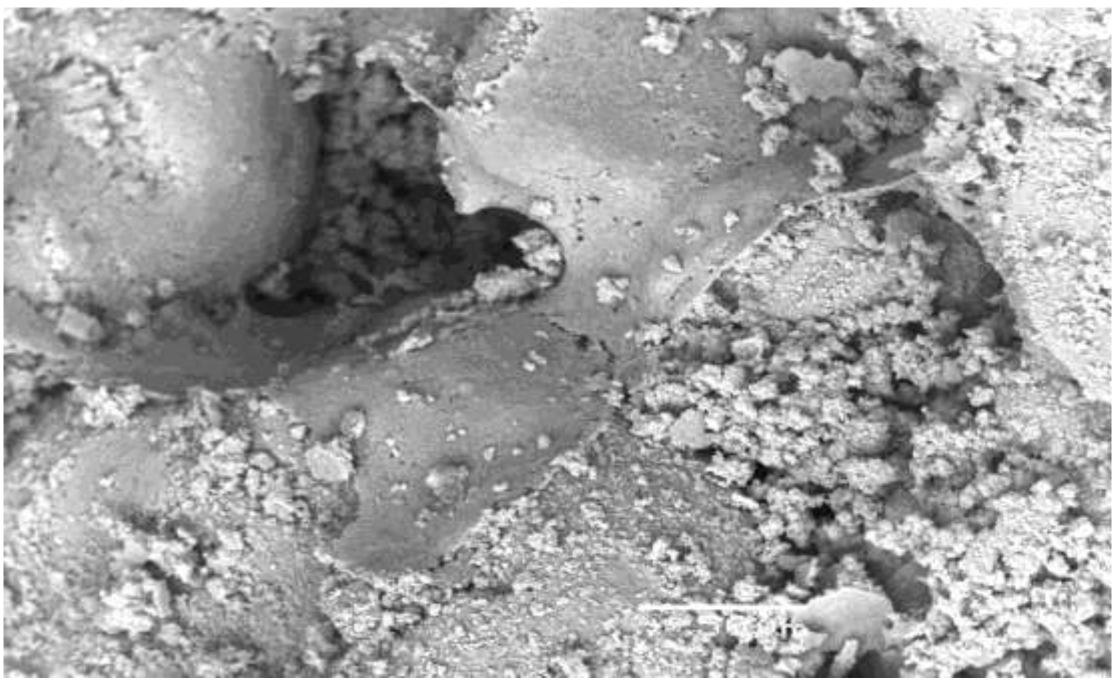
The addition of 2 and 5% cement improved the UCS of sand but none of these dosages improved the UCS of the sand to satisfy the minimum strength (1,380 kPa) specified by ACI [1990] for sub-base course in rigid pavements. For the dosage of 7% cement, the UCS increased to 1,719 kPa which exceeded the 1,380 kPa specified by ACI [1990] for sub-base course in rigid pavement. Therefore, the dune sands stabilized with 7% cement was found suitable as sub-base material in rigid pavements. It is to be noted that the cement content required for sand to attain 1,725 kPa to be used as a sub-base course in flexible pavements is 7.5% as estimated using Equation (4.10).

As it was mentioned in Section 4.5.1.1, the UCS of marl stabilized with 2, 5 and 7% cement was 644, 2,333 and 3,953 kPa, respectively. Hence, the improvement in the UCS of sand mixed with cement was not as high as that in non-plastic marl. That was due to the poor gradation of the investigated sand which consumed a large amount of the cement paste to fill the voids in the sand. Therefore, the strength of the cementitious product, C-S-H, which binds sand particles was low. Consequently, the cementing product provided by the 2 or 5% cement was not enough to develop the necessary strength within the sand-cement mixtures.

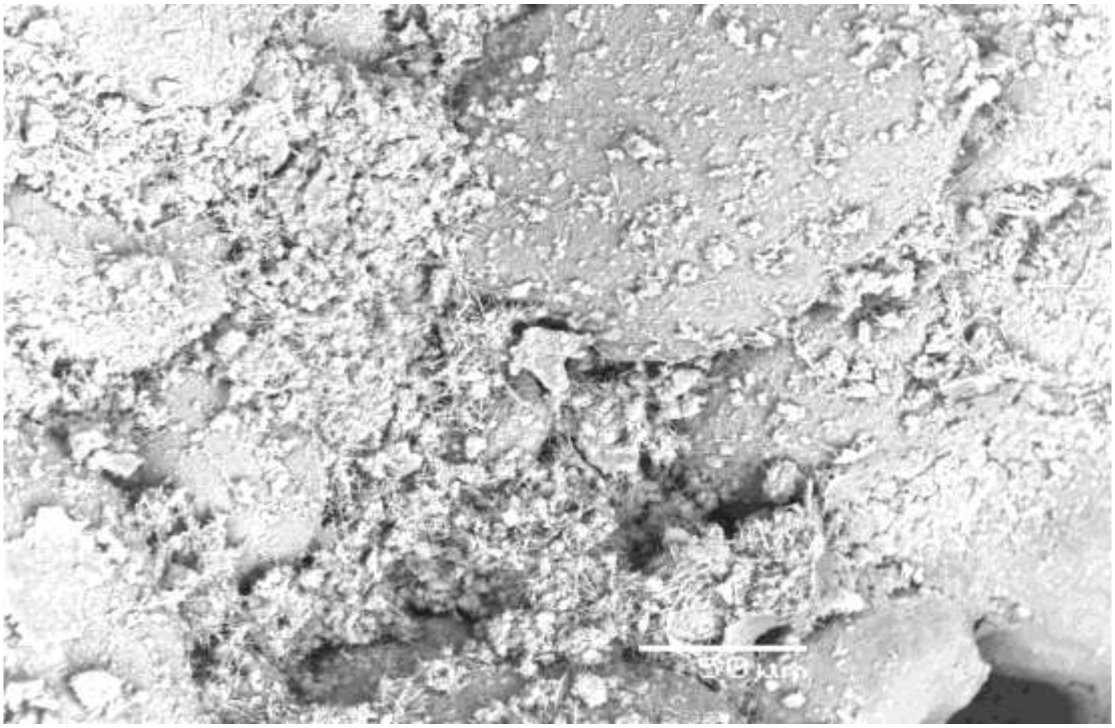
The distribution or the arrangement of sand particles within the sand-cement matrix was, qualitatively, investigated by using the BEI and SEM images. These images are shown in Figure 4-34. Comparison of BEI micrographs of sand stabilized with 2% cement, Figure 4-34(a), with BEI of sand stabilized with 7% cement, Figure 4-34(b), showed that the voids in sand stabilized with 2% cement are more than the voids in sand stabilized with 7% cement. In other words; sand stabilized with 7% cement is denser than the one with 2% cement, which supports the higher dry density and UCS of sand stabilized with 7% cement, as shown in Table 4-5.

The SEM micrograph of sand stabilized with 2% cement, Figure 4-34(c), showed that there were only a few white spots of the cementing product coating some of the sand particles and large voids between the particles by dark spots. In other words; there were a few white fibrous formations of cementing gel, C-S-H, developed by the 2% cement. The EDX, Figure 4-34 (d), shows that the sand stabilized with 2% cement contains Al, Si, K, Ca, Fe and Zn with concentrations of about 1.60, 16.68, 1.25, 17.7, 1.22 and 0.04%, respectively. The presence of Ca and some of Si indicated the component of C-S-H developed by the 2% cement.

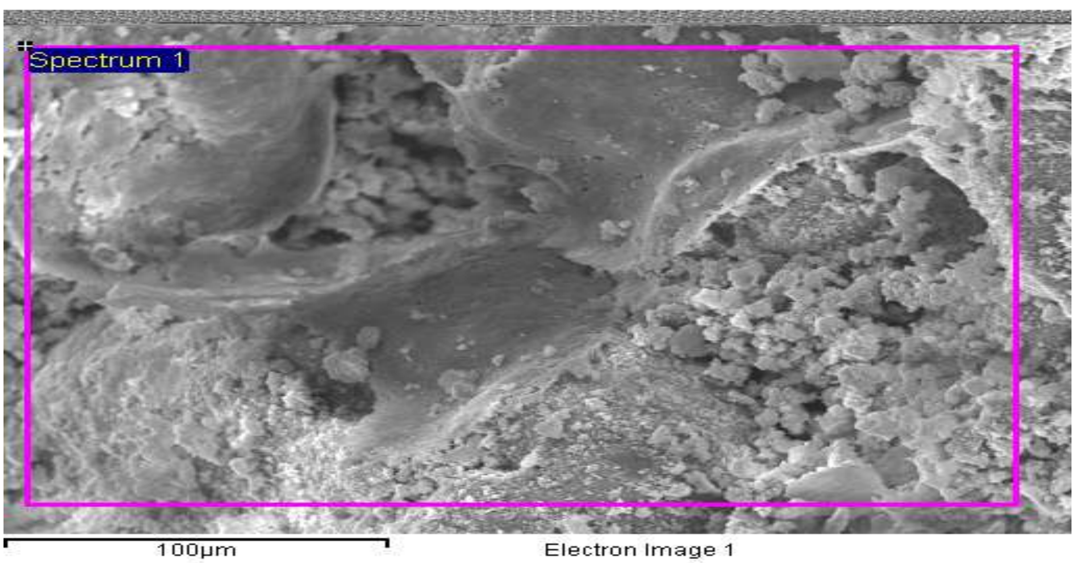
The SEM for sand with 7% cement, Figure 4-34 (e), qualitatively shows a more dense morphology compared to the sand with 2% cement. The EDX, Figure 4-34 (e), shows that the sand stabilized with 7% cement contains Mg, Al, Si, Ca, and Fe with weight proportions of about 0.80, 1.87, 19.03, 20.65 and 1.56%, respectively. The increased amount of calcium, Ca, indicated the higher quantity of cement, in sand with 7% cement, compared to the sand stabilized with only 2% cement. Therefore, cementing gel is greater and the improvement in the UCS was is higher. However, due to the high voids in sand, the improvement in the UCS was lower compared to that developed in marl stabilized with the same amount of cement.



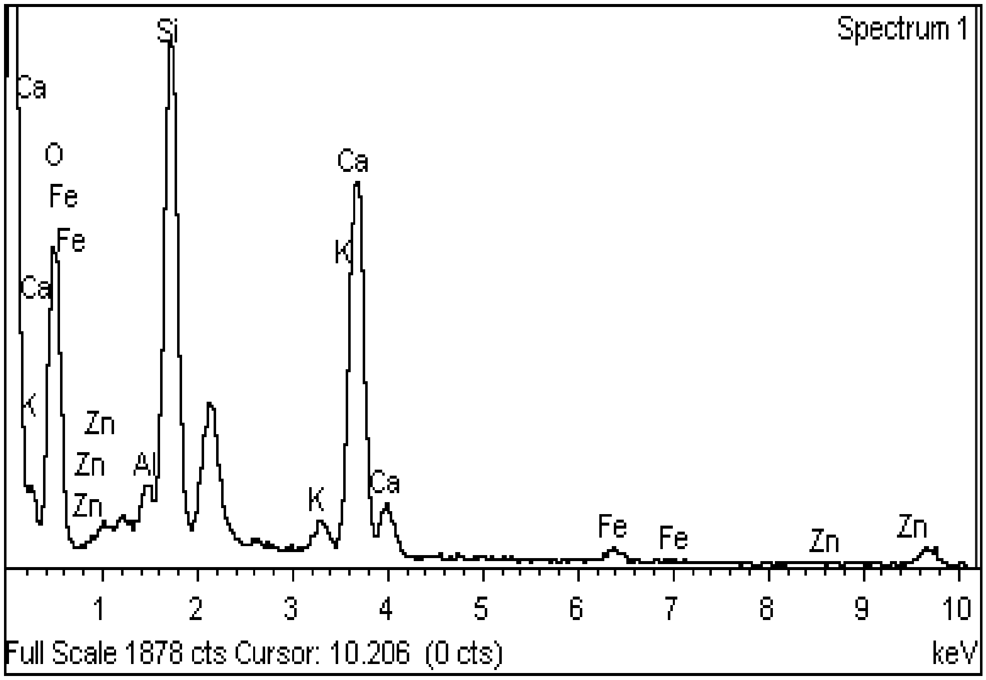
a) BEI of sand stabilized with 2% cement (X400)



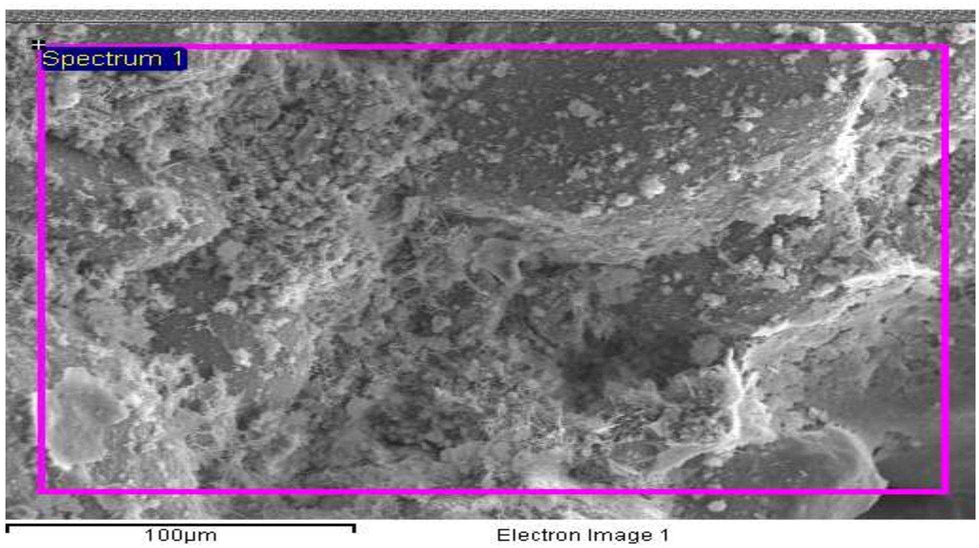
b) BEI of sand stabilized with 7% cement (X400)



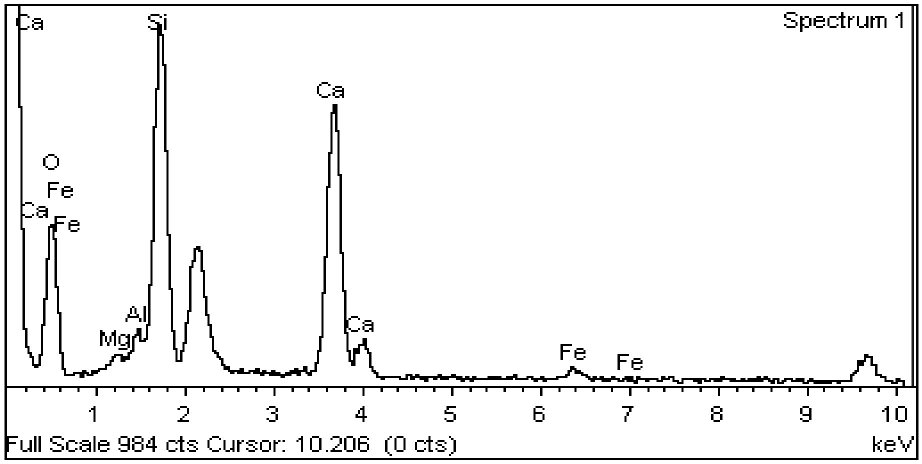
c) SEM of sand stabilized with 2% cement (X400)



d) EDX of sand with 2% cement



e) SEM of sand stabilized with 7% cement (X400)



f) EDX of sand stabilized with 7% Cement

Figure 4-34: BEI, SEM and EDX of Sand Stabilized with Cement (7-Day Sealed Curing)

4.6.1.2 UCS of Sand Stabilized with CKD

Unconfined compression tests were conducted on sand-CKD mixtures after 7-day sealed curing. CKD additions of 10, 20 and 30% were used. The UCS is plotted against the CKD content in Figure 4-35.

The data in Figure 4-35 indicate that UCS increases linearly with an increase in the CKD content. The UCS of sand with 10, 20 and 30% was 103, 400 and 745 kPa, respectively. The relationship between UCS and the CKD content can be expressed by the following equation:

$$UCS = 22.41 * X \qquad R^2 = 0.94 \tag{4.10}$$

Where:

UCS = Unconfined compressive strength of sand stabilized with varying quantity of CKD, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

It should be noted that the UCS of sand mixed with the proposed CKD dosages of 10, 20 and 30% was low compared with that of marl. This was probably due to the effect of many factors, such as the poor gradation of sand, the high LOI and high alkalis in the CKD.

In this investigation, sand with up to 30% CKD did not meet the minimum UCS (1,380 kPa) specified by ACI [1990] for sub-base course in pavements. This indicates that CKD alone is not suitable for stabilization of sand. Therefore, some cement needs to be added to enhance the UCS of sand-CKD mix to meet the ACI requirements.

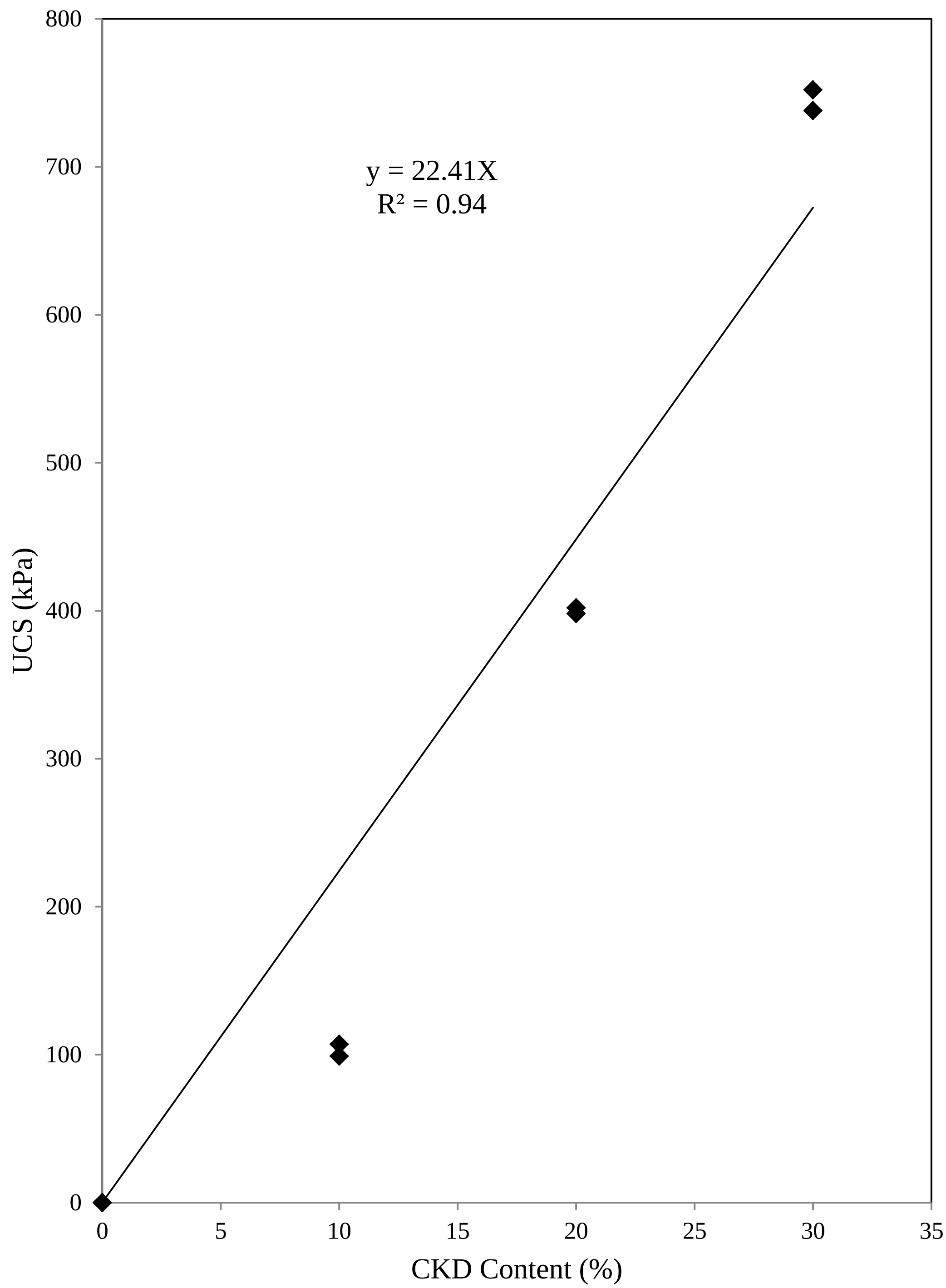


Figure 4-35: Effect of CKD Content on the UCS of Sand (7-Day Sealed Curing)

4.6.1.3 UCS of Sand Stabilized with 2% Cement plus CKD

Unconfined compression tests were conducted on sand with 2% cement and on sand treated with 2% cement plus 10 to 30% CKD. The results are plotted in Figure 4-36.

The data in Figure 4-36 show that the UCS of sand with 2% cement increases with the addition of CKD. The UCS of sand with 2% cement plus 0, 10, 20 and 30% was 369, 418, 800 and 1,381 kPa, respectively. In a previous study, it was reported that the UCS of sand with 2% cement plus 10 or 20% CKD was 755 and 1,140 kPa, respectively [Abdullah, 2009]. The difference in the results of this study and those reported by Abdullah [2009] was probably due to the quality of the sand (i.e. surface texture) he investigated.

The data in Figure 4-36 indicate an exponential relationship between the UCS and the CKD content. The correlation can be expressed by the following relationship:

$$UCS = 321.77 * e^{0.046X} \qquad R^2 = 0.94 \qquad (4.11)$$

Where:

UCS = Unconfined compressive strength of sand stabilized with 2% cement and varying quantity of CKD, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

The addition of 30% CKD plus 2% cement improved the strength of sand (1,381 kPa) to merely satisfy the minimum strength, 1,380 kPa, specified by ACI [1990] for sub-base course in rigid pavements. The higher improvement in the UCS was probably due to the cementing provided by 2% cement in addition to that provided by CKD.

Figure 4- 37(a) is the BEI of sand stabilized with 2% cement plus 30% CKD. This micrograph depicts a dense microstructure and shows a decrease in the voids compared with the BEI of sand stabilized with only 2% cement [Figure 4-34(a)]. The SEM, Figure 4-37(b), of sand stabilized with 2% cement plus 30% CKD also shows a dense microstructure with the formation of cement gel, C-S-H. The EDX, Figure 4-37(c), shows the presence of Al, Si, Cl, Ca and Fe with about 1.50, 15.25, 0.99, 27.05 and 0.98%, respectively. Furthermore, the presence of Si and Ca indicated to the formation of C-S-H.

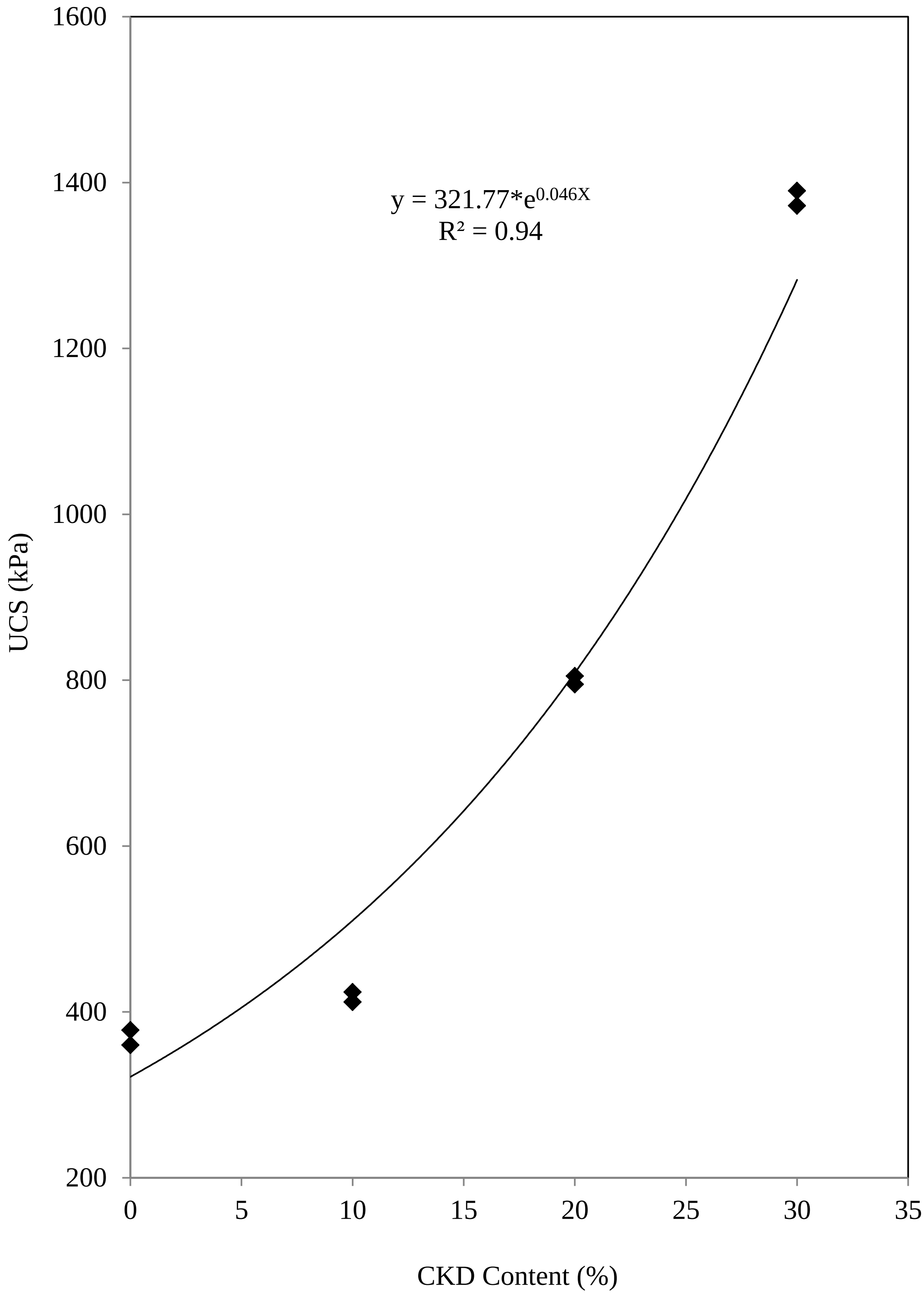
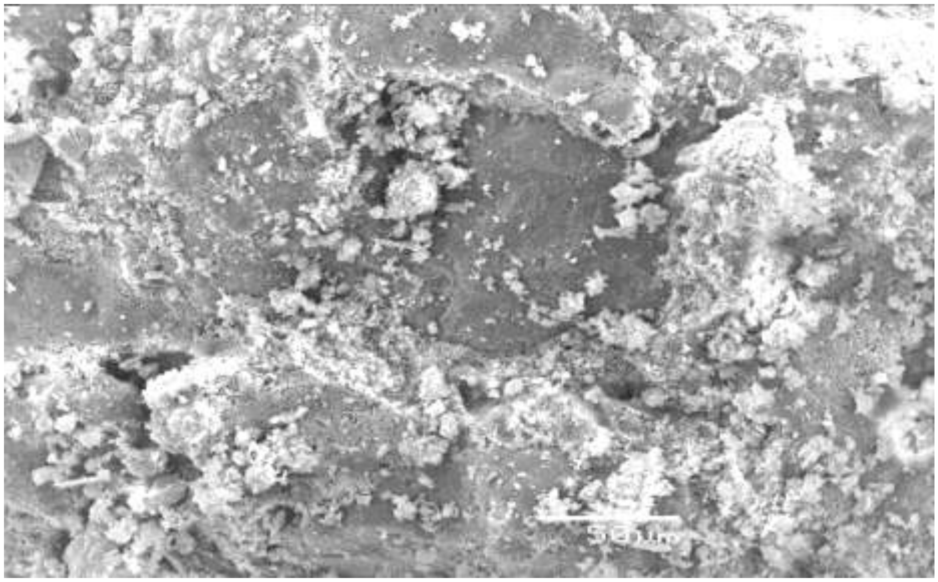
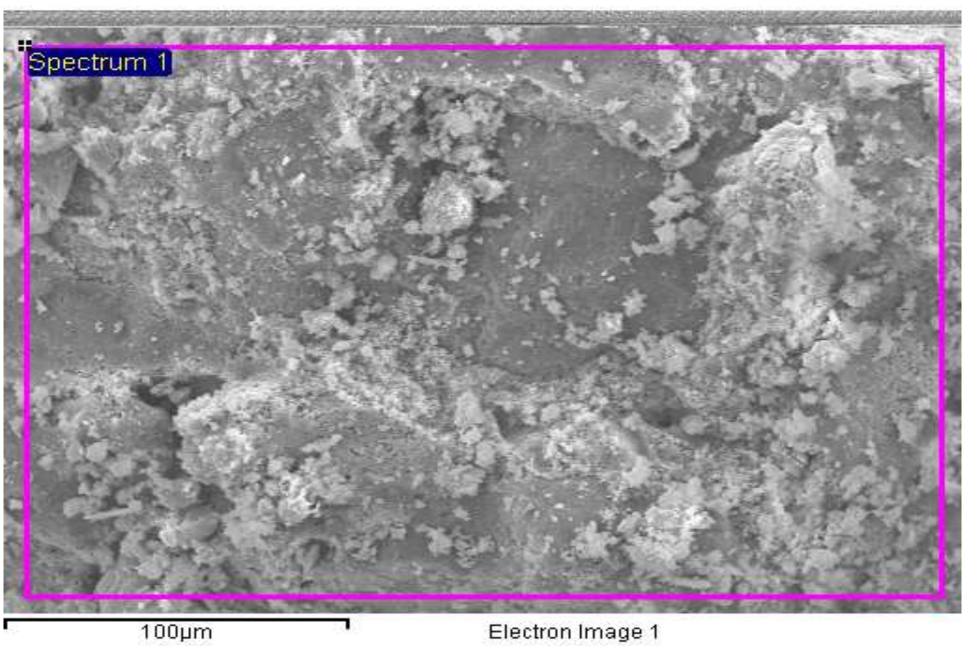


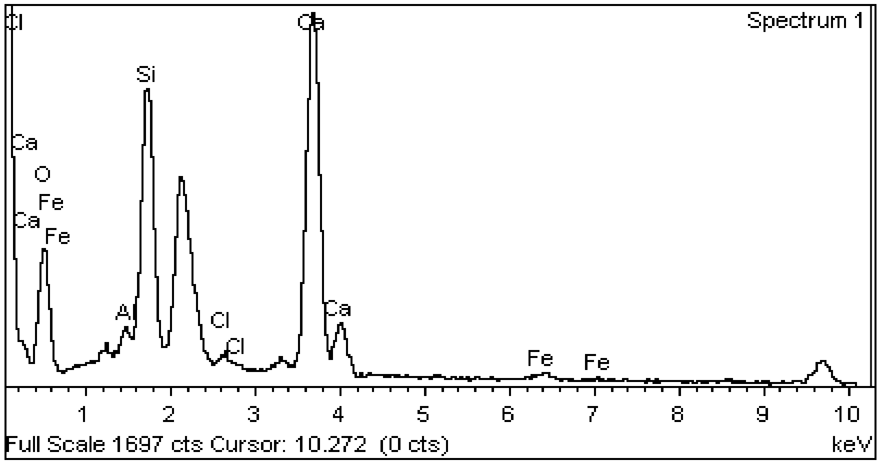
Figure 4-36: Effect of CKD Content on the UCS of Sand with 2% Cement (7-Day Sealed Curing)



a) BEI of sand stabilized with 2% cement plus 30% CKD (X400)



b) SEM of sand stabilized with 2% cement plus 30% CKD (X400)



c) EDX of sand stabilized with 30% CKD plus 2% cement

Figure 4-37: BEI, SEM and EDX of Sand Stabilized with 2% Cement and 30% CKD (7-Day Sealed Curing)

4.6.1.4 UCS of Sand Stabilized with 2% Cement plus EAFD

Unconfined compression tests were conducted on sand with 2% cement and on sand treated with EAFD in the range from 5 to 30% plus 2% cement. The UCS of the investigated sand against the EAFD content plus 2% cement is plotted in Figure 4-38.

The data in Figure 4-38 shows an exponential increase in the UCS with an increase in the quantity of CKD. The UCS of sand with 2% cement plus 0, 5, 10, 20 and 30% EAFD was 369, 392, 532, 1,427 and 2,419 kPa, respectively. The correlation between the UCS and the EAFD content may be presented by the following best fit-model:

$$UCS = 313.94 * e^{0.068X} \qquad R^2 = 0.97 \qquad (4.12)$$

Where:

UCS = Unconfined compressive strength of sand stabilized with 2% cement and varying quantity of EAFD, 7-day sealed curing, in kPa.

X = EAFD content (%) ≤ 30.

R^2 = Correlation coefficient.

The EAFD content should not be more than 30% to avoid negative environmental impact, as will be addressed later.

Comparing these results with the minimum UCS specified by the ACI Committee [1990], mentioned in Table 3-2, it may be noted that 5 and 10% EAFD failed to make the necessary strength improvements to meet the minimum strength requirements. However, the UCS of sand with 2% cement plus 20 or 30% EAFD satisfied the strength requirement for sub-base course in rigid and flexible pavements, respectively.

The qualitative interpretation of the improvement in the UCS of dune sand with 2% cement plus 30% EAFD is shown in the BEI and SEM micrographs (Figure 4-39) in addition to the schematic illustration of the interaction.

The BEI of sand stabilized with 2% cement plus 30% EAFD, Figure 4-39 (a), shows a dense microstructure. The SEM micrograph, Figure 4-39(b), for sand with 2% cement plus 30% EAFD, depicts light white crystalline spots of cementing gel, C-S-H, developed by the 2% cement. The figure also depicts a dense micro-structure of sand with 2% cement plus 30% EAFD. However, micro-cracks could also be noted at several locations.

The EDX, shown in Figure 4-39(c), indicates the presence of Mg, Si, K, Ca, Mn, Fe and Zn. The quantity of each of these elements is about 2.16, 13.75, 1.07, 10.77, 1.03, 23.17

and 7.19%, respectively. The presence of Ca and Si indicates the formation of C-S-H due to the hydration of cement. The high amount of Fe and Zn was contributed by EAFD.

The semi-quantitative result, from XRD, Figure 4-39(d), of the mixture indicated the presence of Quartz [SiO_2], 47%, Calcite [$CaCO_3$], 2.6%, Wustite [FeO], 30.9% and Goethite [FeO(OH)], 19.6%.

Figure 4-39(e) is the molecular diagram of wustite which was formed as a result of interaction between quartz, cement and EAFD. The calcite was ignored due to its low percentage. It is known that cement hydration is exothermic reaction which activates the surface of sand to bind with cement. The electronegativity of Fe, Ca and Si is 1.8, 1.0 and 1.9 Pauling, respectively. Therefore, the mechanism of interaction is supported by the moderate electronegativity of Ca. The moderate electronegativity of Ca facilitates the enhancement of the stability of the bonding interaction between the elements in the structure. Accordingly, in the absence of cement, Ca, the close values of electronegativity of Fe and Si retard the interaction [Weinhold and Landis, 2005].

Therefore, the improvement in the UCS of sand stabilized with 2% cement and varying amounts of EAFD could thus be attributed to the binding and marginal filler effects of EAFD in addition to the improvement in the microstructure of the developed mixture.

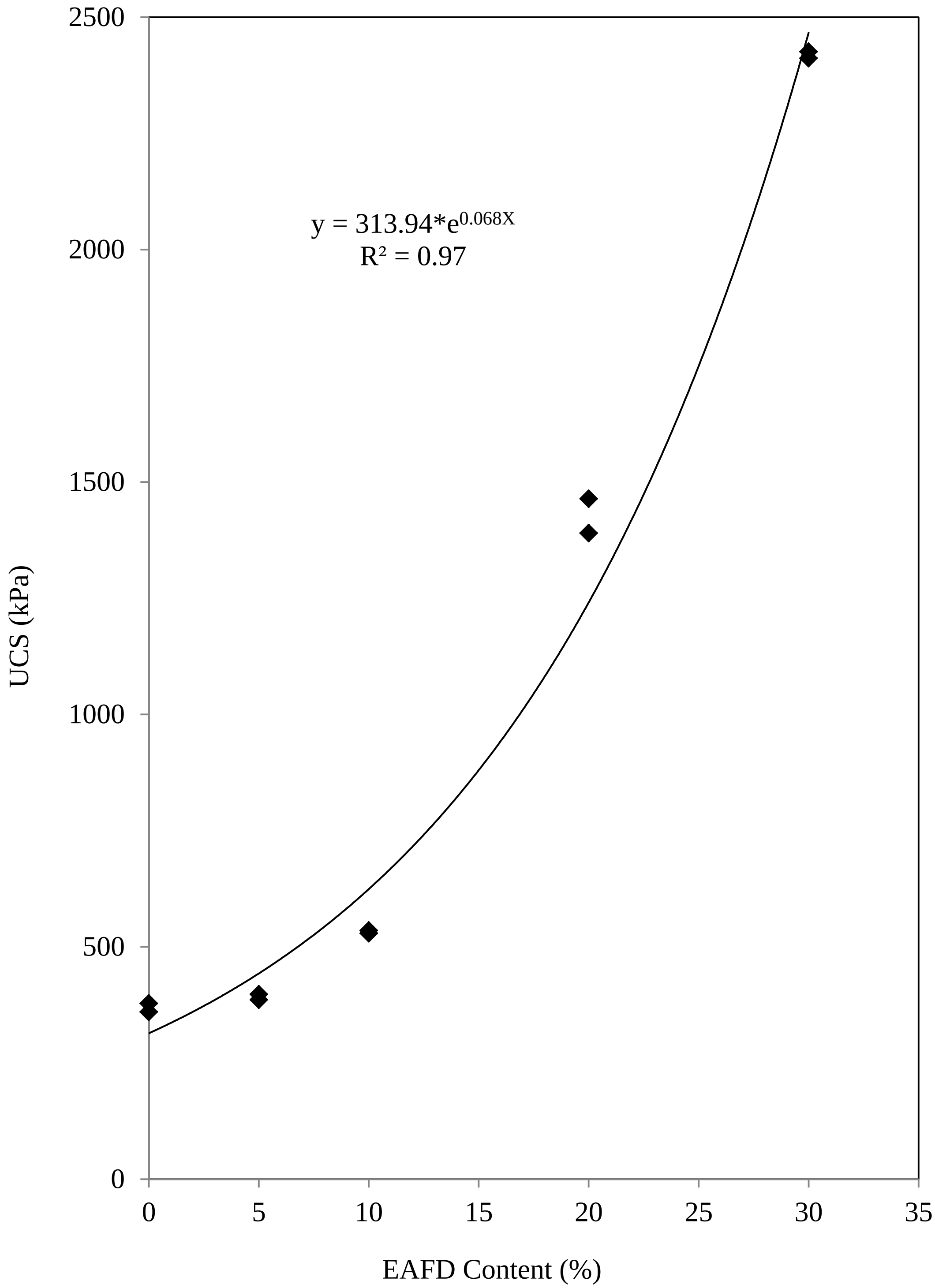
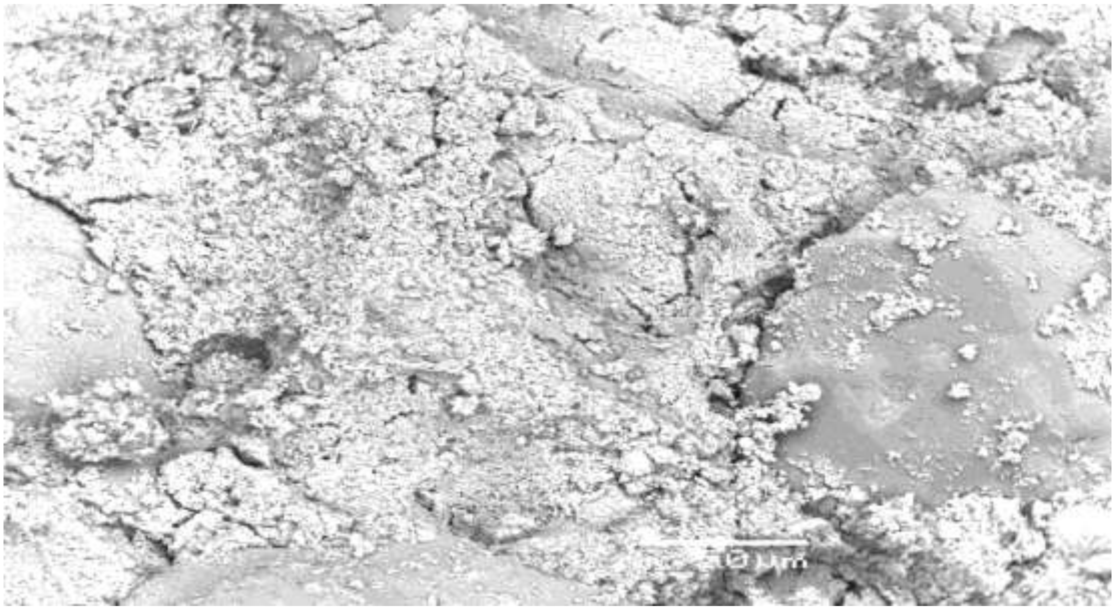
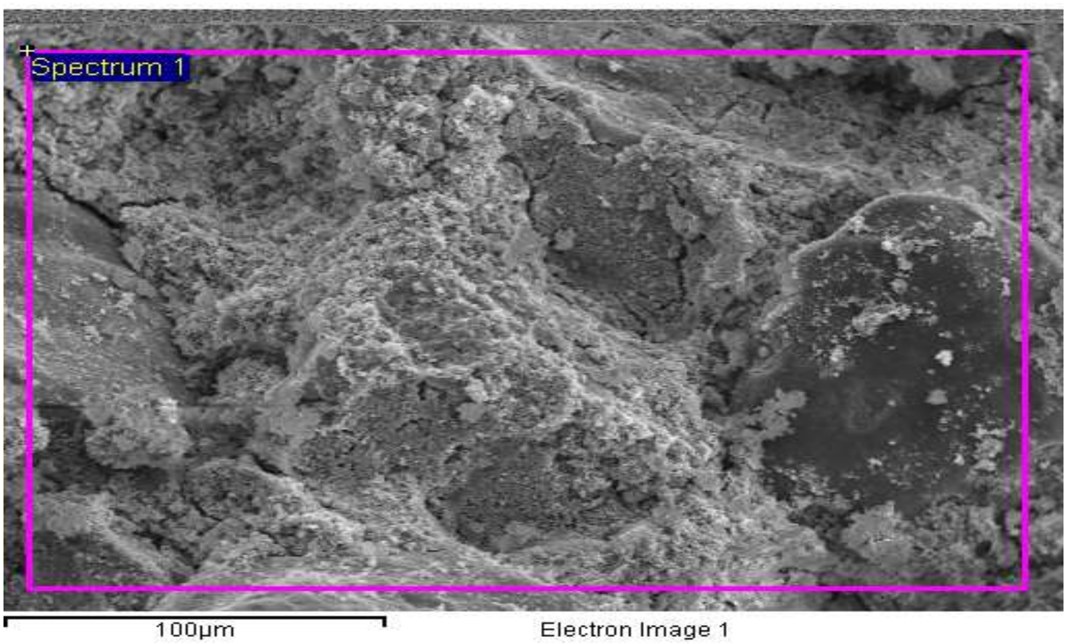


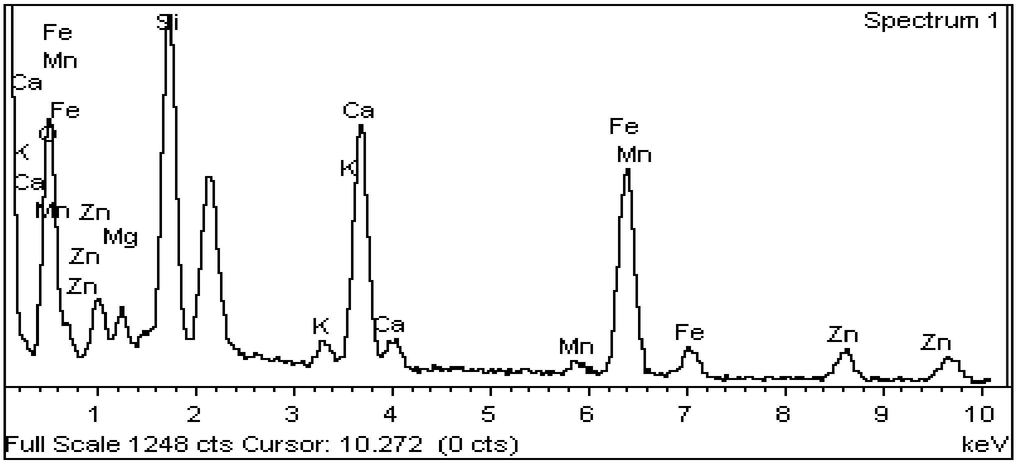
Figure 4-38: Effect of EAFD Content on the UCS of Sand with 2% Cement (7-Day Sealed Curing)



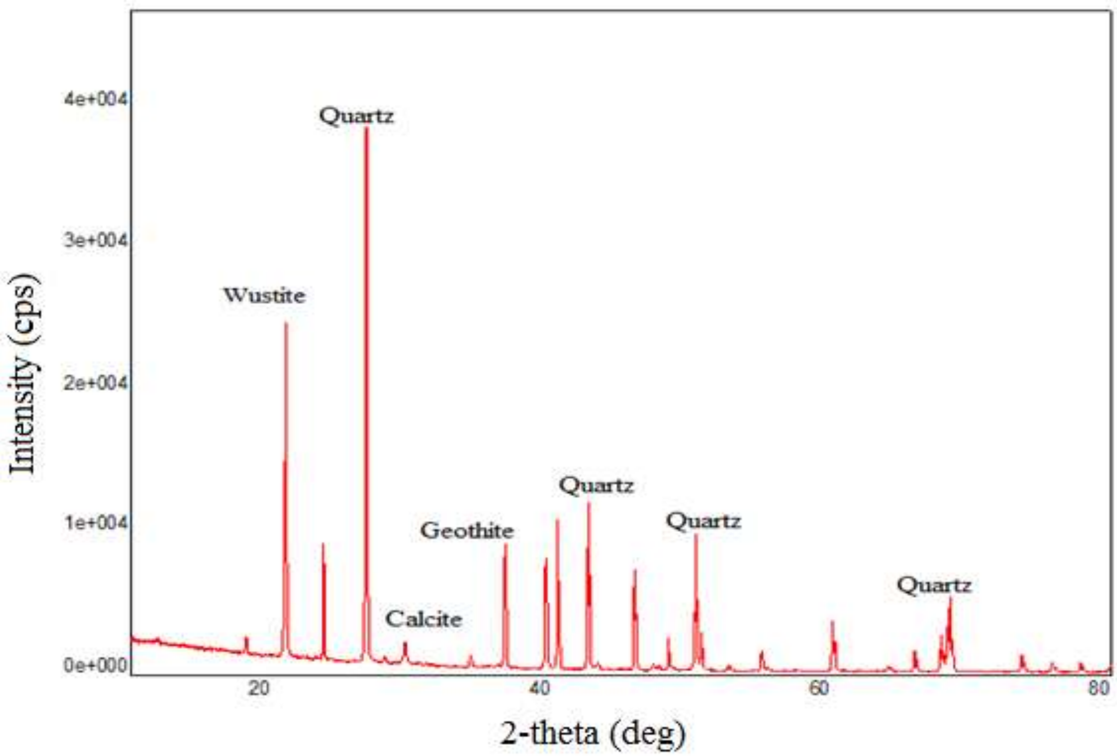
a) BEI of sand stabilized with 2% cement plus 30% EAFD (X400)



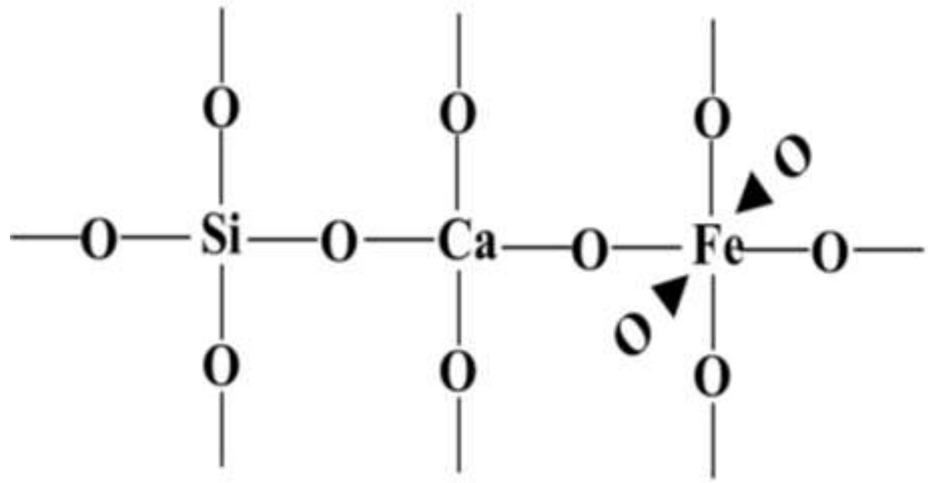
b) SEM of sand stabilized with 30% EAFD plus 2% cement (X400)



c) EDX of sand stabilized with 30% EAFD plus 2% cement



d) X-ray diffractogram of sand stabilized with 30% EAFD plus 2% cement



e) Molecular illustration of interaction for wustite in sand stabilized with 2% cement plus 30% EAFD

Figure 4-39: BEI, SEM, EDX and Molecular interaction of Sand Stabilized with 2% Cement and 30% EAFD (7-Day Sealed Curing)

4.6.1.5 UCS of Sand Stabilized with 2% Cement plus OFA

The data in Table 4-3 indicate that OFA contains trivial amount of calcium and silicon that are required for developing the cementing gel, C-S-H. Therefore, OFA does not have any cementitious property. Therefore, the effect of the OFA content on the strength of sand was studied by adding 2% cement. The unconfined compression tests were conducted on sand with 2% cement and on sand treated with OFA content ranging from 5 to 15% plus 2% cement. The results are reported in Figure 4-40.

The data in Figure 4-40 reveal UCS of sand stabilized with 2% cement plus OFA was 369, 39, 47 and 115 kPa, for OFA contents of 0, 5, 10 and 15%, respectively. The UCS developed by the 2% cement (369 kPa) did not meet the minimum UCS (1,380 kPa) specified by ACI [1990] to qualify the mixture to be used as a sub-base course in rigid pavements.

The relationship between OFA content and the UCS of the sand plus 2% cement could be expressed by the following equation:

$$UCS = 3.97 * X^2 - 74.66 * X + 355 \qquad R^2 = 0.95 \qquad (4.13)$$

Where:

UCS = Unconfined compressive strength of sand stabilized with 2% cement and varying quantity of OFA, 7-day sealed curing, kPa.

X = OFA content (%).

R^2 = Correlation coefficient.

The reduction in the UCS of sand plus 2% cement caused by the OFA content was probably due to the fact that the OFA is of very high LOI, very low alkalis, as shown in Table 4-3, which, in turn, prevented the hydration of the 2% cement. Further, the more dosage of OFA, the more amount of water that is needed for lubrication that allows the hydration of 2% cement and the trivial amount of the calcium and silicon in the OFA [Kolay et al., 2011; and Edil et al., 2006;]. The more amount of water resulted in step up of the UCS of sand plus 2% cement with 10 and 15% OFA mixtures. Moreover; the more amount of the OFA content in stabilized soils, the more reduction was noted in the soaked CBR [Edil et al., 2006].

The sand plus 2% cement mixture with up to 15% OFA failed to be qualified to be used as sub-base or base course in pavements.

The relation between the variables are considered reliable, if the correlation coefficient (R^2) is greater than 0.80 [Montgomery, 2009]. Therefore, the relations (4.9), (4.10), (4.11), (4.12) and (4.13) can be considered reliable, as the value of correlation coefficient (R^2) is 0.97, 0.94, 0.94, 0.97 and 0.95, respectively. The developed relations are useful for estimating the required amount of the stabilizers (cement, CKD, CKD plus 2% cement, EAFD plus 2% cement and OFA plus 2% cement) to be added to dune sands for achieving the UCS at 7-day sealed curing.

In summary; the UCS of the investigated sand mixed with the various stabilizers used in this investigation is summarized in Table 4-11, while the stabilizers and dosages that satisfied the minimum UCS requirements specified by the ACI [1990], as mentioned in Table 3-2, are summarized in Table 4-12

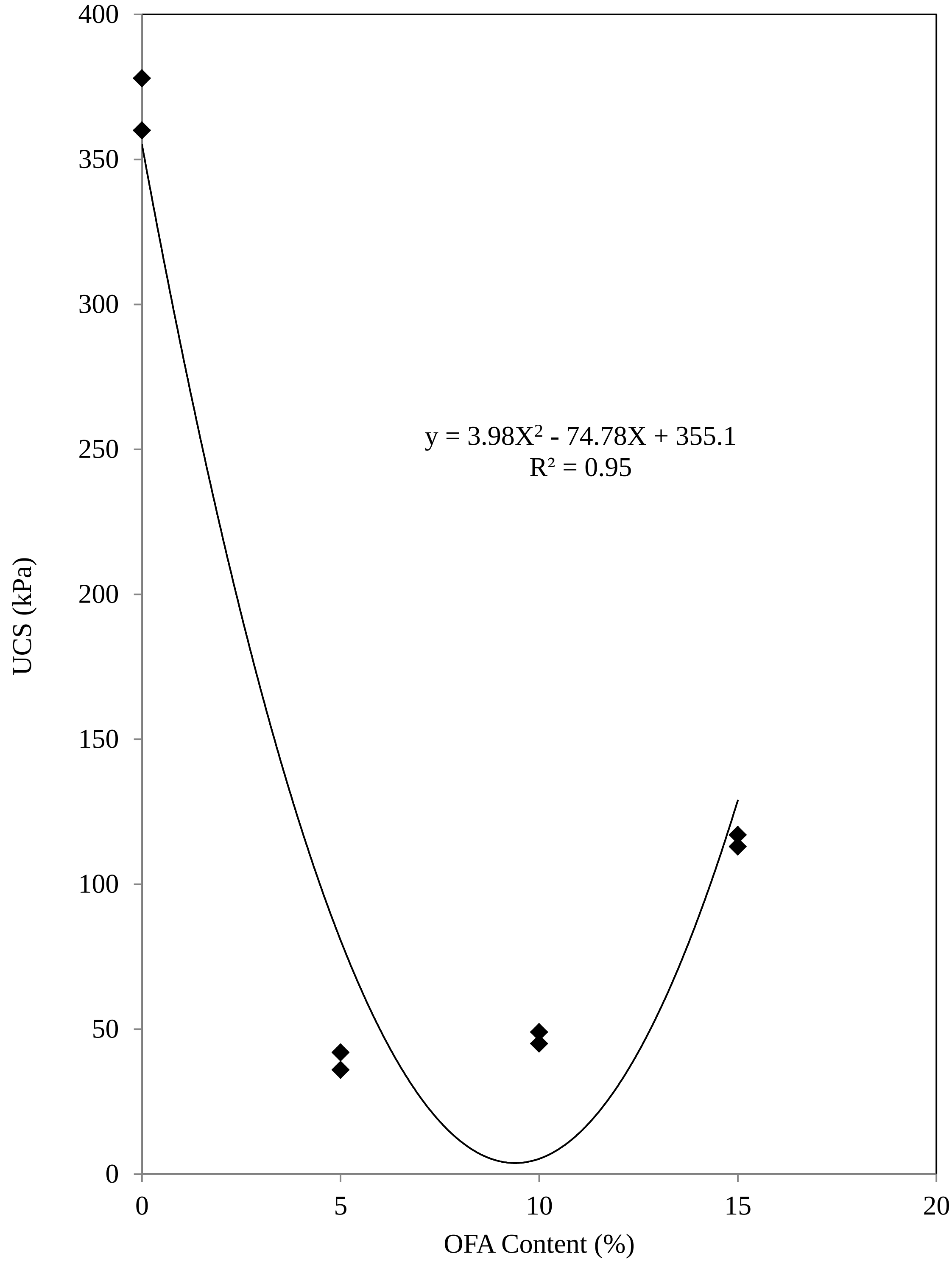


Figure 4-40: Effect of OFA Content on the UCS of Sand with 2% Cement (7-Day Sealed Curing)

From the data in Table 4-12, it is evident that sand with 7% cement or sand with 2% cement plus 30% CKD, 20% or 30% EAFD met the ACI strength requirements mentioned in Table 3-2. It is evident that the addition of 30% CKD or 20-30% EAFD decreased the cement by about 5%. This reduction in the cement will decrease the cost of sand stabilization and also reduce the greenhouses gas emission.

Table 4-11: UCS of Sand with Investigated Additives (7-Day Sealed Curing)

Additive Type and Content	UCS (kPa)		
	Specimen # 1	Specimen # 2	Average
2% Cement	360	378	369
5% Cement	950	1,060	1,005
7% Cement	1,710	1,728	1,719
10% CKD	99	107	103
20% CKD	398	402	400
30% CKD	738	752	745
2% Cement + 10% CKD	412	424	418
2% Cement + 20% CKD	795	805	800
2% Cement + 30% CKD	1,372	1,390	1,381
2% Cement + 5% EAFD	386	398	392
2% Cement + 10% EAFD	529	535	532
2% Cement + 20% EAFD	1,390	1,464	1,427
2% Cement + 30% EAFD	2,412	2,426	2,419
2% Cement + 5% OFA	36	42	39
2% Cement + 10% OFA	45	49	47
2% Cement + 15% OFA	113	117	115

Table 4-12: Additives Meeting the ACI [1990] Requirement for Sand

Additive Type and Content	UCS (kPa)
7% Cement	1,719
2% Cement + 30% CKD	1,381
2% Cement + 20% EAFD	1,427
2% Cement + 30% EAFD	2,419

4.6.2 Results of Soaked CBR Tests on Stabilized Sand

Specimens of sand treated with 2% cement and sand stabilized with the stabilizers that satisfied strength requirements were prepared and tested according to ASTM D 1883. The effect of each stabilizer on the soaked CBR of sand is discussed in the following sub-sections.

4.6.2.1 CBR of Sand Stabilized with Cement

For studying the effect of cement content on the soaked CBR of sand, tests were conducted on sand specimens treated with cement addition. The addition contents were 2, 5 and 7%. The results are reported in Figure 4-41.

It is noticed, from the data in Figure 4-41, that the soaked CBR of the investigated sand increases with an increase in the quantity of cement. The soaked CBR was 171, 258 and 438% for sand with 2, 5 and 7% cement, respectively. Abdullah [2009] reported that the unsoaked CBR of sand with 2 and 5% cement improved from 181 to 273%, respectively. The approximate equality of the results of the soaked CBR (in this study) and unsoaked

CBR (by Abduulah [2009]) is due to the fact that sand is stable, not sensitive to water. Consequently, the results are similar.

It should also be noted that the addition of 2, 5 and 7% cement improved the soaked CBR of the sand (from 0 to more than 50%) to make cement-stabilized sand to be excellent material for base-course in pavements, as shown in Table 3-3.

Figure 4-41 shows that there is an exponential correlation between the quantity of cement and soaked CBR. The correlation can be expressed by the following best-fit model:

$$\text{Soaked CBR (\%)} = 113.3{*}e^{0.185X} \qquad R^2 = 0.95 \qquad (4.14)$$

CBR = California bearing ratio of sand plus cement, 7-day sealed curing, (%).

X = Cement content (%).

R^2 = Correlation coefficient.

CBR results do agree with UCS results so as to confirm the findings that 7% cement makes sand an excellent material for base course.

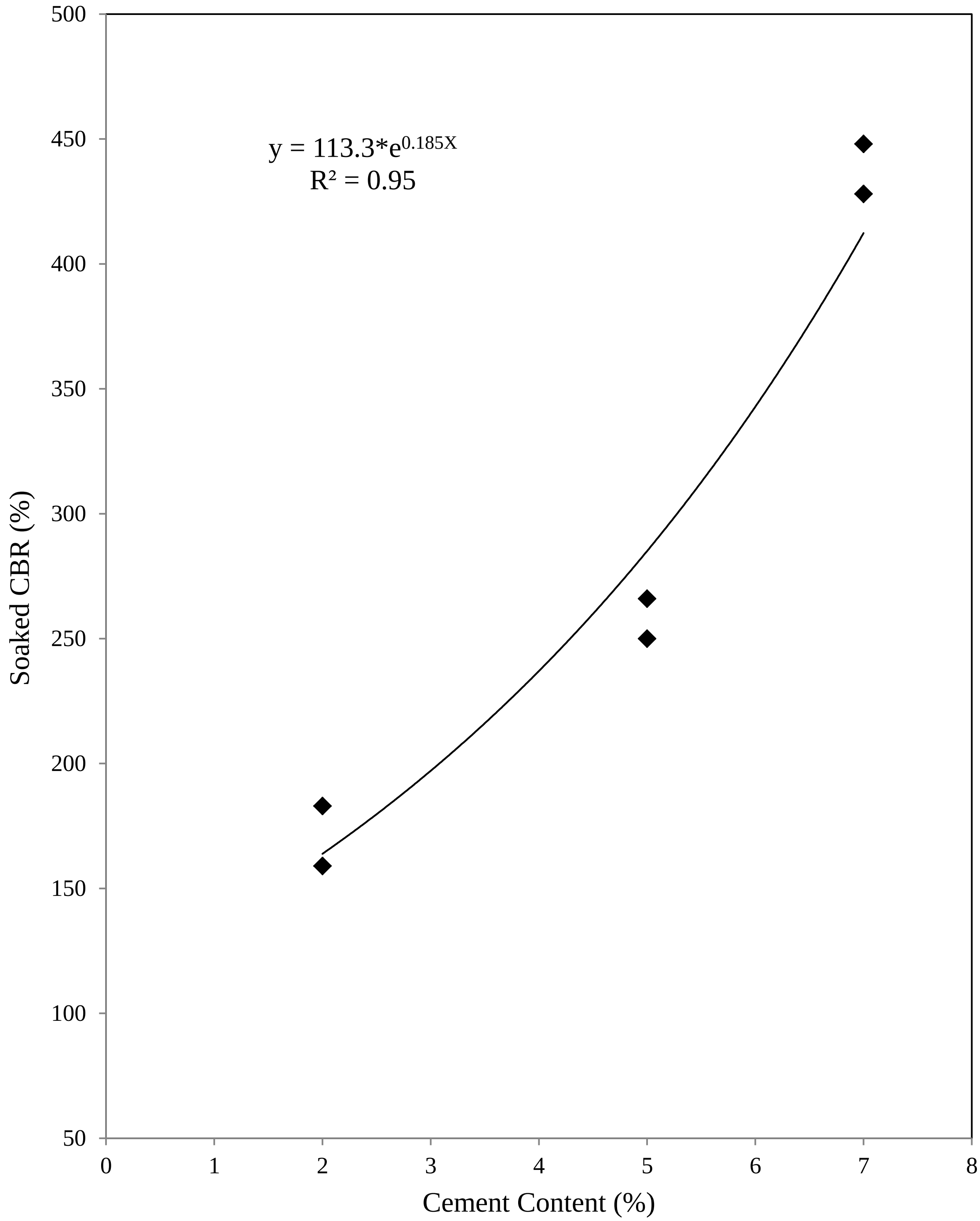


Figure 4-41: Effect of Cement Content on Soaked CBR of Sand (7-Day Sealed Curing)

4.6.2.2 CBR of Sand Stabilized with 2% Cement plus CKD

The results of soaked CBR of sand plus 2% cement and 10 to 30% CKD are plotted in Figure 4-42. The data in this figure indicate that the soaked CBR increases with an increase in the CKD content. The soaked CBR of sand with 2% cement plus 10, 20 and 30% CKD was 189, 283 and 396%, respectively. The soaked CBR of sand with only 2% cement was 171%.

All the dosages of CKD significantly improved the soaked CBR of sand plus 2% cement to make it an excellent material (CBR more than 50%) for base course in pavements, as shown in Table 3-3.

Abdullah [2009] reported that 10 and 20% CKD plus 2% cement improved the CBR of stabilized sand to 351 and 484%, respectively. The difference in the results of this study and those reported by Abdullah [2009] was probably due to the difference in the used optimum moisture contents.

The data in Figure 4-42 show that there is an exponential correlation between the quantity of CKD and the soaked CBR of sand with 2% cement. The correlation can be expressed by the following best-fit model:

$$\text{Soaked CBR (\%)} = 157.9 * e^{0.029X} \qquad R^2 = 0.94 \qquad (4.15)$$

Where:

CBR = California bearing ratio of sand with 2% cement and varying quantity of CKD, 7-day sealed curing, (%).

X = CKD content (%).

R^2 = Correlation coefficient.

The data in Figure 4-42 also indicate that the soaked CBR of sand with 2% cement plus 10, 20 or 30% CKD is more than 50%, which, in turn, makes stabilized sand suitable for use as a base course in pavements from CBR point of view.

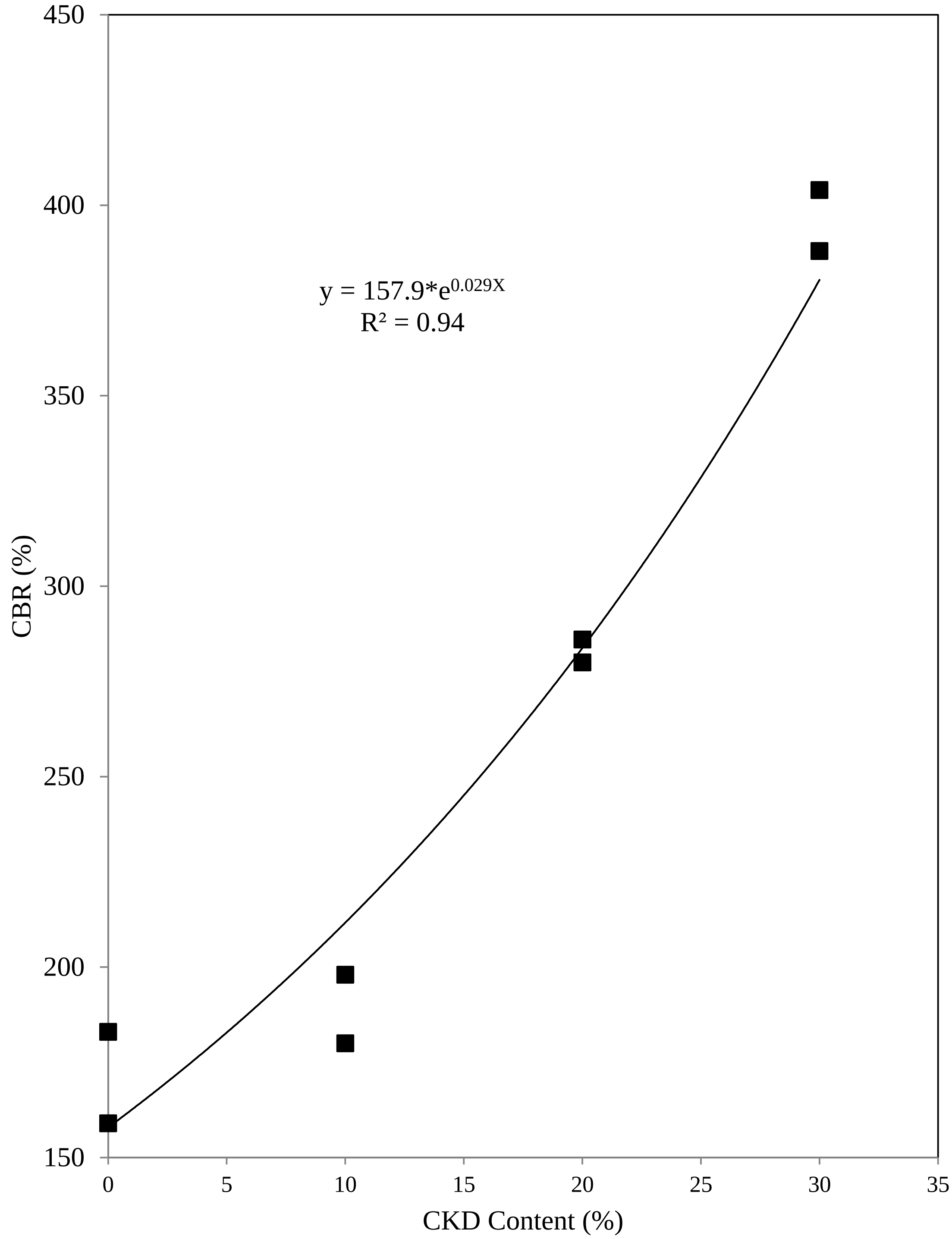


Figure 4-42: Effect of CKD Content on Soaked CBR of Sand with 2% Cement (7-Day Sealed Curing)

4.6.2.3 CBR of Sand Stabilized with 2% Cement plus EAFD

To study the effect of EAFD content on the soaked CBR of sand plus 2% cement mixtures, tests were conducted on sand-EAFD addition plus 2% cement mixtures. The additions of EAFD were in the range of 5 to 30%. The results are reported in Figure 4-43.

The data in Figure 4-43 show that the soaked CBR of the sand plus 2% cement mixture increases with an increase in the EAFD content. The soaked CBR of sand with 2% cement was 171, 380, 541 and 750% for EAFD addition 0, 10, 20 and 30%, respectively. The soaked CBR values for stabilized sand are more than those noted for non-plastic marl stabilized with EAFD-2% cement mixtures. These results prove that sand stabilized with 2% cement plus EAFD is not sensitive to water.

Moreover; the soaked CBR of sand stabilized with EAFD plus 2% cement is more than the requirements for the sand to be used as a base course material in pavements.

The data in Figure 4-34 indicate that there is an exponential relationship between the soaked CBR of sand stabilized with EAFD plus 2% cement and the EAFD content. The statistical model to show the correlation can be expressed by the following best-fit exponential model:

$$\text{Soaked CBR (\%)} = 176.15 * e^{0.052X} \qquad R^2 = 0.92 \qquad (4.16)$$

Where:

CBR = California bearing ratio of sand stabilized with 2% cement and varying quantity of EAFD, 7-day sealed curing, (%).

X = EAFD content (%), ≤ 30.

R^2 = Correlation coefficient.

In summary; the relation between the variables are considered reliable, if the correlation coefficient (R^2) is greater than 0.80 [Montgomery, 2009]. The values of correlation coefficient (R^2) for Equations 4.14 through 4.16 are 0.95, 0.94 and 0.92, respectively. Therefore, the relations can be considered reliable since the correlation coefficients are greater than 0.80. The developed relations will be useful in estimating the required quantity of investigated stabilizers (cement, CKD plus 2% cement and EAFD plus 2% cement, respectively) to obtain the desired soaked CBR at 7-day sealed curing.

The soaked CBR results on stabilized sand are summarized in Table 4-13. It may be noticed from the data in Table 4-13 that sand stabilized with 2, 5 and 7% cement achieved pronounced CBR improvement. Further, the soaked CBR of sand with 2% cement plus 20% or 30% EAFD was more than that of sand plus 7% cement.

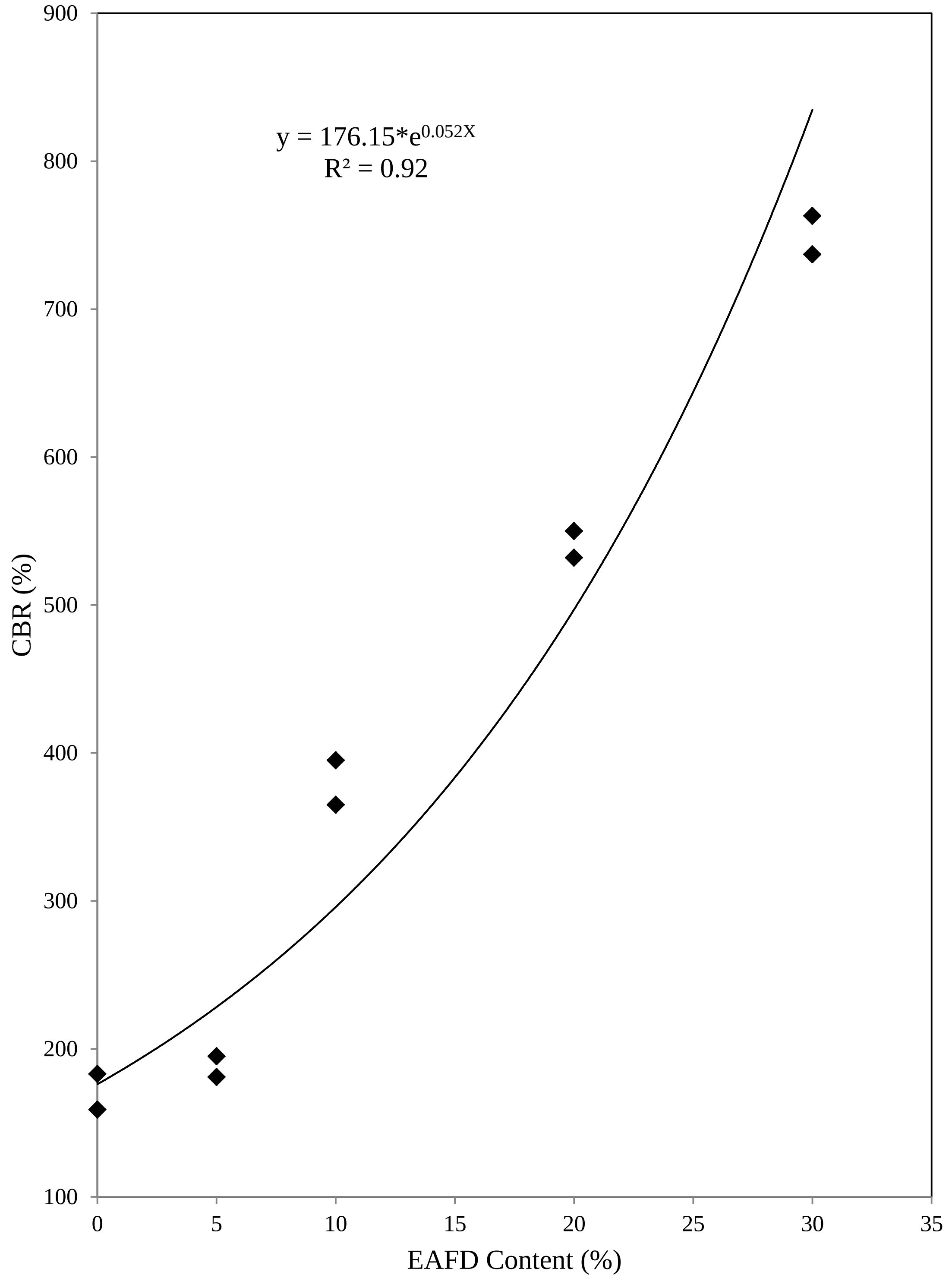


Figure 4-43: Effect of EAFD Content on Soaked CBR of Sand with 2% Cement (7-Day Sealed Curing)

Table 4-13: Soaked CBR Results for Sand

Additive Type and Content	UCS (kPa)	Soaked CBR (%)		
		Specimen#1	Specimen#2	Average
2% Cement (Reference)	369	159	183	171
5% Cement	1,005	250	266	258
7% Cement	1,719	428	448	438
2% Cement + 10% CKD	418	180	198	189
2% Cement + 20% CKD	800	280	286	283
2% Cement + 30% CKD	1,381	388	404	396
2% Cement + 5% EAFD	392	181	195	188
2% Cement + 10% EAFD	532	365	395	380
2% Cement + 20% EAFD	1,427	532	550	541
2% Cement + 30% EAFD	2,419	737	763	750

4.6.3 Results of the Durability Tests on Stabilized Sand

ASTM D 559 durability tests were conducted on specimens of sand stabilized with the type and the content of the proposed stabilizers that satisfied the minimum UCS requirements specified by ACI [1990]. The results are summarized in Table 4-14. The results indicated that the highest weight loss, 9.1%, occurred in sand stabilized with 20% EAFD plus 2% cement. The lowest weight loss, 6.1%, was measured in sand stabilized with 7% cement. The weight loss was 6.7% in sand stabilized with 30% CKD plus 2% cement. The data in Table 4-14 show that weight loss of sand plus 2% cement decreases with an increase in the quantity of EAFD. The weight loss was 9.1 and 7.2% for the sand stabilized with 2% cement plus 20 and 30% EAFD, respectively. The observed weight loss of sand-30% CKD-2% cement is marginally less than that reported by Abdullah [2009], which was about 8%.

Generally, the measured weight loss is less than the allowable weight loss of 14% according to the Portland Cement Association (PCA) [ACI, 1990]. Therefore, it should be noted that the stabilizers and dosages shown in Tables 4-13 and 4-14 are satisfactory for stabilizing dune sand from strength and durability perspectives.

Table 4-14: Weight Loss of Stabilized Sand

Additive Type and Content	**Weight Loss (%)**
7% Cement	6.1
2% Cement + 30% CKD	6.7
2% Cement + 20% EAFD	9.1
2% Cement + 30% EAFD	7.2

4.6.4 Results of TCLP Tests on the Stabilized Sand

As shown in Table 4.2, EAFD contains toxic metals, such as cadmium, lead and nickel. Since the addition of 30 and 20% EAFD with 2% cement improved the strength of the investigated sand to meet the strength and durability requirements, it is necessary to investigate the leaching of toxic elements to the surrounding environment mainly during rainfall or rise of the ground water table. Therefore, the concentration of toxic elements was measured according to the USEPA (TCLP) procedures [USEPA, 1998]. The results are summarized in Table 4-15.

The data in Table 4-15 indicate the maximum allowable USEPA concentration limits of the toxic metals and the measured concentration of toxic metals in sand stabilized with

2% cement plus 20 or 30% EAFD. The data revealed that, except for silver, the concentration of toxic elements increases with an increase in the quantity of EAFD. The presence of arsenic was not noted since EAFD does not contain this element. The concentration of nickel and vanadium was measured despite the fact that these two elements are not regulated by the USEPA.

The measured concentrations of other elements, regulated by USEPA, were far below the maximum allowable concentrations that are specified by USEPA (EPA limits in Table 3-4). It can be noticed from the data in Table 4-15 that the concentration of cadmium was 0.819 and 0.969 (mg/l) for the EAFD dosages of 20 and 30%, respectively. The maximum allowable concentration of this element is 1 (mg/l). Thus, the cadmium concentration in sand with 30% EAFD is very close to the allowable limit specified by the USEPA. Consequently, it can be concluded that sand with 2% cement plus more than 30% EAFD may contribute to leaching of cadmium to the environment. Therefore, more than 30% EAFD should not be recommended for stabilizing dune sand that is intended to be used as a base or sub-base course in pavements.

Table 4-15: TCLP for Sand Stabilized with 2% Cement plus EAFD

Metal		**EPA Limits**	**Measured Values**	
			20 % EAFD	**30 % EAFD**
Name	Symbol	(mg/l)	(mg/l)	(mg/l)
Silver	Ag	5	0.012	0.008
Arsenic	As	5	0000	0000
Barium	Ba	100	1.038	1.133
Cadmium	Cd	1	0.819	0.969
Chromium	Cr	5	0.002	0.003
Mercury	Hg	0.2	0.016	0.018
Lead	Pb	5	0.246	0.186
Selenium	Se	1	0.080	0.092
Nickel	Ni	NR	0.051	0.062
Vanadium	V	NR	0000	0000

NR: Not regulated by EPA

4.7 Evaluating the Treatment of the Investigated Sabkha Soil

The effects of the proposed stabilizers on the investigated sabkha were assessed by determining the unconfined compressive strength, soaked CBR and wet-dry durability. The environmental impact of the stabilizer on the leaching of heavy metals was evaluated for mixtures that satisfied the minimum strength and durability requirements.

4.7.1 Results of the Unconfined Compression Tests on Sabkha

The unconfined compression tests were carried out to evaluate the effect of the proposed stabilizers and contents on the strength of the investigated sabkha. The correlations between the stabilizer type and content and the UCS are discussed in the following sub-sections.

4.7.1.1 UCS of Sabkha Stabilized with Cement

Unconfined compression tests were carried out on plain sabkha and on sabkha treated with 2 to 7% cement. The results of the UCS against cement content are reported in Figure 4-44. The data in therein show that the UCS increased exponentially with an increase in the cement content. The UCS of sabkha with 0, 2, 5, and 7% cement was 150, 348, 898 and 1,485 kPa, respectively.

The correlation between UCS and the cement content in sabkha can be expressed by the following best fit-model:

$$UCS = 164.19*e^{0.326X} \qquad R^2 = 0.99 \tag{4.17}$$

Where:

UCS = Unconfined compressive strength of cement–stabilized sabkha, kPa (7-day sealed curing).

X = Cement content (%).

R^2 = Correlation coefficient.

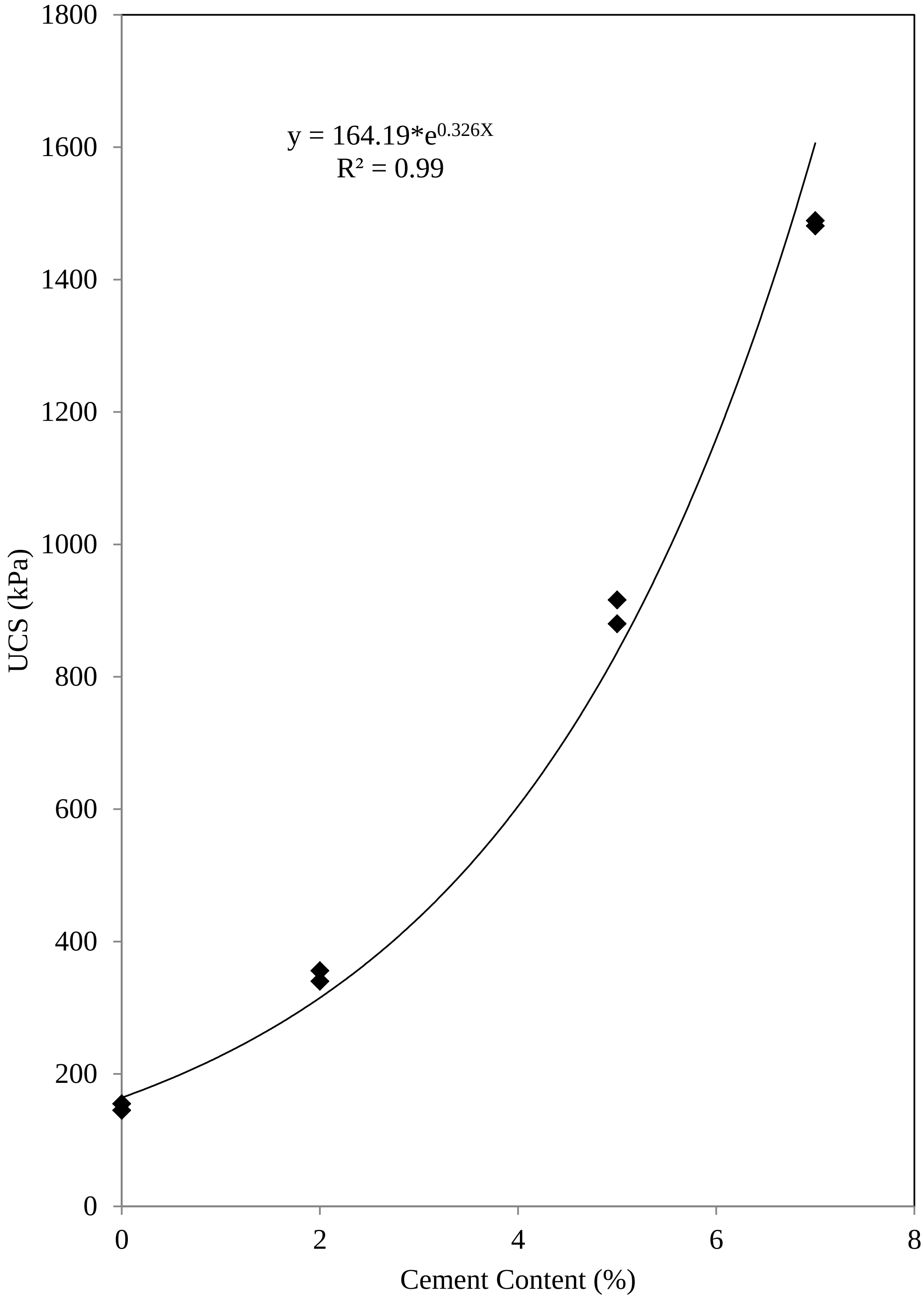


Figure 4-44: Effect of Cement Content on the UCS of Sabkha (7-Day Sealed Curing)

It may be noted that sabkha with 7% cement satisfies the minimum strength requirement of 1,380 kPa, specified by ACI [1990] for sub-base course in rigid pavements.

Al-Amoudi [1994] reported that the addition of 2.5, 5, 7.5 and 10% cement improved the UCS of Ras-Al-Ghar sabkha from 70 kPa to 271, 736, 1,180 and 1,391 kPa, respectively. He recommended 10% cement for the Al-Ghar Sabkha to be used for sub-base course in rigid pavements. The high amount of cement recommended and the low UCS were probably due to the low compaction energy (i.e., standard Proctor compaction) in casting the specimens in addition to the low rate of deformation in testing (i.e. 0.5 mm/min). Similarly; Mohamadzin and Al-Rawas [2010] reported that 7.5% cement was a suitable stabilizer for the Omani sabkha. That was probably due to the low compaction energy used (i.e., standard Proctor compaction) in casting of the tested specimens.

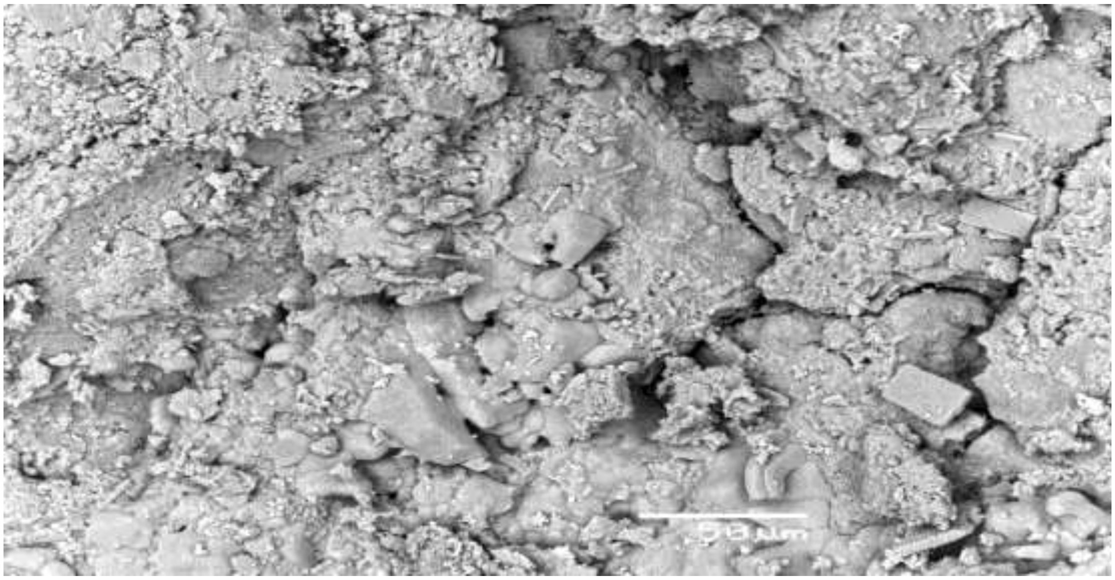
The improvement achieved in the UCS of sabkha due to cement addition was not as much as that noted in non-plastic marl despite the fact that the two soils were classified as SM. The low strength in sabkha stabilized with cement may be attributed to the presence of high amount of halite and gypsum in the investigated sabkha, as was revealed by the chemical composition shown in Figure 3-6. In the presence of water, calcium from cement reacts with chloride from sabkha to form calcium chloride which might have reduced the strength [Reddy et al., 2011]. Furthermore, the presence of gypsum in the sabkha, which leads to the formation of etringite, might have contributed to the lower quality of C-S-H gel, thus leading to reduction in strength as compared with the strength of cement-marl specimens.

Figure 4-45 (a, b, c, d, e and f) shows the BEI, SEM and EDX images of sabkha with 2 and 7% cement.

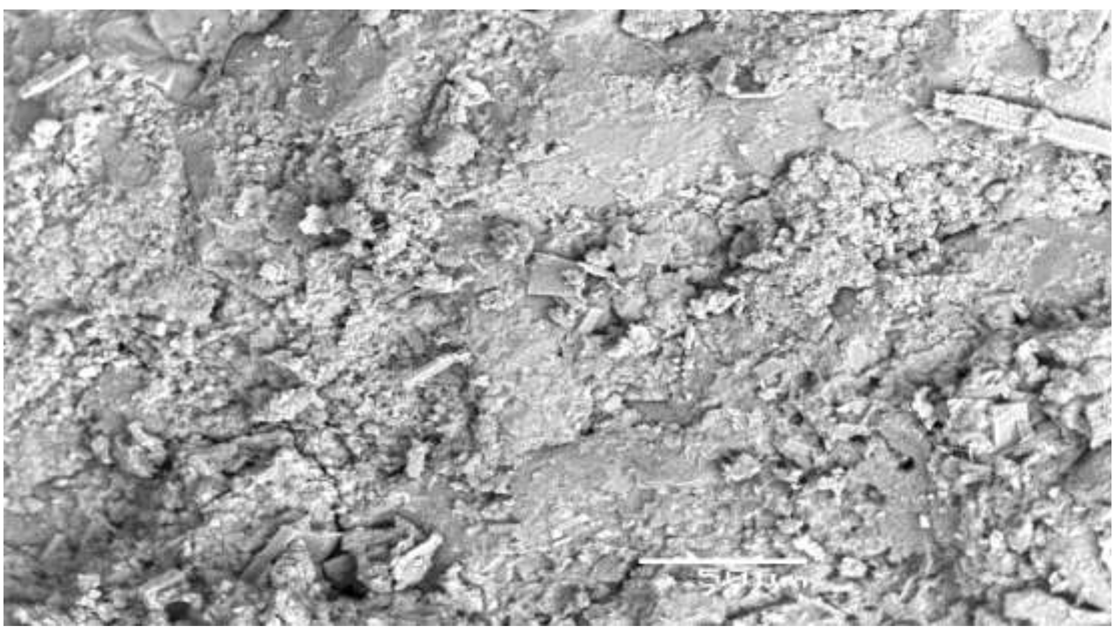
The BEI of sabkha with 2% cement, Figure 4-45(a), revealed a randomly oriented system consisting of partly-clothed sand and/or silt interaction. Face to face particle interactions as well as connectors are apparent. Voids of different sizes are also visible. BEI of sabkha with 7% cement, Figure 4-45(b), shows reduction in the voids. However, a few voids are still visible. The denseness in the latter mixture probably tended to increase its UCS compared to sabkha with 2% cement.

The SEM of sabkha with 2% cement, Figure 4-45(c), shows a platy morphology with isolated crystalline structure of gypsum shown the XRD of sabkha, Figure 4-3. The EDX, Figure 4-45(d), shows the presence of Na, Mg, Si, Cl, Ca and Fe with weight proportion of 0.71, 7.36, 22.12, 1.26, 9.42 and 1.15%, respectively. It is noticed that there is a significant quantity of chloride, which is mostly contributed by halite in the sabkha. Calcium, silica and iron are contributed by cement.

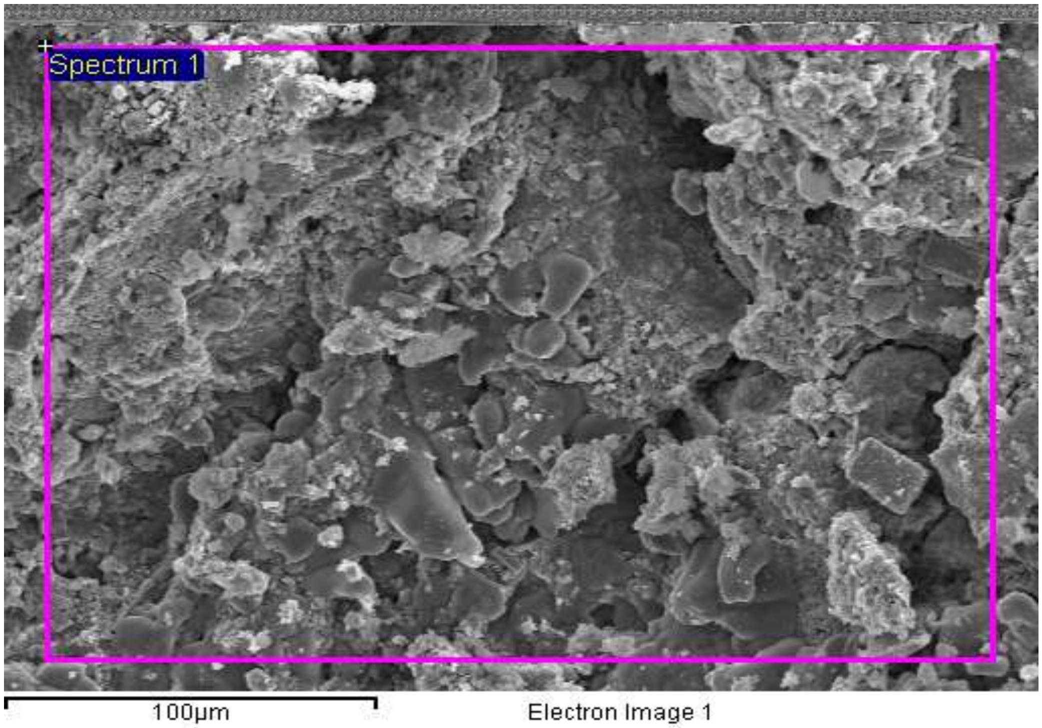
The SEM of sabkha stabilized with 7% cement, Figure 4-45(e), also shows platy structure due to the hydration of cement as reflected by the fibrous needles (C-S-H) were noted at several locations. The EDX, Figure 4-45(f), of sabkha stabilized with 7% cement indicated the presence of Na, Mg, Si, Cl, Ca and Fe with weight proportion of 1.26, 9.55, 15.96, 1.64, 15.10 and 2.01%, respectively. The presence of calcium and silica indicated the C-S-H gel, formed due to the addition of cement.



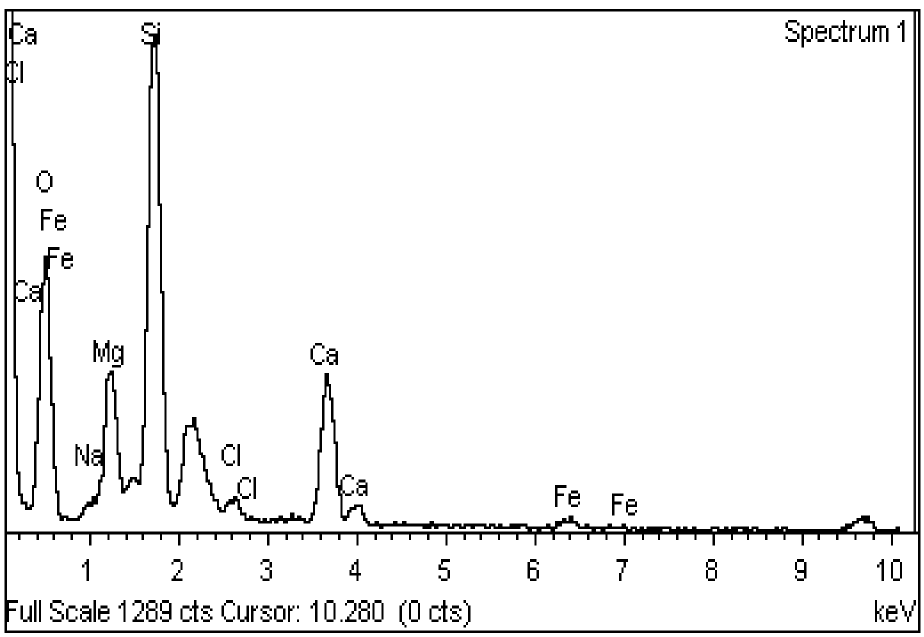
a) BEI of sabkha stabilized with 2% cement (X400)



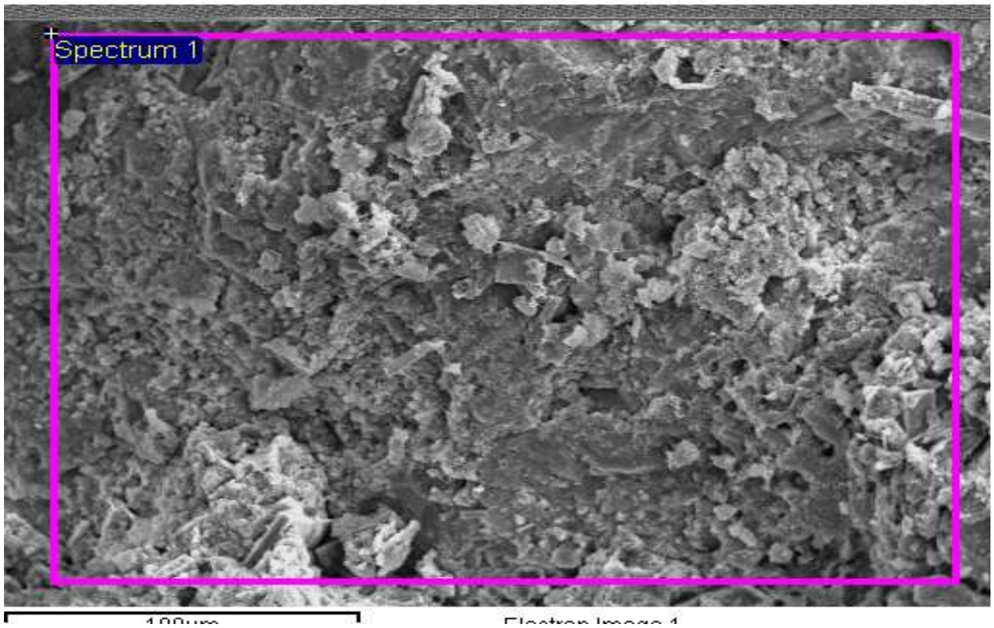
b) BEI of sabkha stabilized with 7% cement (X400)



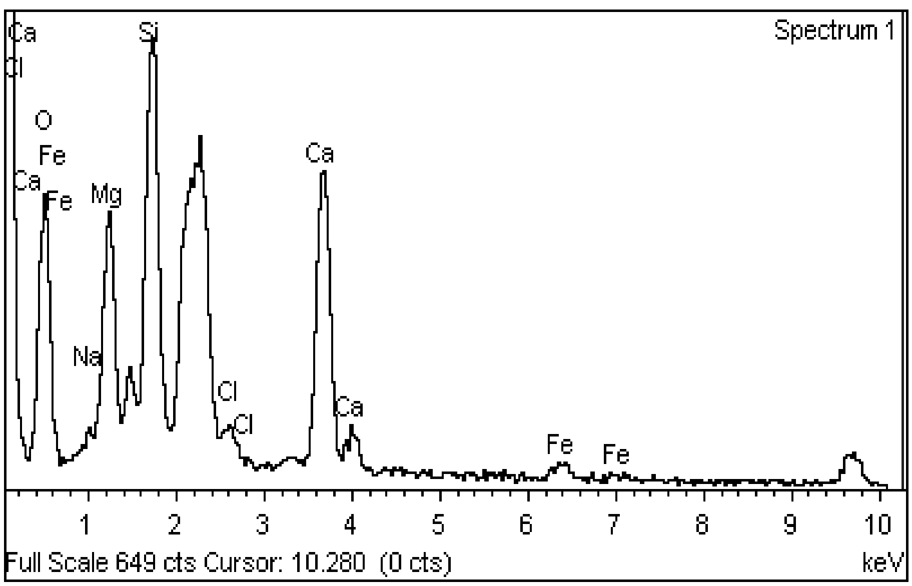
c) SEM of sabkha stabilized with 2% cement (X400)



d) EDX of sabkha stabilized with 2% cement



e) SEM of sabkha stabilized with 7% cement (X400)



f) EDX of sabkha stabilized with 7% cement

Figure 4-45: BEI, SEM and EDX of Sabkha Stabilized with Cement (7-Day Sealed Curing)

4.7.1.2 UCS of Sabkha Stabilized with CKD

Unconfined compression tests were carried out on plain sabkha and on sabkha treated with CKD contents ranging from 10 to 30%. The results of the UCS vs CKD content are reported in Figure 4-46. The data therein indicate that the UCS of the investigated sabkha increases with an increase in the quantity of CKD. The UCS was 150, 262, 676 and 974 kPa for sabkha with 0, 10, 20 and 30% CKD, respectively.

Figure 4-46 shows that there is an exponential relationship between the quantity of CKD and UCS that can be expressed by the following equation:

$$UCS = 153.8*e^{0.068X} \qquad R^2 = 0.92 \qquad (4.18)$$

Where:

UCS = Unconfined compressive strength of CKD- stabilized sabkha, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

Rahman et al., [2011] reported that for sealed curing for 14 days specimens, the improvement of the UCS for sabkha soils was from 214 kPa to 2,752 kPa corresponding to 0 and 50% CKD contents. The high improvement reported was due to the long period of curing of 14-day and the larger content of CKD.

From the data in Figure 4-46, it is evident that none of the investigated CKD contents (10, 20 and 30%) improved the UCS of sabkha to meet the minimum strength requirement, 1,380 kPa, specified by ACI [1990] for sub-base course in pavements from strength point of view. That was probably due to the presence of halite in sabkha in addition to the high LOI and high alkalis of the investigated CKD, as shown in Table 4-1.

The high LOI reduced the performance of the CKD while the high alkalis weakened the strength developed by the CKD [Chusilp et al., 2009]. Moreover; in the presence of water, magnesium from the CKD reacts with chloride from sabkha and the CKD to form magnesium chloride, which attacks and weakens the cementing product produced by the CKD, C-S-H, whereby magnesium replaces calcium to produce non-cementitious product, Mg-S-H [Mussato et al., 2004]. Further, the presence of gypsum in sabkha has reduced the quality and strength of the C-S-H gel. Though the presence of gypsum increases the amount of C-S-H gel, the quality the gel is weak. This increase, in the amount of C-S-H gel, is caused by partial substitution of silica by sulfate in the C-S-H gel as reported by Ali [2004].

4.7.1.3 UCS of Sabkha Stabilized with 2% Cement plus CKD

Unconfined compression tests were carried out using the investigated sabkha treated with 2% cement and on the sabkha treated with CKD contents ranging from 10 to 30% plus 2% cement. The results of UCS are reported in Figure 4-47.

The data in Figure 4-47 indicate that UCS increases with an increase in the quantity of CKD. The UCS of sabkha with 2% cement plus 0, 10, 20 and 30% CKD was 348, 530, 892 and 1,519 kPa, respectively.

The relationship between UCS and CKD content in sabkha with 2% cement in Figure 4-47 can be expressed by the following relation:

$$UCS = 337*e^{0.049X} \qquad R^2 = 1 \qquad (4.19)$$

Where:

UCS = Unconfined compressive strength of sabkha stabilized with 2% cement and varying quantity of CKD, 7-day sealed curing, kPa.

X = CKD content (%).

R^2 = Correlation coefficient.

It can also be observed from the data in Figure 4-47 that the UCS of the investigated sabkha with 2% cement plus 30% CKD exceeded the minimum strength requirement, 1,380 kPa, specified by ACI [1990] for sub-base course material in rigid pavements.

Shabel [2006] reported that the UCS of Jazan sabkha with 2% cement plus 10, 15 or 20% CKD was 235, 722, 1,190 and 2,002 kPa, respectively. The low LOI in CKD, 8.35%, free chloride and the low salinity of Jazan sabkha (compared to high salinity of the sabkha in this investigation) may have contributed to the high strength of Jazan sabkha as compared with the sabkha in this investigation.

The improvements achieved by the CKD additions with 2% cement in sabkha soil were not as much as the improvements achieved by the same additive content in non-plastic marl or sand soils. That could be due to the presence of halite and gypsum in the sabkha as discussed above.

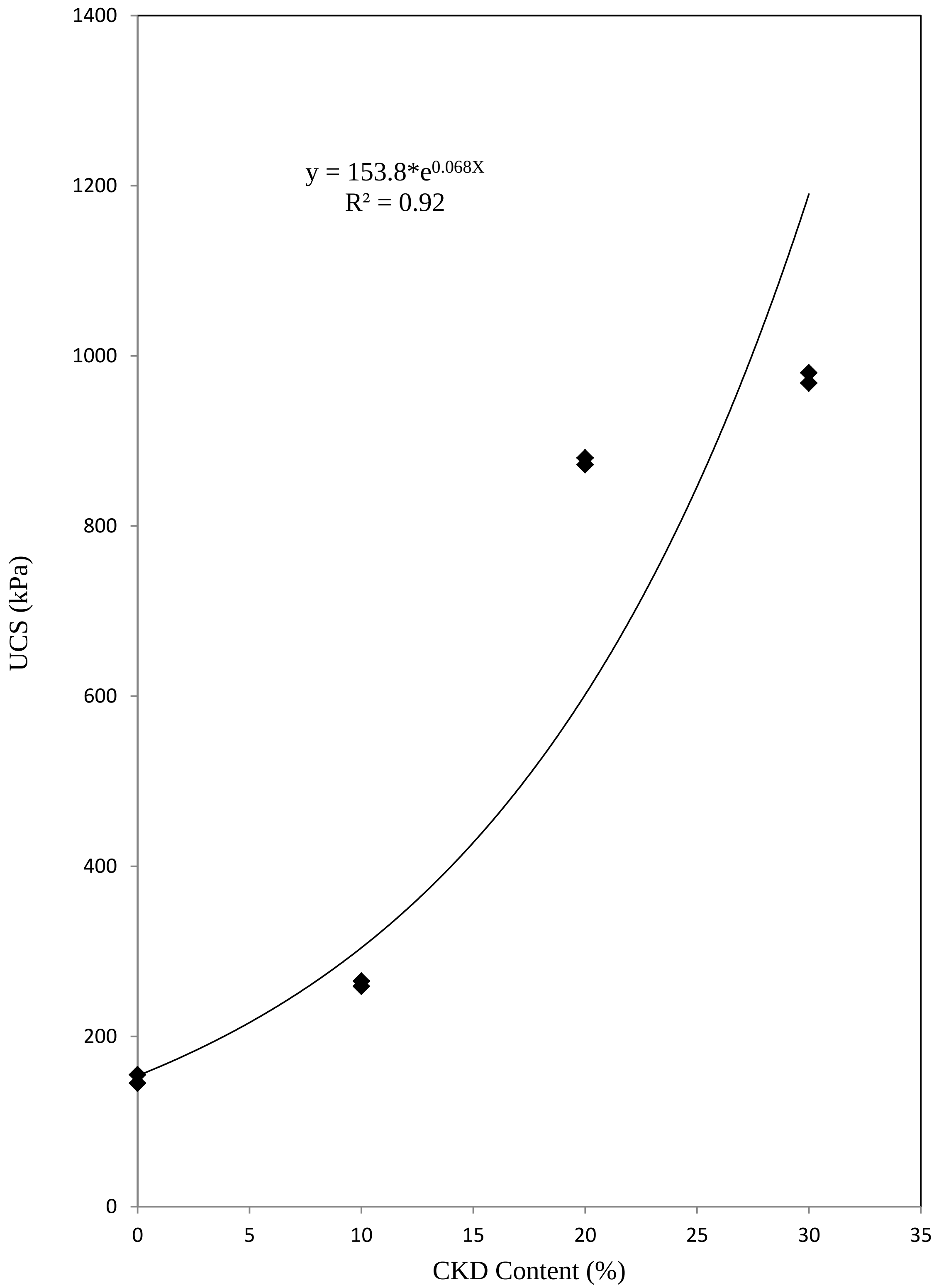


Figure 4-46: Effect of CKD Content on the UCS of Sabkha (7-Day Sealed Curing)

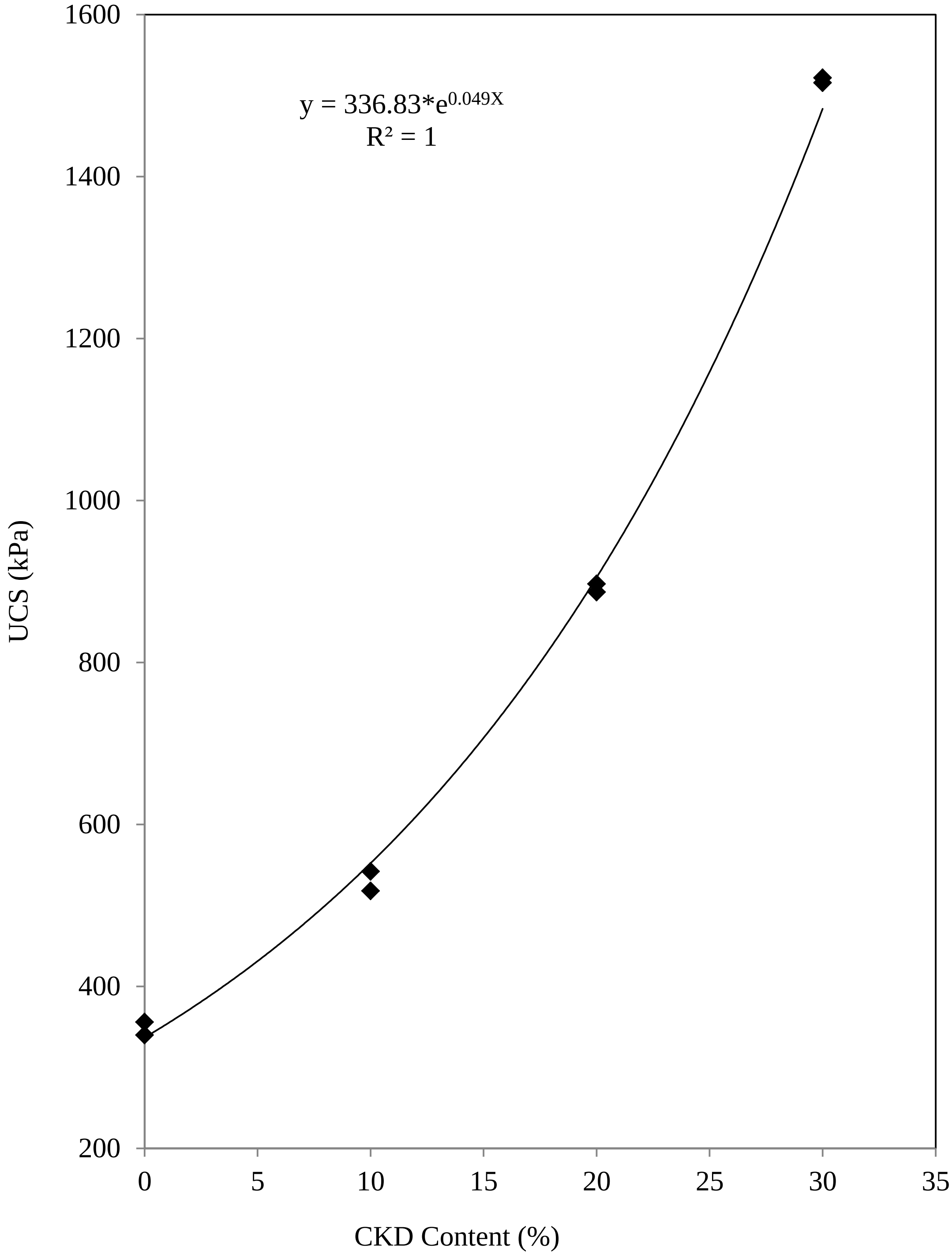


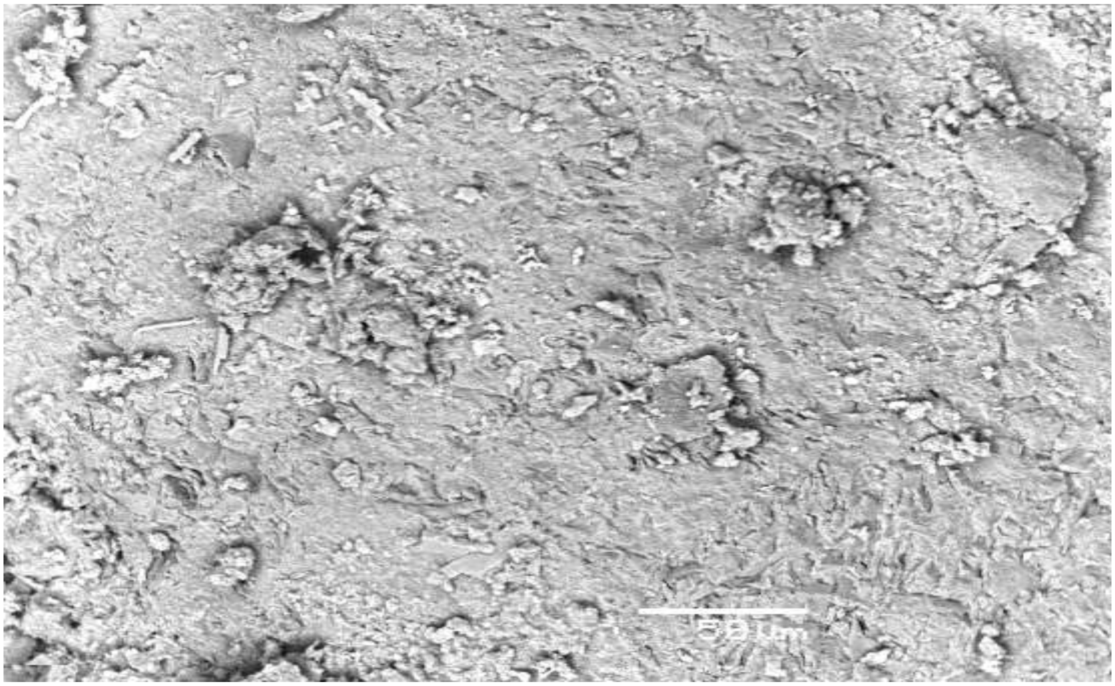
Figure 4-47: Effect of CKD Content on the UCS of Sabkha with 2% Cement (7-Day Sealed Curing)

As mentioned before, the cementing performance of the CKD with sabkha was not as high as that with marl soil. Moreover; in the presence of water, magnesium in CKD reacts with chloride, present in CKD and sabkha, to form magnesium chloride which attack and weaken the cementing product produced by the CKD, C-S-H. Magnesium replaced calcium to produce non-cementitious product, Mg-S-H [Mussato et al., 2004]. Further, the presence of gypsum has reduced the quality and strength of the C-S-H gel. Though, the presence of gypsum causes an increase in the amount of C-S-H gel. This increase, in the amount of C-S-H gel, is caused by partial substitution of silica by sulfate in the C-S-H gel as it was reported by Ali [2004].

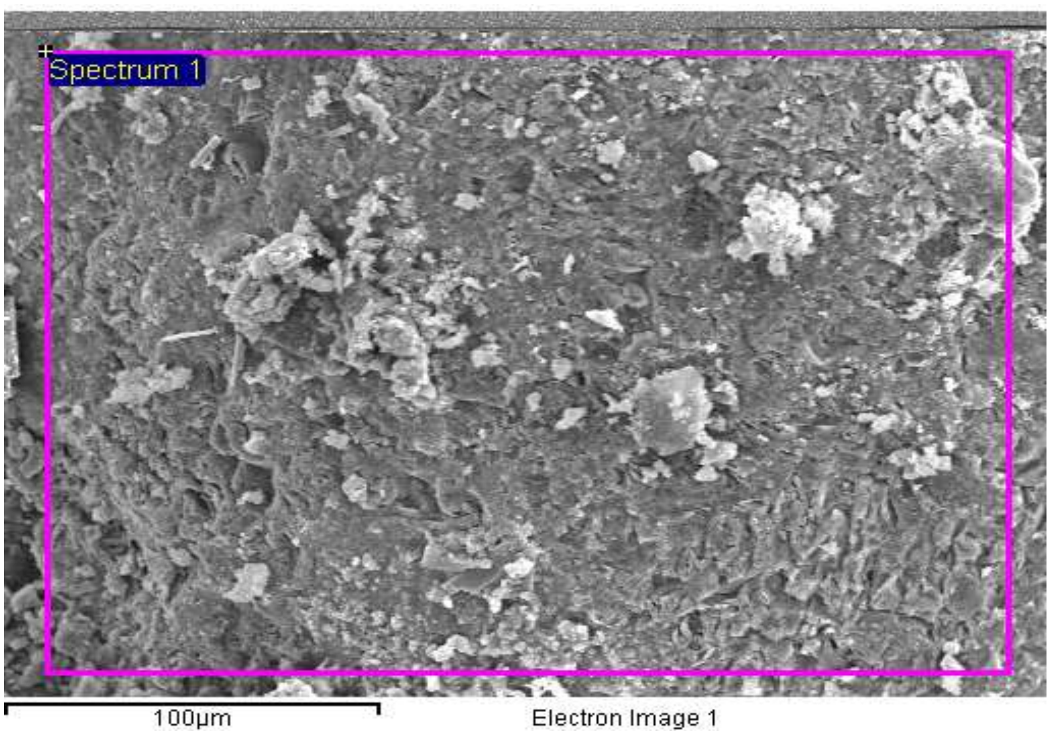
Therefore, the investigated sabkha stabilized with 30% CKD plus 2% cement is suitable for sub-base course in rigid pavement from strength point of view.

Figures 4- 48 (a, b and c) show the BEI and SEM with EDX of sabkha with 2% cement and sabkha-30% CKD plus 2% cement mixtures، respectively.

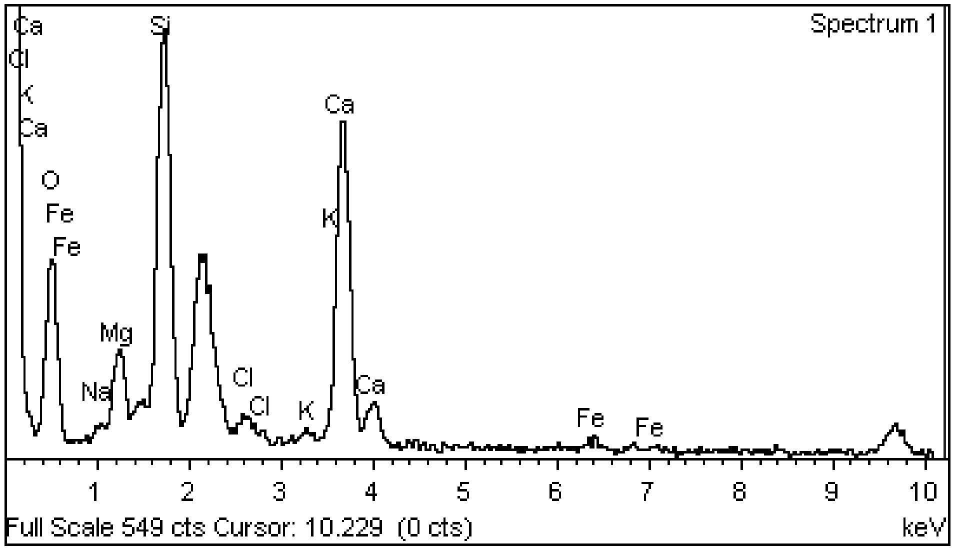
.



a) BEI of sabkha stabilized with 2% cement plus 30% CKD (4700)



b) SEM of sabkha stabilized with 2% cement plus 30% CKD (X400)



c) EDX of sabkha stabilized with 2% cement plus 30% CKD

Figure 4-48: BEI, SEM and EDX of Sabkha Stabilized with 30% CKD and 2% Cement (7-Day Sealed Curing)

The BEI micrograph of sabkha stabilized with 2% cement plus 30% CKD, Figure 4-48 (a), shows dense soil matrix. No voids are visible. The microstructure is denser than that of sabkha with 2% cement alone (Figure 4-47 (a)).

The SEM micrograph of sabkha stabilized with 2% cement plus 30% CKD, Figure 4-45 (b) shows high concentration of the white fibrous cloth-like formations, C-S-H, cementing gel, coating the sand and/or silt particles resulted in improving the UCS of the stabilized sabkha. Individual sand and/or silt grains are embedded within the system. Face to face particle interactions as well as connectors are apparent. EDX indicated that the stabilized soil matrix consists of Na, Mg, Si, Cl, K, Ca and Fe with weight proportion of 0.87, 4.33, 17.94, 1.38, 0.61, 19.00 and 1.47%, respectively. The presence of chloride in the sabkha and in the CKD in addition to the high LOI and high alkalis in the CKD might have hindered the CKD from achieving higher UCS than 1,520 kPa.

4.7.1.4 UCS of Sabkha Stabilized with 2% Cement plus EAFD

Unconfined compression tests were carried out on sabkha treated with 2% cement and on sabkha treated with 2% cement plus EAFD contents ranging from 5 to 30%. The results of the UCS against EAFD content are depicted in Figure 4-49.

A study of Figure 4-49 reveals that 5 and 10% EAFD additions have resulted in a collapse of the UCS of sabkha-2% cement. However, 20 and 30% EAFD additions caused marginal recovery of the UCS of sabkha–2% cement. The UCS was 348, 0, 0, 225 and 325 kPa for 2% cement-stabilized sabkha with 0, 5, 10, 20 and 30% EAFD, respectively.

The trend of the effect of the EAFD on the UCS of sabkha-2% cement was due to the fact that the EAFD contains about 33.3% iron (Fe), 9.4% calcium (Ca) and 2.4% silicon (Si), as shown in Table 4-2. Therefore, in the presence of water, an anodic reaction takes place, when the iron dissolves in the pore water and gives up electrons [Broomfield, 1997; Eglinton, 1987, quoted by Ali, 2004], as is explained in the following equation:

$$Fe \rightarrow Fe^{2+} + e^{+1} \rightarrow Fe^{3+}$$

Consequently, these ironic ions, presented in the EAFD, react with the chloride (Cl) present in the sabkha in the presence of water. The reaction is explained in the following equation [Broomfield, 1997; Elington, 1987, quoted by Ali, 2004; and Montemor et al., 2003], thereby forming hydrochloric acid:

$$Fe^{3+} + 3Cl^{-} + 3H_2O \rightarrow Fe\,(OH)_3 + 3HCl$$

The hydrochloride acid breaks down the bond in the cementing gel, C-S-H, produced by the 2% cement and the amount of the calcium and the silicon in the EAFD. Moreover; the marginal upturn in the UCS took place when the chloride in the sabkha was consumed by iron and due to the agglomeration of sabkha particles caused by the 20 and the 30% EAFD that resulted in the recovery of the UCS of the sabkha with 2% cement plus EAFD mixtures.

The formation of hydrochloric acid was confirmed by measurement of the pH of the EAFD-sabkha mixture, which was carried out in accordance with ASTM D 4972, Method A. Sample of sabkha soil passing sieve #10 was dried in an oven at 70^{o} C till a constant weight was observed. The sabkha plus 2% cement was mixed with 5, 10, 20 and 30% EAFD. Then, 10 g of each mixture was mixed with 10 ml of distilled water and left for one hour. Then the pH was measured. The results show that 5, 10, 20 and 30% EAFD reduced the pH of the sabkha plus 2% cement from 9.93 to 8.16, 8.25, 8.79 and 8.61, respectively.

However, sabkha with 2% cement plus EAFD dosages did not meet the minimum strength, 1,380 kPa, specified by ACI [1990] for the sub-base course pavements. Therefore, EAFD additions with 2% cement failed to work as a stabilizer for sabkha from the strength perspective.

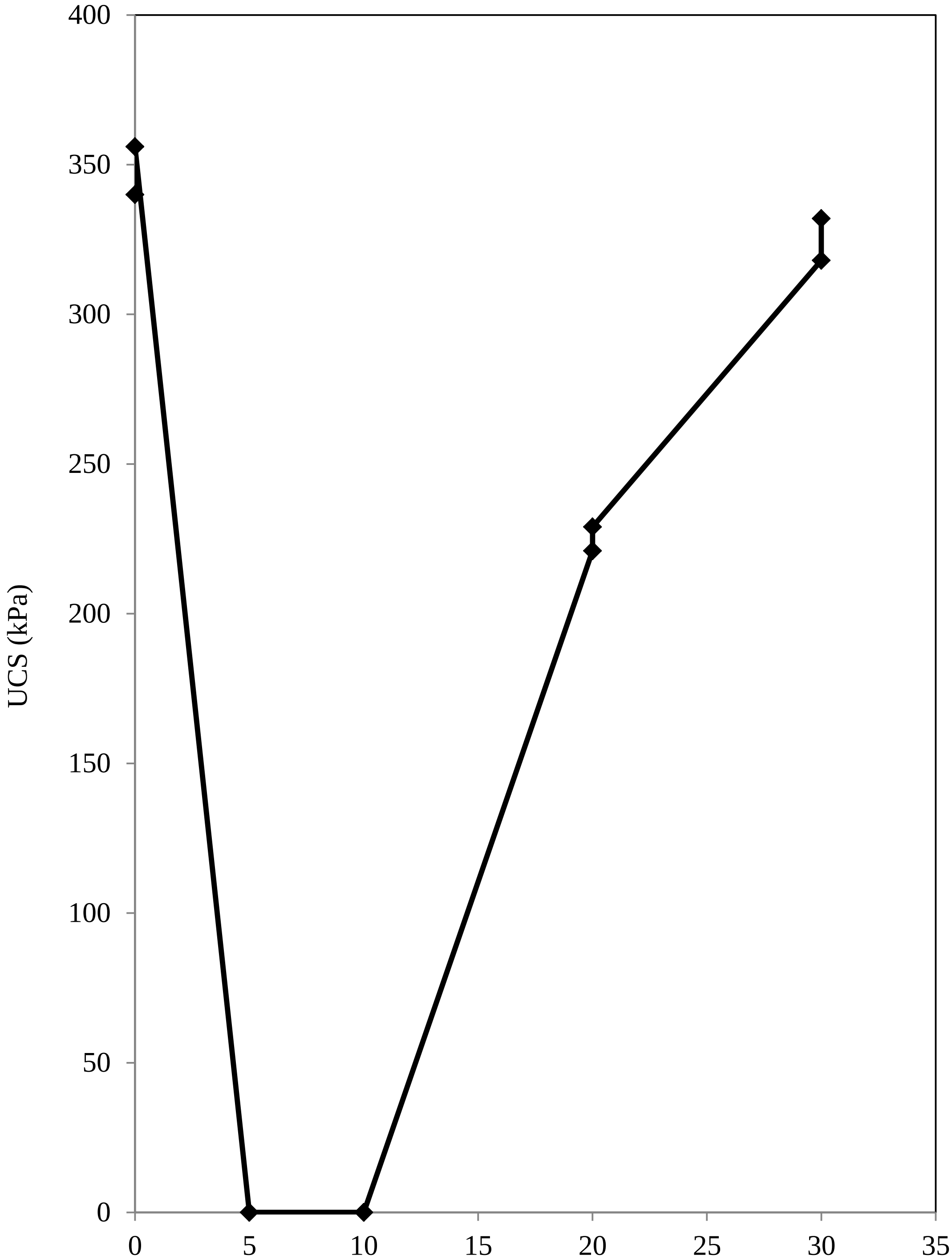


Figure 4-49: Effect of EAFD Content on the UCS of Sabkha with 2% Cement (7-Day Sealed Curing)

4.7.1.5 UCS of Sabkha Stabilized with 2% Cement plus OFA

To study the effect of the OFA contents on the unconfined compressive strength (UCS) of the investigated sabkha plus 2% cement, unconfined compression tests were conducted on sabkha treated with 2% cement and on sabkha treated with OFA contents ranging from 5 to 15% with 2 % cement. The UCS versus OFA contents are depicted in Figure 4-50.

Figure 4-50 shows that the OFA content caused a variation in the UCS of the investigated sabkha-2% cement mixture. The 5 and 10% OFA decreased UCS from 348 kPa to 0 kPa and the 15% OFA reduced the UCS from 348 kPa to 138 kPa, which can be considered as a sort of recovery in the UCS.

Generally; the trend of the effect of OFA content on UCS of sabkha-2% cement is almost similar to the effect of the EAFD content, shown in Figure 4-49. Moreover, the effect of the OFA content on the UCS of sabkha soil follows the same trends for the other two soils, marl and sand, as shown in Figures 4-29 and 4-40.

The effect of 5 and 10% OFA content on the UCS of sabkha-2% cement was due to the fact that the LOI of OFA is very high (60.6 %) and it has very low alkalis (0.55%), as shown in Table 4-3, which retarded the hydration of the 2% cement. Consequently, the strength that is supposed to be developed by the 2% cement (348 kPa) was reduced. Besides; OFA contains about 17.48% magnesium (Mg), as shown in Table 4-3, and the sabkha contains about 10% halite (NaCl). Therefore, the chloride in the sabkha might have reacted with magnesium in the OFA and produced magnesium chloride that caused severe deterioration to the cementitious C-S-H gel more than NaCl or $CaCl_2$, which reacts with the cementitious C–S–H in the cement paste to produce non-cementitious magnesium–silicate–hydrate (M–S–H) and $CaCl_2$ [Reddy et al., 2011; and Mussato et al., 2004] as per the following reaction:

$$MgCl_2 + C\text{-}S\text{-}H \rightarrow M\text{-}S\text{-}H + CaCl_2$$

Further, the formation of soluble $CaCl_2$ might have caused strength loss.

As OFA has very low alkalis (0.55), as shown in Table 4-3, so the more amount of OFA is, the more amount of the water needed for the lubrication, activates the hydration of the 2% cement [Kolay et al., 2011; and Edil et al., 2006;]. The more water resulted in upgrading of the unconfined compressive strength of sabkha – 15% OFA-2% cement mixture. However, the improvement made by the 15 % of OFA was negligible and the UCS was still lower than the UCS achieved by adding 2% cement to sabkha alone.

Therefore, the OFA with 2% of cement is not a successful stabilizer for sabkha soil.

Summary, the relations in Equations 4.17 through 4.19 can be considered reliable, as the value of correlation coefficient (R^2) is 0.99, 0.92 and 1, respectively. The developed relations are useful for estimating the required amount of the stabilizers cement, CKD and CKD plus 2% cement for sabkha to gain the desired UCS after 7-day sealed curing

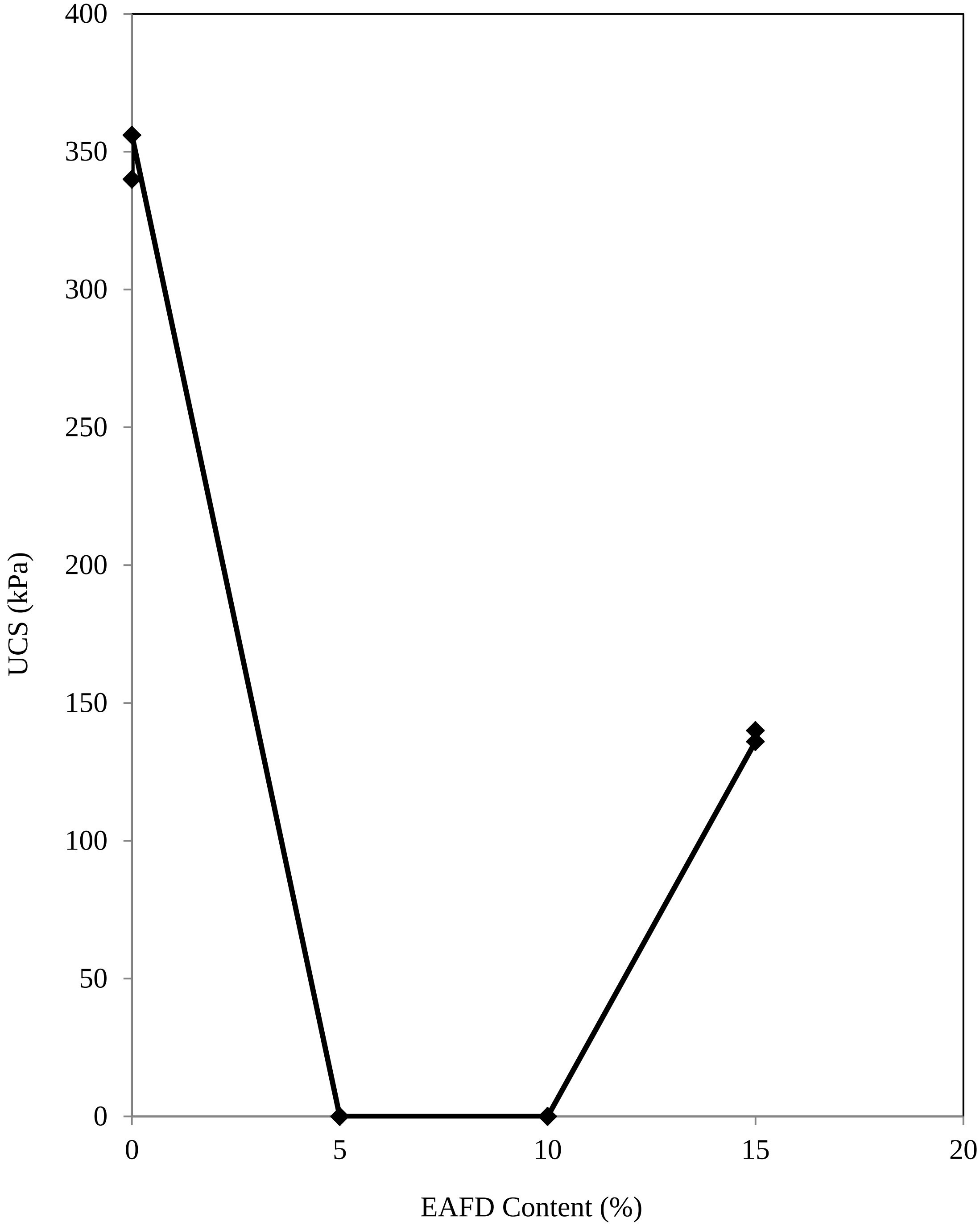


Figure 4-50: Effect of OFA Content on the UCS of Sabkha with 2% Cement (7-Day Sealed Curing)

The results of the unconfined compression test on treated and untreated sabkha are summarized in Table 4-16. The data therein indicate that the UCS of the plain sabkha, 150 kPa, is greater than the UCS of the plain marl, 61 kPa. Though both sabkha and marl soils are classified SM and A-3 according to the USCS and the AASHTO systems, respectively, the low UCS of plain marl could have been due to the high calcite content in the marl [Mohamedzain and Al-Rawas, 2011].

Additionally; the data in Table 4-16 show that the improvements in the strength of the investigated-stabilized sabkha developed by the indicated stabilizers are lower than the strength improvements for the stabilized marl. That was attributed to the presence of the halite and gypsum in the sabkha and the presence of the calcite and fine particles in the marl soil.

Moreover; the data in Table 4-16 indicate that sabkha treated with 7% cement and that stabilized with 2% cement plus 30% CKD satisfied the ACI strength requirement for sub-base in rigid pavements. The addition of 30% CKD decreases the quantity of cement from 7 to 2% cement, a reduction of 5% cement. This will lead to economic and environmental benefits.

Table 4-16: Results of the Unconfined Compression Tests of Sabkha

Additive Type and Content	**UCS (kPa)**		
	Specimen # 1	Specimen # 2	Average
Plain Sabkha (No Additive)	145	155	150
2% Cement	340	356	348
5% Cement	880	916	898
7% Cement	1,481	1,489	1,485
10% CKD	259	265	262
20% CKD	872	880	676
30% CKD	968	980	974
2% Cement + 10% CKD	518	542	530
2% Cement + 20% CKD	887	897	892
2% Cement + 30% CKD	1,516	1,522	1,519
2% Cement + 5% EAFD	0	0	0
2% Cement + 10% EAFD	0	0	0
2% Cement + 20% EAFD	221	229	225
2% Cement + 30% EAFD	318	332	325
2% Cement + 5% OFA	0	0	0
2% Cement + 10% OFA	0	0	0
2% Cement + 15% OFA	136	140	138

4.7.2 Results of the Soaked CBR Tests for Stabilized Sabkha

Specimens of the investigated sabkha were prepared with the dosages of selected stabilizers that satisfied the minimum strength requirements of ACI [1990], and they were subjected to soaked CBR tests. Further, specimens of plain sabkha and with 2, 5 and 7% cement were also tested according to ASTM D 1883. The specimens were sealed and cured for 7 days at laboratory condition (22 ± 3^{o}C). Then, they were soaked in tap water for 96 hours before testing. The effect of each stabilizer on the soaked CBR of sabkha is discussed in the following sub-sections.

4.7.2.1 CBR Tests Results of Sabkha Stabilized with Cement

In order to study the correlation between cement addition and the soaked CBR of sabkha, soaked CBR tests were carried out on sabkha-cement mixtures and on plain sabkha. The plain sabkha was taken as a reference. The results are presented in Figure 4-51.

The data in Figure 4-51 indicate that as the cement content in sabkha increases, the soaked CBR increases. The addition of 2, 5 and 7% cement improved the soaked CBR from 11% to 52, 137 and 248%, respectively. A linear relationship was noted between the soaked CBR and cement content in sabkha. The relationship can be expressed by the following relationship:

$$\text{Soaked CBR (\%)} = 30.4*X + 11 \qquad R^2 = 0.94 \qquad (4.20)$$

Where:

CBR = California bearing ration of cement- stabilized sabkha, 7-day sealed curing (%).

X = Cement content (%).

R^2 = Correlation coefficient.

Furthermore, all of the investigated cement contents, in this study, improved the soaked CBR of the investigated sabkha soil to be excellent for base-course in pavements.

Shabel [2006] conducted immediate (without curing) CBR tests on the stabilized sabkha he studied. The addition of 5, 7.5, 10 and 15% cement improved the CBR of sabkha from 51% to 56, 37, 30 and 28%, respectively. It can be noticed that the immediate CBR of the plain sabkha was 51% but in this study the soaked CBR of the plain sabkha is 11% which indicates that the sabkha is very sensitive to water.

The results of the present study indicate that sabkha with 7% cement that satisfied the minimum strength requirement specified by ACI [1990] ,1,380 kPa, is suitable for use in rigid pavement as a sub-course from strength and CBR perspective.

4.7.2.2 CBR Tests Results of Sabkha Stabilized with 2% Cement plus CKD

For studying the effect of CKD content on the soaked CBR of sabkha plus 2% cement, soaked CBR tests were carried out on sabkha with 10, 20 and 30% CKD by dry weight of soil. The results are reported in Figure 4-52. It is evident from the data Figure 4-52 that the soaked CBR increases with an increase in the quantity of CKD. The addition of 10, 20 and 30% CKD to sabkha plus 2% cement, improved the soaked CBR from 11% to 55, 95 and 129%, respectively. Further, the data in this figure reveal that there is an exponential relationship between soaked CBR and the CKD content which can be expressed by the following relationship:

$$\text{Soaked CBR (\%)} = 46.79 * e^{0.033X} \qquad R^2 = 0.87 \qquad (4.21)$$

Where:

CBR = California bearing ratio of sabkha stabilized with 2% cement and varying quantity of CKD, 7-day sealed curing, (%).

X = CKD content (%)

R^2 = Correlation coefficient.

The results of soaked CBR show that addition of 20% or 30% CKD to sabkha plus 2% cement enables it to satisfy the requirement for treated sabkha to be used as base–course in pavements.

Sabkha stabilized with 30% CKD plus 2% cement is appropriate for use as a sub-base in rigid pavements from strength and soaked CBR perspective.

It is worth mentioning that Shabel [2006] conducted immediate CBR tests on sabkha stabilized with CKD. The addition of 5, 7.5, 10 and 15% CKD improved the CBR of sabkha from 51% to 56, 75, 50 and 70%, respectively.

In summary; the correlations in Eq. 4.20 and 4.21 can be considered reliable, as the value of the correlation coefficient (R^2) is 0.94 and 87, respectively. The developed relations are useful for estimating the required quantity of the stabilizer to enable sabkha to meet the minimum soaked CBR requirement.

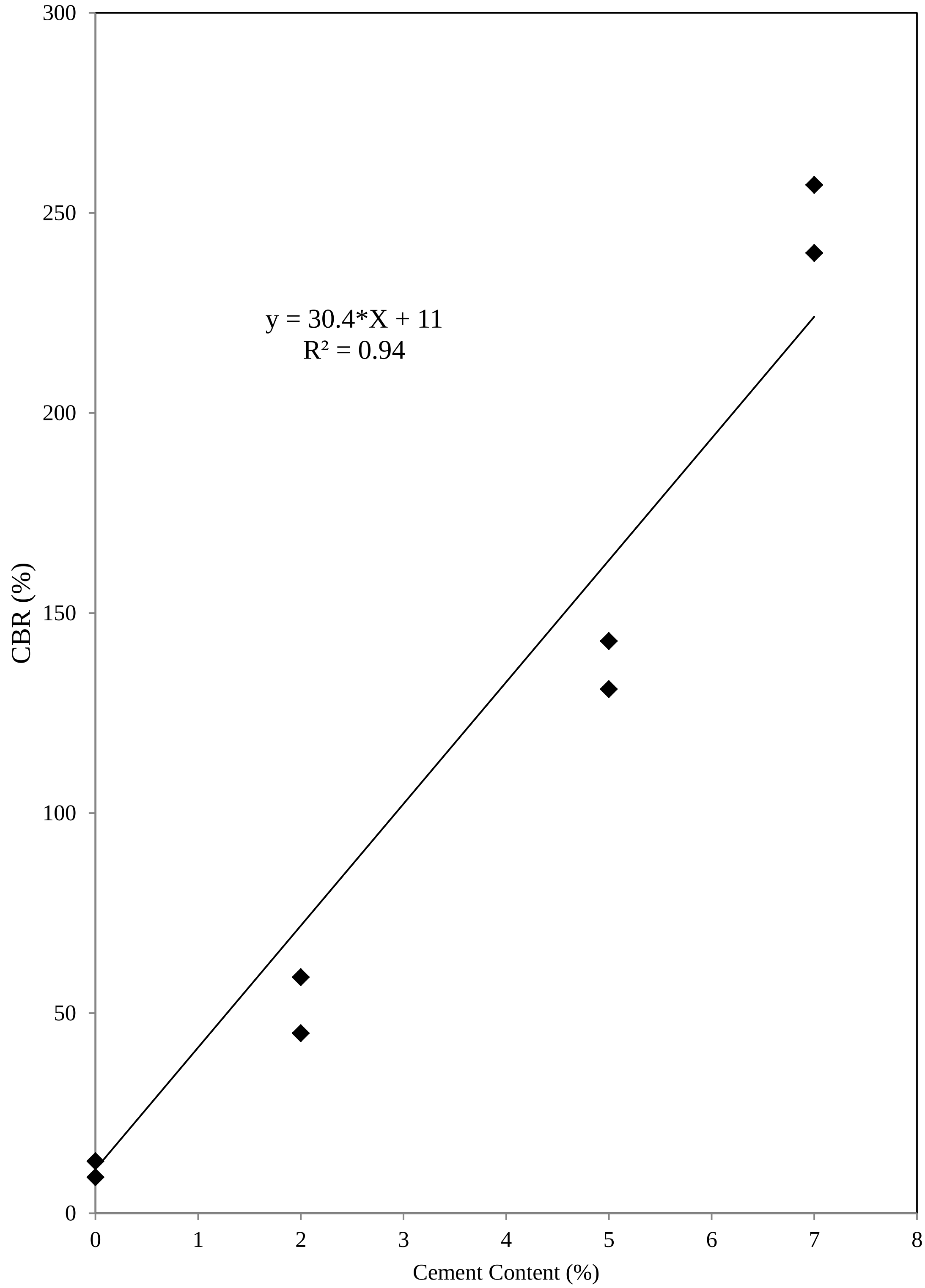


Figure 4-51: Effect of Cement Content on Soaked CBR of Sabkha (7-Day Sealed Curing)

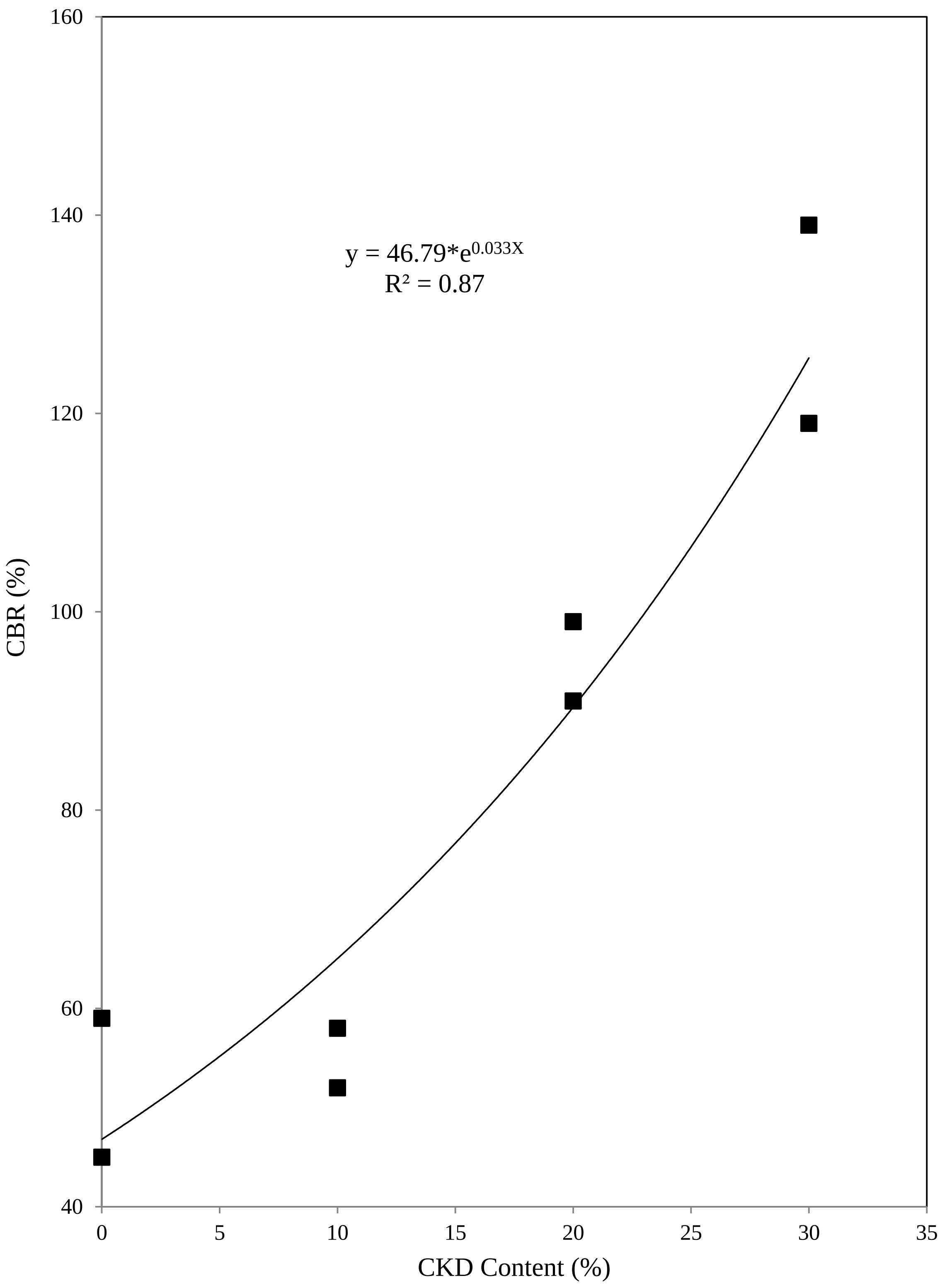


Figure 4-52: Effect of CKD Content on Soaked CBR of Sabkha with 2% Cement (7-Day Sealed Curing)

The results of the soaked CBR tests on sabkha are summarized in Table 4-17.

The data in Table 4-17 indicate that the stabilization of sabkha with cement content of 2, 5 and 7% increased the soaked CBR from 11% to 52, 137 and 248%, respectively. The soaked CBR of sabkha with 2% cement plus 10, 20 or 30% CKD was 55, 95 and 129%, respectively. It is obvious that the soaked CBR result of plain sabkha, 11%, was very low, due to the sensitivity of sabkha to water, less than 20%, to be used as a sub-base course in pavements.

Table 4-17: Results of Soaked CBR of Stabilized Sabkha

Stabilizer Type and Content	**UCS (kPa)**	**Soaked CBR (%)**		
		Specimen#1	Specimen#2	Average
Plain Sabkha (No Additive)	150	9	13	11
2% Cement	348	45	59	52
5% Cement	898	131	143	137
7% Cement	1,485	240	256	248
2% Cement + 10% CKD	530	52	58	55
2% Cement + 20% CKD	892	91	99	95
2% Cement + 30% CKD	1,519	119	139	129

4.7.3 Results of Durability Tests on Stabilized Sabkha

Durability tests were performed to check whether the investigated sabkha stabilized with the selected stabilizers will maintain its stability during long-term exposure to harsh environment. These tests were conducted only on the mixtures that met the strength requirement. Since sabkha mixed with 30% CKD plus 2% cement and that stabilized with only 7% cement met the strength requirements, durability tests were performed on these two mixes in accordance with ASTM D 559 only on these two mixtures.

The specimens were prepared using the optimum water content determined in the compaction tests. Two specimens were prepared for each mixture. After compaction, the specimens were cured in plastic bags at room temperature for 7 days. The weight loss was determined after 12 cycles of wetting/drying and brushing. The results indicate that for the sabkha soil stabilized with 7% cement, the weight loss was about 8.4% and for the sabkha stabilized with 30% CKD plus 2% cement, the weight loss was about 10.5%. The measured weight loss is less than the maximum allowable weight loss of 14% according to the Portland Cement Association (PCA) and of 11% according to USA Corps of Engineers (USACE) for soils classified as SP and soils having plasticity index (PI) < 10, respectively, ACI [1990].

Therefore, sabkha stabilized with 7% cement or with 30% CKD plus 2% cement can be used as a construction material for sub-base in rigid pavements from strength and durability perspective. However, the use of 30% CKD plus 2% cement will reduce the cement by 5%, which, in turn, lead to economic and environmental benefits.

4.8 Correlation between Soaked CBR and UCS for the Investigated Soils

The CBR is an indicator of strength and bearing capacity of soil which is widely used in the design of pavement layers. Cement stabilized soils are often used for the construction of these layers. The CBR is, therefore, a common indicator test used to evaluate the strength of soils for these applications.

The data in Tables 4-8, 4-13 and 4-17, of the UCS and the soaked CBR for each of the three investigated soils were utilized to develop correlations between UCS and soaked CBR. These correlations are discussed for each of the investigated soil in the following sub-sections.

4.8.1 Correlation between Soaked CBR and UCS for Marl

The data in Figure 4-53 represent the UCS and soaked CBR results for plain marl and marl stabilized with cement, CKD plus 2% cement and with EAFD plus 2% cement. A linear correlation was noted between UCS and soaked CBR. The relationship can be expressed by the following equation:

Soaked CBR (%) = 0.14 * UCS (kPa) + 11 $\qquad R^2 = 0.88 \qquad$ (4.22)

Where:

UCS = Unconfined compressive strength of stabilized marl at 7-day sealed curing, kPa.

CBR = California bearing ratio of stabilized non-plastic marl at 7-day sealed curing.

R^2 = Correlation coefficient.

The UCS-Soaked CBR correlation model (Equation 4.22) for the investigated non-plastic marl was used to best-fit all the data with coefficients of determination (R^2) value of about 0.88. Since R^2 value is relatively high (i.e., more than 0.80), the data could be considered as reliable [Montgomery, 2009].

The high value of R^2 for the UCS-soaked CBR correlation suggests that this relationship is valid for the untreated as well as for marl treated with either cement, CKD with 2% cement or EAFD with 2% cement. This type of relationship is useful since the soaked CBR can be assessed by knowing the UCS values.

4.8.2 Correlation between Soaked CBR and UCS for Sand

The data in Figure 4-54 depict the relationship between UCS and soaked CBR for dune sand stabilized with cement, CKD plus 2% cement or with EAFD plus 2% cement. A linear correlation between UCS and soaked CBR can be expressed by the following best-fit model:

$$\text{Soaked CBR (\%)} = 0.25 * \text{UCS (kPa)} + 103 \qquad R^2 = 0.83 \qquad (4.23)$$

Where:

UCS = Unconfined compressive strength of stabilized sand at 7-day sealed curing, kPa.

CBR = California bearing ratio of stabilized dune sands at 7-day sealed curing.

R^2 = Correlation coefficient.

The UCS-soaked CBR correlation model (Equation 4.23) for the investigated dune sands was used to best fit all the data with a coefficient of determination (R^2) value of about 0.83. Since R^2 value is more than 0.80, the relation (4.23) can be considered reliable.

The high value of R^2 (> 0.80) for the UCS-soaked CBR correlation suggests that this relationship is valid for the stabilized dune sand soils treated with either cement, 2% cement plus CKD or 2% cement plus EAFD. This type of relationship is useful in determining the soaked CBR when the UCS is known.

4.8.3 Correlation between Soaked CBR and UCS for Sabkha

The data in Figure 4-55 represent the UCS and soaked CBR results for plain sabkha and also for sabkha stabilized with cement or with 2% cement plus CKD up to 30% by weight of dry sabkha. A linear correlation was noted which can be expressed by the following best-fit model:

$$\text{Soaked CBR (\%)} = 0.13 * \text{UCS (kPa)} \qquad R^2 = 0.76 \qquad (4.24)$$

Where:

UCS = Unconfined compressive strength of stabilized sabkha at 7-day sealed curing, kPa.

CBR = California bearing ratio of stabilized sabkha at 7-day sealed curing.

R^2 = Correlation coefficient.

Since the coefficient of determination (R^2) value is relatively low (< 0.80), the relationship cannot be considered as reliable [Montgomery, 2009].

The scatter in the data in Figure 4-55 may be attributed to the fact that soaked CBR tests was used and due to the high sensitivity of the sabkha to inundation, the UCS results did not correlate well with that of the soaked CBR tests results.

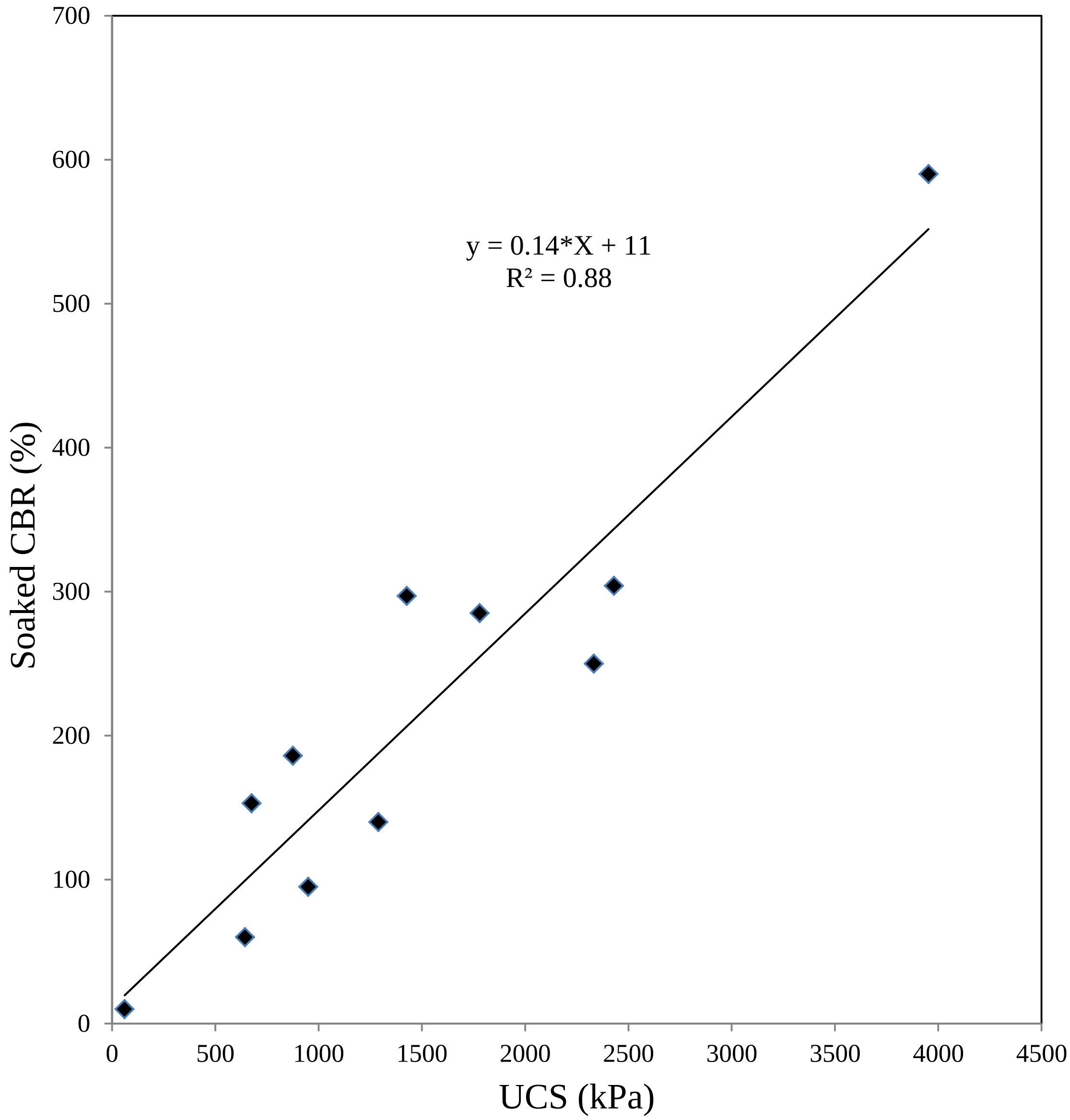


Figure 4-53: Correlation between Soaked CBR and UCS for Marl (7-Day Sealed Curing)

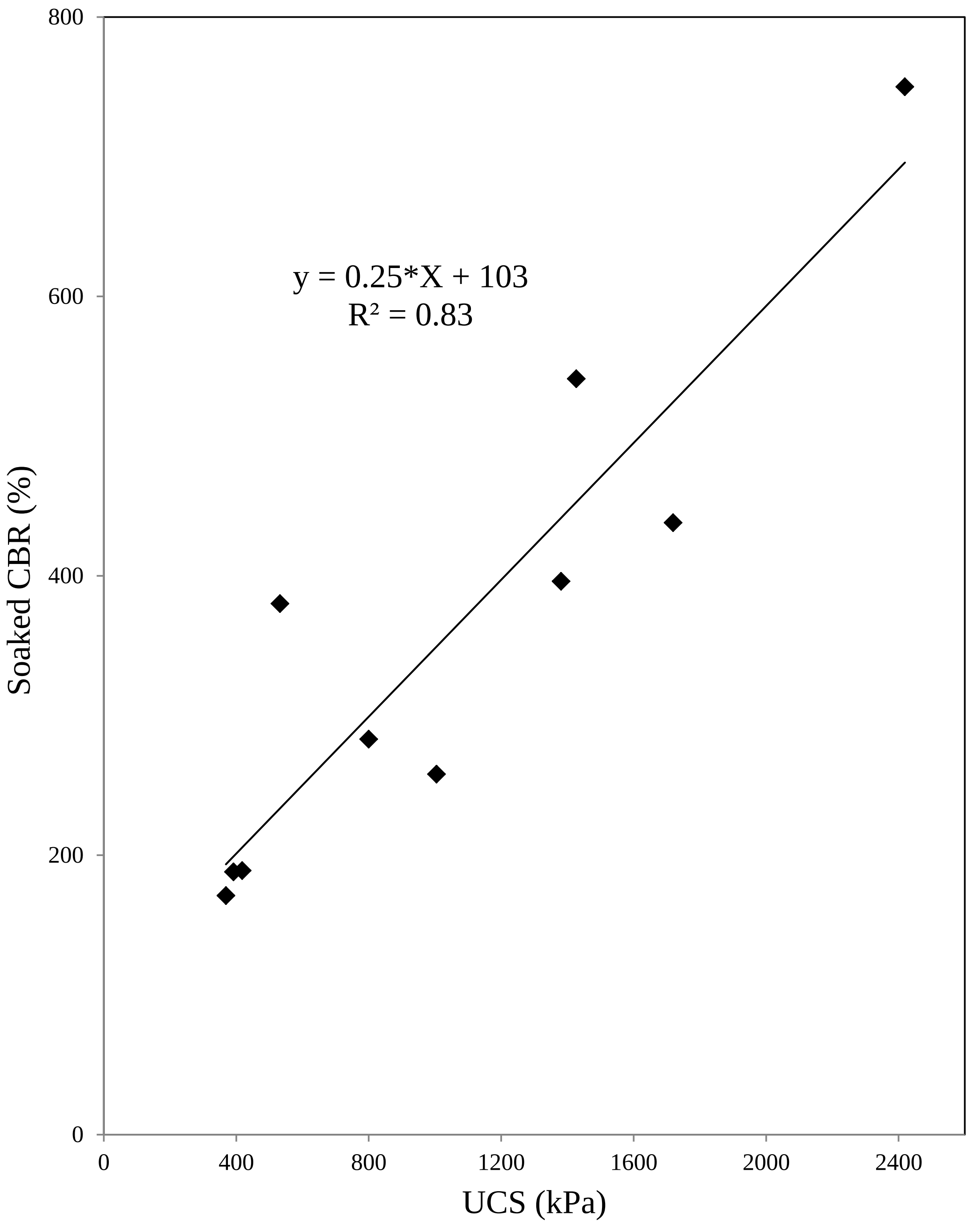


Figure 4-54: Correlation between Soaked CBR and UCS for Sand (7-Day Sealed Curing)

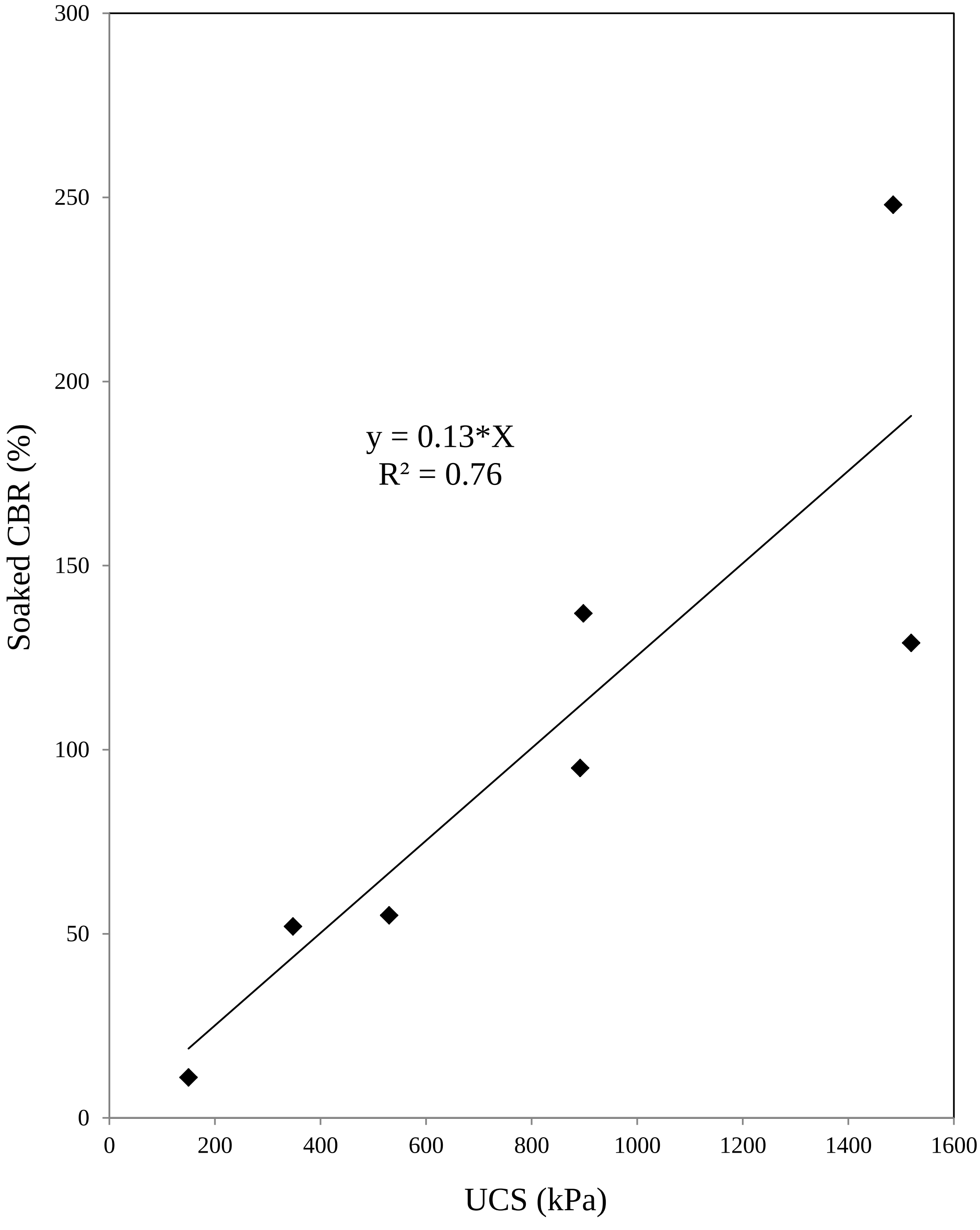


Figure 4-55: Correlation between Soaked CBR and UCS for Sabkha (7-Day Sealed Curing)

4.9 Summary of the Results of the Stabilized Soils

The stabilized soils that met the strength requirements and satisfied the durability limits are summarized in Table 4-18.

The data in Table 4-18 summarize the general findings of this investigation. This table helps engineers to choose the appropriate stabilizer and dosage to stabilize eastern Saudi soils to be used as effective construction materials in pavement construction. For estimating the quantity of each stabilizer(s) required for stabilizing soils with desired strength, the models developed in Equations 4.1 through 4.22 can be used as described in Sections 4.7 through 4.7.

Table 4-18: Summary of the Stabilized Soils

Stabilizer Types and Contents	**Soil**	**layer**	**Pavement**
7% Cement	Non-Plastic Marl	Base	Rigid
	Sabkha and Sand	Sub-base	Rigid
5% cement	Non-Plastic Marl	Sub-base	Flexible
2% Cement + 30% CKD	Non-Plastic Marl	Sub-base	Flexible
	Sand and Sabkha	Sub-base	Rigid
2% Cement + 20% EAFD	Non-Plastic Marl and Sand	Sub-base	Rigid
2% Cement + 30% EAFD	Non-Plastic Marl and Sand	Sub-base	Flexible

4.10 Economic Advantage

It is well known that cement, being the most commonly used conventional soil stabilizing agent, is not only expensive but also its production consumes a lot of energy. Further, the manufacturing process of cement results in greenhouse gases that is not environment-friendly. Therefore, there are concerted efforts worldwide to use materials other than cement for construction purposes. However, the used materials have to be cost effective and eco-friendly.

Since only flexible pavements are used in Saudi Arabia, cost estimate for producing 100 m^3 of stabilized soils in sub-bases in flexible pavements, utilizing cement, 2% cement plus CKD or EAFD was conducted. The amount of stabilizers required to satisfy an UCS of 1,725 kPa was predicted using the models developed for each stabilizing material (Equations 4.1 through 4.22). The project site (where the pavement was assumed to be constructed) was located in Dhahran area. The price of one ton of cement was assumed to be SR 300. Other materials, such as CKD and EAFD were considered for free (as waste materials) with loading cost of 5 SR/ton and transportation cost of 10 SR/ton. The transportation cost of material from Jubail to the site was estimated to be SR 300 for a truck of 30 ton capacity. The dry unit weight was either interpolated or taken from the data in Table 4-5.

Table 4-19 shows the amount of cement required to achieve UCS of 1,725 kPa for non-plastic marl, dune sand and sabkha using or extrapolating Equations 4.1, 4.9 and 4.7, respectively. The cost of cement required to stabilize 100 m^3 of these soils for use in sub-base of flexible pavements was estimated. The cost of cement in marl, sand and sabkha was SR 1,980, 4,130 and 4,390, respectively.

Table 4-19: Cost of Cement for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	Cement	Cement	Cost
	ton/m^3	m^3	(%)	(ton)	SR
Non-Plastic Marl	1.89	100	3.5	6.62	1,980
Dune Sand	1.72	100	7.5	13.76	4,130
Arabian Gulf Sabkha	1.95	100	8	14.63	4,390

The amount of soils (marl, sand and sabkha) was estimated considering the volume of CKD added to soils in order to have total volume of stabilized soils of 100 m^3. Equations 4.3, 4.11 and 4.19 were used or extrapolated to determine the amount of CKD to stabilize the three soils to gain 1,725 kPa. The material cost of 100 m^3 of marl, sand and sabkha stabilized with 2% cement plus CKD is shown in Table 4-20. The cost is SR 1,590, 1,690 and 1,625, respectively. Comparing the cost of stabilization with only cement (Table 4-19), to that utilizing 2% cement plus CKD (Table 4-20) it is evident that the use of CKD would lead to saving of 20, 60 and 63% for marl, sand and sabkha, respectively.

Table 4-20: Cost of 2% Cement plus CKD for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	CKD	2% Cement	CKD	Cost	Reduction
	ton/m^3	m^3	(%)	(ton)	(ton)	SR	(%)
Non-Plastic Marl	2	80	30	3.02	45.4	1,590	20
Dune Sand	2	85	37	2.92	54.1	1,690	60
Arabian Gulf Sabkha	1.9	75	34	2.93	49.7	1,625	63

Similarly; the quantity of EAFD required for stabilizing marl and sand (sabkha soil with EAFD failed to satisfy the strength requirement) was determined by utilizing Equations 4.4 and 4.12, respectively. Table 4-21 shows the materials and cost of 100 m^3 of marl and sand stabilized with 2% cement plus EAFD. The cost is SR 1,690 and 1,620, respectively. Comparing the cost of stabilizing the investigated soil with only cement (Table 4-19) to that utilizing 2% cement plus EAFD (Table 4-21), it could be easily noted that the use of EAFD leads to saving of 15 and 61% for marl and sand, respectively.

Table 4-21: Cost of 2% Cement plus EAFD for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	EAFD	2% Cement	EAFD	Cost	Reduction
	ton/m^3	m^3	(%)	(ton)	(ton)	SR	(%)
Non-Plastic Marl	2.2	93	24	3.52	42.2	1,690	15
Dune Sand	2.2	95	26	3.27	42.5	1,620	61

Note: EAFD did not improve the UCS of sabkha

Therefore, reducing the amount of cement required for stabilizing the three indigenous soils was the direct benefit of using by-products in the stabilization of local soils. Furthermore, there are indirect benefits of using by-products in stabilization of weak soils. Reducing the needed energy for producing cement contributes to mitigating the amount of the greenhouse gases and the consequent positive environment effects. Moreover, while some by-products contain volatile gases which cause air pollution, other contains heavy metals which cause land and ground water contamination. Consequently, the disposal of these by-products is costly. Therefore, using contaminant by-products for soil stabilization will result in avoiding the disposal cost and in meeting the environmental requirements. Consequently, the priceless outcome of using theses waste materials in stabilizing indigenous eastern Saudi soils is keeping sound-environment.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research was designed to stabilize three eastern Saudi soils, namely non-plastic marl, dune sand and sabkha. The potentiality of using stabilizers, cement, as a reference, and other industrial by-products in improving the properties of these soils was investigated. The stabilizing by-products included oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD).

Characterization of the investigated soils was performed including specific gravity, Atterberg limits, grain-size distribution and mineralogical composition. Further, specific gravity and chemical composition of the candidate stabilizers were determined.

The optimum moisture content corresponding to the maximum dry density of the investigated soils without and with the proposed dosages of the three stabilizers was determined using the modified Proctor compaction. Specimens of parent and stabilized soils were prepared with the optimum moisture content. The evaluation of the improvement of the three soils was performed by macro-characterization and micro-characterization techniques.

Macro-characterization study including unconfined compression, soaked CBR and durability tests were conducted to assess the engineering properties of treated and untreated soils. The environmental impact of the stabilizers containing toxic elements and succeeded to improve the soils to meet the ACI requirements for usage in pavement structures was studied using TCLP tests.

Micro-characterization study using XRD and/or SEM devices was utilized to depict qualitatively the mechanisms of improvement of the soils by the additives.

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

(i) Cement was found to be superior in stabilizing the three local soils from strength and durability points of view.

(ii) As the CKD and the EAFD contents plus 2% cement increased, the strength and the soaked CBR of stabilized marl and sand increased.

(iii) CKD content alone was not adequate for effective stabilization of dune sand, non-plastic marl and sabkha soils. Even 30% CKD did not meet the ACI strength requirements.

(iv) Micro-characterization techniques utilizing BEI and SEM showed, in the case of using 2% cement plus CKD in stabilizing the three soils, more fibrous formations in the three stabilized soils than that with 2% cement alone which contributed to the high improvement in the UCS to meet the ACI requirements.

(v) The stabilized soils with any stabilizer that satisfied the minimum strength and CBR requirements satisfied also the durability requirements.

(vi) 20 and 30% EAFD with 2% cement were adequate for effective stabilization of non-plastic marl and sand to be used as construction material for sub-base in rigid and flexible pavements.

(vii) Ankerite and wustite formations in marl stabilized with 2% cement plus EAFD were found to be the primary cementing product in theses mixtures.

(viii) Wustite formation in sand stabilized with 2% cement plus EAFD was found to be the principal cementing product in theses mixtures.

(ix) None of the EAFD contents plus 2% cement was effective in the stabilization of sabkha.

(x) OFA plus 2% cement was not a suitable stabilizer for any of the investigated eastern Saudi soils.

(xi) TCLP tests results indicated that the investigated industrial by-products that satisfied the strength requirements were eco-friendly within the dosages reported herein.

(xii) Economic analysis indicated that the use of these industrial by-products for stabilizing eastern Saudi soils is cost effective, particularly for stabilizing sand and sabkha soils.

5.2 Recommendations

- 7% cement was found to be the proper stabilizer for dune sand and sabkha to be used as a sub-base course in rigid pavements and for non-plastic marl to be used as a base course in rigid pavements.

- 5% cement was a suitable stabilizer for non-plastic marl to be used as a sub-base in flexible and rigid pavements.
- A CKD content of 30% plus 2% cement was found to be adequate for the effective stabilization of non-plastic marl soils to be used as a base course in flexible pavements and of dune sand and sabkha soils to be used as a sub-base course in rigid pavements. It met the strength and durability requirements.
- EAFD contents of 20 and 30% plus 2% cement were found to be adequate for the effective stabilization of dune sand and non-plastic marl soils to be used as a sub-base in rigid and flexible pavements, respectively.
- The developed correlative equations between the stabilizer type and content with the UCS and the soaked CBR of the stabilized soils are summarized in Tables 5-1 through 5-3. These equations help the practicing engineers select and estimate the appropriate dosage of the industrial by-product(s) in terms of strength and soaked CBR.

Table 5-1: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Non-Plastic Marl (7-Day Sealed Curing)

Stabilizer Type	**Non-Plastic Marl**	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$509.8 * X + 61$, $R^2 = 0.96$	$13.12 * e^{0.569X}$, $R^2 = 0.97$
2% Cement + CKD	$657.76 * e^{0.034X}$, $R^2 = 0.99$	$56.88 * e^{0.051X}$, $R^2 = 0.96$
2% Cement + EAFD	$523.32\ e^{0.051X}$, $R^2 = 1$	$8.08 * X + 95$, $R^2 = 0.89$
Soaked CBR (%) = 0.14* UCS (kPa) +11, $R^2 = 0.88$		

Table 5-2: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Dune Sand (7-Day Sealed Curing)

Stabilizer Type	**Dune Sand**	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$228.12*X$, $R^2 = 0.97$	$113.7*e^{0.184X}$, $R^2 = 0.95$
2% Cement + CKD	$321.72*e^{0.046X}$, $R^2 = 0.94$	$157.9*e^{0.029X}$, $R^2 = 0.94$
2% Cement + EAFD	$313.94*e^{0.068X}$, $R^2 = 0.97$	$176.15*e^{0.052X}$, $R^2 = 0.92$
Soaked CBR (%) = 0.25* UCS (kPa)+103 , $R^2 = 0.83$		

Table 5-3: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Sabkha (7-Day Sealed Curing)

Stabilizer Type	**Sabkha**	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$164.19*e^{0.326X}$, $R^2 = 0.99$	$30.4*X + 11$, $R^2 = 0.94$
2% Cement + CKD	$336.8*e^{0.049X}$, $R^2 = 1$	$46.79*e^{0.033X}$, $R^2 = 0.87$
Soaked CBR (%) = 0.13* UCS (kPa) , $R^2 = 0.76$		

Conditions for Tables 5-1 through 5-3:

- X is the weight content of stabilizer to the dry weight of soil (%).
- The mixtures are to be prepared at the optimum moisture contents using modified Proctor compaction energy.

5.3 Future Research

Following are the recommendations for future research:

- The potentiality of using EAFD with more than 2% cement for qualifying non-plastic marl and dune sand soils to be used as a base course in flexible pavements should be studied.

- The potentiality of using CKD with more than 2% cement to upgrade the three soils to satisfy the strength requirements specified by ACI [1990] for base materials in flexible pavements.

- The usage of these stabilizing agents in low traffic volume roads, embankments, rail roads, etc., should be investigated.

- The usage of CKD from other sources (with various LOI and chloride concentration) in the stabilization of local soils should be investigated.

- This investigation was concerned with the requirements of pavement structures. Therefore, it was based on determining UCS, CBR and durability of stabilized soils. The effect of these by-products on other geotechnical properties of soils (i.e. cohesion and angle of internal friction) should be investigated.

REFERENCES

Abdullah, G. M. S., "Stabilization of eastern Saudi soils using heavy fuel oil fly ash and cement kiln dust", *MS. Thesis, Department of civil Engineering, King Fahd University of Petroleum and Minerals*, Dhahran, Saudi Arabia, 2009.

Abu-Taleb, M.G. and Egeli, I., "Some geotechnical problems in the Eastern Province of Saudi Arabia", *Proceedings, Symposium on Geotechnical Problems in Saudi Arabia, King Saud University,* Riyadh, vol. II, pp. 799-811, 1981.

ACI Committee, "State-of-the-art," report on soil cement, *ACI Cement Committee 230", Materials Journal*, Vol. 87, No.4, July-August 1990.

Ahmed, H.R.,"Characterization and stabilization of Eastern Saudi marls", *MS. Thesis, Department of civil Engineering , King Fahd University of Petroleum and Minerals,* Dhahran, Saudi Arabia, 1995.

Aiban,S.A., "A study of sand stabilization in Eastern Saudi Arabia ", *engineering geology* , Vol. 38, pp. 65-79, 1994b.

Aiban, S.A., "Strength and compressibility of Abqaiq Marl, Saudi Arabia", *Eng. Geol.*, Vol. 39, pp. 203–315, 1995.

Aiban, S.A, Al-Abdul Wahhab, H.I. and Al-Amoudi, O.S.B., "Identification, evaluation and improvement of Eastern Saudi soils for construction purposes", *final report,* King Abdulaziz City for Science and Technology (KACST AR-14-61), Riyadh, Saudi Arabia, 1998.

Aiban,S.A., Al-Ahmadi, H.M., Asi, I.M. , Siddique, Z.U. and Al-Amoudi, O.B., "Effect of geotextile and cement on the performance of sabkha sub-grade", *Building and Environment*, Vol. 41 , pp. 807–820, 2006.

Aiban, S.A., Al-Amoudi, O.S.B., Al-Abdul Wahhab, H.I. and Ahmed, H.R. ,"Characterization and properties of eastern Saudi calcareous sediments", *Proceedings of the second international conference on engineering for calcareous soils,* Manama, Bahrain, pp. 371–81, 1988.

Aidan, C. and Trevor, C., "Cement kiln dust", *Concrete*, pp. 40-42, October 1995.

Al-Aghbari, M.Y. and Dutta, R.K., "Effect of cement and cement by-pass dust on the engineering properties of sand", *An International Conference on Geotechnical Engineering*, Vol. 2, pp. 425-431, 2008.

Al-Amoudi, O.S.B., "A review of the geotechnical and construction problems in sabkha environment and methods of treatment", *The Arabian journal for Sciences and Engineering*, Vol. 20, No. 3, pp. 405-432, July 1995a.

Al-Amoudi, O. S. B., "Characterization and chemical stabilization of Al-Qurayyah sabkha soil", *ASCE Journal of Materials in Civil Engineering*, Vol. 14, No. 6, pp. 478-484, 2002.

Al-Amoudi, O.S.B.,"Chemical stabilization of sabkha soils at high moisture contents", *Engineering geology*, Vol. 36, pp. 279-291, 1994.

Al-Amoudi, O.S.B., "Soil stabilization and durability of reinforced concrete in Sabkha environments", *Proc. 4th Engineering Conference, King Abdulaziz University*, Jeddah, Vol. II, pp. 313-338, 1995b.

Al-Amoudi, O.B., "Studies on soil-foundation interaction in the sabkha environment of the Eastern Province of Saudi Arabia", *Ph.D. Dissertation, Department of Civil Engineering, King Fahd University of Petroleum and Minerals*, Dhahran, Saudi Arabia, Vol. I and II, 1992.

Al-Amoudi, O.S.B.," Usage of cement kiln dust for the stabilization of Eastern Saudi soils", *An International Conference on Geotechnical Engineering*, Singapore, 11-13 December 2006.

Al-Amoudi, O.S.B, El-Naggar, Z.R. and Siyed,I.M., "The sabkha in the Kingdom of Saudi Arabia and its engineering problems", *Al-Muhandis (The Engineer),* Vol. 6, Issue. 2, pp. 56-62 (In Arabic), 1992.

Al-Amoudi, O.S.B., Khan, K. and Al-Kahtani, N. S., "Stabilization of a Saudi calcareous marl soil", *Construction and Building Materials*, Vol. 24, pp. 1848–1854, 2010.

Al-Amoudi, O.S.B. and Abduljauwad,S.N., "Compressibility and collapse characteristics of arid saline sabkha soils", *Engineering Geology*, Vol. 39, pp. 185-202, 1995.

Al-Gunaiyan, K. A.,"Assessment of the geotechnical properties of stabilized sand-marl mixtures for constructional purposes", *MS. Thesis, Department of Civil Engineering, King Fahd University of Petroleum and Minerals*, Dhahran, Saudi Arabia, 1998.

Alhassan, M, "Potentials of rice husk ash for soil stabilization", Australasian Journal of Technology, Vol. 11, No. 4, pp. 246-250, 2008.

Ali, M. E., " Studies on soil-foundation interaction in the sabkha environment of Eastern Saudi Arabia", *MS. Thesis, Department of Civil Engineering, King Fahd University of Petroleum and Minerals*, Dhahran, Saudi Arabia, 2004.

Alkali, W., "Study on sabkha sand of Eastern Arabia", *Proceeding Symposium on Geotechnical Problems in Saudi Arabia*, King Saud University, Riyadh, Vol. 22, pp. 75-775, 1981.

Al-Refeai, T. and Al-Karni, A., "Experimental study on the utilization of cement kiln dust for ground modification", *J. King Saud University*, Eng. Sci., Vol. 11, No. 2, pp. 217-232, 1999.

Amin, A., "Comparative study of the geotechnical properties of the coastal sabkhas of Saudi Arabia and their hazardous effects", *Bull. Eng. Geol. Env*., Vol. 63, pp. 309–314, 2004.

Asharq Al-Awsat, "Governmental projects and steel demand", Issue no. 12284, (Arabic), 2012.

Azzam, W. R., "Reduction of the shrinkage–swelling potential with polymer nanocomposite stabilization", *Journal of Applied Polymer Science*, Vol. 123, pp. 299–306, 2012.

Bagnold, R. A., The physics of blown sands and desert dunes, 2nd edition , Champman Hail, London, 1971.

Brady, N. C. and Weil, R. R., Elements of the nature and properties of soils, 3rd edition, Pearson Prentice Hall, 2010.

Chusilp, N., Jaturapitakkul, C, and Kiattikomol, K.," Effects of LOI of ground bagasse ash on the compressive strength and sulfate resistance of mortars", *Construction and Building Materials journal*, Vol. 23, pp. 3523-3531, 2009.

Coklin, A. R., "Introduction to soil chemistry, analysis and instrumentation", *A John Wiley & Sons, Inc, Publication*, 2005.

Cuisinier, O., Le Borgne, T., Deneele, D. and Masrouri, F., "Quantification of the effects of nitrates, phosphates and chlorides on soil stabilization with lime and cement", *Engineering Geology*, Vol. 117, pp. 229–235, 2011.

Daous, M. A.," Utilization of cement kiln dust and fly ash in cement blends in Saudi Arabia", *Journal of King Abdul Aziz University, Eng. Sci*., Vol. 15, No. 1, pp. 33-45, 2004.

Dincer, I. and AL-Rashed, B., ”Energy analysis of Saudi Arabia, *"International Journal of Energy Research,* Vol. 26, pp. 263-278, 2002.

Dyer, T.D., Halliday, J.E. and Dhir, R.K., "An investigation of the hydration chemistry of ternary lends containing cement kiln dust", *Journal of Materials Science,* Vol. 34, No. 20, pp. 4975– 4983, 1999.

Edil, T.B., Acosta, H.B. and Beson, C.H., "Stabilizing soft fine-grained soils with fly ash", *Journal of Materials in Civil Engineering*, Vol. 18, No. 2, pp. 283-294, 2006.

El-Sayed , Abdel- Alhalim H., " Potential use of blast furnace slag and steel making slag for consolidation of friable sandstone reservoirs", *Journal of King Saud University, Eng. SCi.*, Vol. 2, pp. 271-285, 2000.

Fredericci, C. et al., "Crystallization mechanism and properties of a blast furnace slag glass", *Journal of Non-Crystalline Solids,* Vol. 273, No. (1-3), pp. 64–75, 2000.

Ghazali, F.M., Fatani, M.N.Y. and Khan, A.M., "Geotechnical properties of sabkha soils of Jeddah and Jazan, Saudi Arabia", *Proceedings*, *2nd , Saudi Engineers Conference, KFUPM,* Dhahran, Vol. 1, pp. 286-307, 1985.

Helmuth, R.A.," Fly ash in cement and concrete", *SP040, Portland Cement Association*, Skokie, Illinois, U.S .A, 1987.

Homauoni, Z.J. and Yasrobi, S. S, "Stabilization of dune sand with poly (Methyl Methacrylate) and polyvinyl acetate using dry and wet processing", J*ournal of Geotechnical and Geology Engineering* ,Vol. 29, pp. 571–579, 2011.

Johnson, H., Kamal, M.R., Pierson, G.O. and Ramsay, J.B., Sabkha of eastern Saudi Arabia, in Al-Sayari, S.S. and Zotl, J.G. (Ed.), *Quaternary Period in Saudi Arabia, Springer-Village,* Austria, pp. 84-93, 1978.

Juillie, Y. and Sherwood, D.E., "Improvement of sabkha soil of the Arabian Gulf coast", *Proceedings, 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki,* Vol. 2, Session 7-121, pp. 781-788, 1983.

Kazemain, S and Barghchi, M.,"Review of soft soils stabilization by grouting and injection methods with different chemical binders", *Journal of Scientific Research and Essays*, Vol. 4 , No. 24, pp. 2104-2111, 2012.

Kolay, P.K., Amin, M.R.,Taib, S.N. and Mohd zain, M.I., "Stabilization of tropical peat soil from Sarawak with different stabilizing agents", *Geotech. Geol. Eng.*, Vol. 29, pp. 1135–1141, 2011.

Kessler, G.R.,"Cement kiln dust (CKD) methods for reduction and control", *IEEE Transaction on Industry Applications,* Vol. 31, No. 2, pp. 407–412, 1995.

Kwon, W. T., Kim, D. H. and Kim, Y. P.,"Characterization of heavy oil fly ash generated from a power plant", *Journal of Materials Online,* Vol. 1, pp. 1-8, 2005.

Liu, C and Evett, J., Soil properties, Prentice Hall, Ohio, 6th edition, 2009.

Maslehuddin, M., Rasheeduzzafar and Al-Mana, A.I.,"The effect of aggregate grading and admixtures on concrete durability", *Proceeding 3rd Saudi Engineering Conference , King Saud University , Riyadh,* Vol.1, pp.103-109, 1991.

Matschei, T., Lothenbach, B. and Glasser, F., "The role of calcium carbonate in cement hydration", *Cement and Concrete Research,* Vol. 37, pp. 551–558, 2007.

Miller, C.T., Bensch, D.G., and Colony, D.C.," Use of cement kiln dust and fly ash in pozzolanic concrete base courses, in emulsion mix design, stabilization, and compaction", *TRB, Transportation Research Record No. 754, National Academy of sciences*, Washington, D.C., U.S.A., pp. 36-41, 2003.

Mohamedzain, Y.A and Al-Rawas, A.A," Cement-stabilization of sabkha soils from Al-Auzayba, Sultanate of Oman", *Geotech.Geol. Eng.*, Vol. 29, pp. 999–1008, 2011.

Montemor, M.F., Simoes, A.M.P., and Ferreira, M.G.S., " Chloride-induced corrosion on reinforcing steel: from the fundamentals to the monitoring techniques", *Cement and Concrete Composites*, Vol. 25, No. 4-5, pp. 491-502, 2003.

Montgomery, D.C., Design and analysis of experiments, 7th ed. New York: Wiley, 2009.

Mussato ,B.T., Gepraegs, O. K. and Farnden, G., "Relative effects of sodium chloride and magnesium chloride on reinforced concrete", Transportation Research Record: *Journal of the Transportation Research Board*, No. 1866, TRB, National Research Council, Washington, D.C., pp. 59–66, 2004.

Najamuddin, S.K., "Production of medium to low strength concrete utilizing indigenous waste products", *MS. Thesis, Department of Civil Engineering, King Fahd University of Petroleum and Minerals*, Dhahran, Saudi Arabia, 2011.

Netterberg F., "Geotechnical properties and behavior of calcretes in South and Southwest Africa", *ASTM STP 777, American Society for Testing and Materials*, Philadelphia, pp. 296–309, 1982.

Peethamparan, S., Olek, J. and Lovell, J.,"Influence of chemical and physical characteristics of cement kiln dust (CKDs) on their hydration behavior and potential suitability for soil stabilization", *Cement and Concrete Research*, 2008.

Qahwash, A.A., "Geotechnical properties of fine-grained calcareous sediments for engineering purposes", *Eng. Geol.*, Vol. 26, pp.161–169, 1989.

Rahman, M. K. et al., "Literature review on cement kiln dust and waste stabilization and experimental investigation", *International Journal of Research and Reviews in Applied Sciences,* Vol. 7, No. 1, pp. 77-87, 2011.

Recupac, "Electric Arc Furnace Dust",< http://www.recupac.com/eaf_dust.htm> (2012)

Reddy, V., Ramana, N., Gnaneswar, K. and Sashidhar, C., "Effect of magnesium chloride ($MgCl_2$) on ordinary Portland cement concrete", *Indian Journal of Science and Technology*, Vol. 4, No. 6, pp. 642-645, 2012.

Renfro, A.R., "Genesis of evaporate-associated stratiform metalliferous deposits = A sabkha process", *Economics Geology,* Vol. 69, No. 1, pp. 33-45, 1994.

Saudi Geological Survey,
<http://www.sgs.org.sa/english/geology/phanerozoic/pages/default.aspx>, 2013.

Seco, A., "The use of non-conventional additives in marls stabilization", *Journal of Applied Clay Science*, Vol. 51, pp. 419–423, 2011.

Shabel, I.M.," Stabilization of Jazan sabkha soil using cement and cement kiln dust", *MS. Thesis, Dept. of Civil Engineering, King Saud University,* Riyadh, Saudi Arabia, 2006.

Sobhan, K. and Mashnad, M.,"Tensile strength and toughness of soil–cement–fly-ash composite reinforced with recycled high-density polyethylene strips", *Journal of Materials in Civil Engineering,* Vol. 14, No. 2, pp.177-184, 2002.

Solanki, P., Khoury, N. and Zaman, M., "Engineering behavior and microstructure of soil stabilized with cement kiln dust," *Geotechnical Special Publication, Soil Improvement,* Vol. 172, pp. 1-10, 2007.

The Saudi Economist Magazine, http://www.aleqt.com/2012/11/03/article_706395.html, 2012.

Todres, H.A., Mishulovich, A. and Ahmad, I., "Cement kiln dust management", *Permeability, Research and Development Bulletin RD103T, Portland Cement Association*, Skokie, Illinois, U.S.A, 1992.

USEPA, "Technical background document on ground water controls at CKD landfills", Office of Solid Waste, U.S., Environmental Protection Agency, Washington, D.C, 1998.

Wang, L.,"Cementitious stabilization of soils in the presence of sulfate*" Ph. dissertation, Department of Civil & Environmental Engineering*, Louisiana State University, USA, 2002.

Watson, A., "The control of wind-blown sand and moving dunes: A review of the methods of sand control in desert, with observations from Saudi Arabia", *Quarterly Journal of Engineering Geology,* London, Vol. 18, pp. 237-252, 1985.

Weinhold, F. and Landis, C., Valency and bonding, 1st edition, Cambridge, 2005.

Wikipedia, (2011), "http://en.wikipedia.org/wiki/Polyethylene_terephthalate".

World atlas, http://www.worldatlas.com/webimage/countrys/asia/lgcolor/sacolor.htm, 2004

Yildirim, I. Z. and Prezzi, M., "Use of steel slag in sub-grade applications", *Publication FHWA/IN/ JTRP-2009/32, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University,* West Lafayette, Indiana, 2009.

VITAE

PERSONAL INFORMATION:

Name: Abdullah Ahmed Khaled Al-Homidy.

Nationality: Yemeni.

Date of Birth: September 26, 1964.

Permanent Address: P.O. Box 1036, Taiz, Yemen.

Present Address: Room #215, Bld # 823, KFUPM, Dhahran, Saudi Arabia.

Voice Mail: +967-771919850

+966-554240938

Email: al_homidy@yahoo.com

EDUCATION:

- **Bachelor of Science in Civil Engineering** from King Abdul Aziz University, Saudi Arabia (May 1989).
- **Master of Higher Education,** Texas Tech. University, Texas, USA, (February 2001).
- **Master of Science in Civil Engineering,** Texas Tech. University, Texas, USA (December 2002).

EXPERIENCES:

- **Full time student** in the Department of Civil Engineering and Environment, King Fahd University of Petroleum & Minerals (KFUPM), (February 2006 – April 2013).
- **Instructor,** Department of Civil Engineering, Thamar University, Yemen, (August 2003-December 2005), (Now on study leave, Thamar University, Yemen).
- **Teacher, Civil** Engineering Department, Technical and Industrial Institute, Taiz, Yemen (January 1990-August 1998).