IMPROVEMENT OF BEARING CAPACITY OF A SOFT SOIL BY THE ADDITION OF FLY ASH

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MURAT AZİZ ÖZDEMİR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

MAY 2011

Approval of the thesis:

IMPROVEMENT OF BEARING CAPACITY OF A SOFT SOIL BY THE ADDITION OF FLY ASH

submitted by **MURAT AZİZ ÖZDEMİR** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan ÖZGEN
Dean, Graduate School of **Natural and Applied Sciences** __________

Prof. Dr. Güney ÖZCEBE
Head of Department, **Civil Engineering** __________

Prof. Dr. Erdal ÇOKÇA
Supervisor, **Civil Engineering Dept., METU** __________

Assoc. Prof. Dr. Murat GÜLER
Co-supervisor, **Civil Engineering Dept., METU** __________

Examining Committee Members:

Prof. Dr. Sadık BAKIR
Civil Engineering Dept., METU __________

Prof. Dr. Erdal ÇOKÇA
Civil Engineering Dept., METU __________

Assist. Prof. Dr. Nejan HUVAJ SARIHAN
Civil Engineering Dept., METU __________

Inst. Dr. S. Osman ACAR
Civil Engineering Dept., METU __________

Civ.Eng. (M.Sc.), A. Gürkan GÜNGÖR
General Directorate of State Highways __________

Date: 10.05.2011

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Murat Aziz ÖZDEMİR

Signature:

ABSTRACT

IMPROVEMENT OF BEARING CAPACITY OF A SOFT SOIL
BY THE ADDITION OF FLY ASH

ÖZDEMİR, Murat Aziz

M.Sc., Department of Civil Engineering
Supervisor : Prof. Dr. Erdal ÇOKÇA
Co-Supervisor : Assoc. Prof. Dr. Murat GÜLER

May 2011, 119 pages

Soft soils are not suitable for use in runway and highway construction due to their undesirable characteristics such as poor grading, low strength, excessive plasticity, tendency to shrink or swell. By stabilizing such soils with appropriate agents, their engineering properties can be improved. One of the stabilizing agents is Class C fly ash.

This study aimed at investigation of bearing capacity improvement of a soft soil (from Elmadağ area) by using Class C fly ash (from Soma Thermal Power Plant).

In the experimental study, index properties of soft soil and fly ash stabilized samples are determined. Then modified Proctor compaction, soaked California Bearing Ratio, and Unconfined Compressive Strength characteristics of the samples are investigated.

During the study, the stabilized soil samples are prepared at different fly ash contents, i.e., 0%, 3%, 5%, 7%, and 10%. The samples are subjected to soaked California Bearing Ratio tests after 0, 7, and 28 days of curing. In addition to California Bearing Ratio tests, Unconfined Compressive Strength tests with 0, 7, and 28 days of curing are performed samples. For comparison purpose, hydrated lime is also used instead of fly ash in Unconfined Compressive Strength tests at predetermined contents, i.e., 3%, 5%, and 7%. In order to observe microstructures of samples, Scanning Electron Microscope - Energy Dispersive X-ray analysis are performed.

The results of the study show that bearing capacity of Elmadağ soft soil can be improved substantially and swell can be reduced significantly by using Class C fly ash.

Keywords: California Bearing Ratio, Unconfined Compressive Strength, Stabilization, Soft Soil, Fly Ash

ÖZ

UÇUCU KÜL KATKISI İLE YUMUŞAK BİR ZEMİNİN
TAŞIMA KAPASİTESİNİN İYİLEŞTİRİLMESİ

ÖZDEMİR, Murat Aziz

Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. Erdal ÇOKÇA
Ortak Tez Yöneticisi : Doç. Dr. Murat GÜLER

Mayıs 2011, 119 sayfa

Zayıf gradasyon, düşük mukavemet, yüksek plastisite ve şişme-büzülme gibi arzu edilmeyen özelliklerinden dolayı yumuşak zeminlerin pist ve karayolu inşaasında kullanımı uygun değildir. Bu gibi zeminler uygun katkılar ile stabilize edildiklerinde mühendislik özellikleri iyileştirilebilir. Bu katkılardan biri de C tipi uçucu küldür.

Bu çalışmanın amacı, Elmadağ bölgesinden temin edilen yumuşak bir zeminin taşıma kapasitesinin Soma Termik Santrali'nden temin edilen C tipi uçucu kül kullanılarak iyileştirilmesinin araştırılmasıdır.

Deneysel çalışmada, yumuşak zeminin ve uçucu kül ile stabilize edilen numunelerin indeks özellikleri (Atterberg limitleri, özgül ağırlık, elek analizi) belirlenmiştir. Daha sonra numunelerin modifiye Proktor sıkışma karakteristikleri ile yaş Kaliforniya Taşıma Oranı ve Serbest Basınç Dayanımı özellikleri araştırılmıştır.

Çalışma esnasında farklı uçucu kül muhtevalarıyla (0%, 3%, 5%, 7%, 10%) stabilize edilen zemin numuneleri hazırlanmıştır. Maksimum kuru yoğunlukta sıkıştırılan numuneler 0, 7 ve 28 günlük kürden sonra yaş Kaliforniya Taşıma Oranı deneylerine tabi tutulmuştur. Yaş Kaliforniya Taşıma Oranı deneylerine ilave olarak 0, 7 ve 28 günlük kür süreleri sonunda, numuneler üzerinde Serbest Basınç Dayanımı deneyleri gerçekleştirilmiştir. Serbest Basınç Dayanımı deneylerinde, uçucu kül katkısı yerine karşılaştırma amacıyla 3%, 5% ve 7% oranlarında sönmüş kireç de kullanılmıştır. Yumuşak zemin, uçucu kül ve uçucu kül ile stabilize edilen numunelerin mikroyapılarını gözlemek amacıyla Taramalı Elektron Mikroskobu – Enerji Dağılımlı X-ray analizleri gerçekleştirilmiştir.

Deneysel çalışmanın sonuçları C tipi uçucu kül katkısı kullanılarak, Elmadağ'dan temin edilen yumuşak zeminin taşıma kapasitesinin önemli derecede iyileştirilebileceğini ve şişmenin önemli ölçüde azaltılabileceğini göstermiştir.

Anahtar Kelimeler: Kaliforniya Taşıma Oranı, Serbest Basınç Dayanımı, Stabilizasyon, Yumuşak Zemin, Uçucu Kül

To My Wife, Yasemin

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor Prof. Dr. Erdal ÇOKÇA, and my co-supervisor Assoc. Prof. Dr. Murat GÜLER for their guidance, advice and throughout the research.

I would kindly like to thank to Middle East Technical University Civil Engineering Department Soil Mechanics and Transportation Laboratory staff for supplying experimental investigation conditions and General Directorate of State Highways Technical Research Department staff for their guidance and help.

Finally, I am thankful to my family and my wife for their endless encouragement.

This research study consists of personal opinions of the researcher. Information and conclusion presented in this document do not reflect the opinions of Turkish Armed Forces.

Bu çalışma öğrencinin kişisel görüşlerini içermektedir. Çalışmada sunulan bilgiler ve değerlendirmeler Türk Silahlı Kuvvetleri'nin görüşlerini yansıtmamaktadır.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACAA	American Coal Ash Association
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CCP	Coal Combustion Product
CL	Clay with Low Plasticity
EDX	Energy Dispersive X-ray
FA	Fly Ash
G_S	Specific Gravity
ICAO	International Civil Aviation Organization
KGM	General Directorate of State Highways
L	Lime
LL	Liquid Limit
LOI	Loss on Ignition
MDD	Maximum Dry Density
METU	Middle East Technical University
M_R	Resilient Modulus
MTA	Mineral Research and Exploration
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
SEM	Scanning Electron Microscope
SOS	Soft Soil
TRB	Transportation Research Board

TS	Turkish Standards
UCS	Unconfined Compressive Strength
USAEWES	United States Army Engineer Waterways Experiment Station

CHAPTER 1

INTRODUCTION

1.1 Scope

This study aimed at using self-cementing Class C fly ash in various proportions for the bearing capacity improvement of a soft soil.

Soft soil samples were obtained from area nearby Ankara-Samsun State Highway in Elmadağ Province. Elmadağ is located approximately 41 km east of Ankara, the capital city of Turkey. Stabilizing agent namely self-cementing Class C fly ash was obtained from Soma Thermal Power Plant. Soma is located approximately 87 km north of Manisa. A location map for Elmadağ and Soma is provided in Figure 1.1.

1.2 Soma Thermal Power Plant

Class C fly ash used in this research was obtained from Soma Thermal Power Plant. The plant is a lignite-fired production plant located in Soma District of Manisa Province and 90 km to Manisa. Soma Thermal Power Plant is shown in Figure 1.2.

Figure 1.1 Location map for Elmadağ and Soma

Figure 1.2 Soma Thermal Power Plant (www.seas.gov.tr)

Soma coal mining area used as fuel basin is around 18,000 hectares. In the basin, approximately 650,000,000 tons of coal reserve is present. The amount of coal reserve is expected to increase with additional drills. The calorific value of the coal reserve which is suitable for operating the power plant is around 1,550 – 5,000 kcal/kg.

Some characteristics of Soma Thermal Power Plant are tabulated in Table 1.1.

Table 1.1 Characteristics of Soma Thermal Power Plant (www.seas.gov.tr)

Location	Soma / Manisa / Turkey		
Plant	Soma - A	Soma - B	Soma - B
Fuel Basin	Soma Lignite Basin	Soma Lignite Basin	Soma Lignite Basin
Main Fuel Used	Lignite	Lignite	Lignite
Calorific Value (kcal/kg)	3,325	2,400	1,550
Units	7 - 8	1 - 2 - 3 - 4	5 - 6
Commercial Operation Date	1957	1984 - 1986	1990 - 1991
Installed Capacity (MW)	22 x 2	4 x 165	2 x 165
Daily Fuel Consumption (ton)	800	22,000	22,000
Electricity Generation (kWh)	7,437,000,000		

1.3 The Research Program

In order to investigate geotechnical properties of Elmadağ soft soil and fly ash stabilized samples, intensive laboratory testing program was performed.

Atterberg limits, specific gravity, sieve analysis tests were carried out to determine the index properties of the samples. Fly ash stabilized samples were prepared at different fly ash contents , i.e., 0%, 3%, 5%, 7%, and 10% by weight of dry sample.

As optimum moisture contents and maximum dry densities of the fly ash-soil mixtures were determined as a result of modified Proctor compaction tests, California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) characteristics of the samples were investigated.

For soaked CBR tests, the samples were compacted to the maximum dry densities at the optimum moisture contents and then cured for three different curing periods, i.e., 0, 7, and 28 days. After each curing period and 4 days of soaking, samples were subjected to CBR tests. At the end of these tests, the moisture contents of the samples were also obtained. For UCS tests, predetermined fly ash contents, i.e., 3%, 5%, 7%, and 10% by weight of dry sample, were used with same curing periods.

In order to compare stabilization characteristics of fly ash with hydrated lime, another well known stabilizing agent, samples were prepared at different hydrated lime contents, i.e., 3%, 5%, and 7% by weight of dry sample. The required bulk densities for compacting UCS samples were calculated by using the maximum dry densities obtained from the modified Proctor compaction tests and the moisture contents obtained from the soaked CBR tests.

In order to reveal microstructures of fly ash stabilized and unstabilized samples Scanning Electron Microscope (SEM) technique with Energy Dispersive X-Ray (EDX) analysis was also performed on the selected samples. The SEM images and EDX diagrams were taken at the METU Central Laboratory.

Throughout this research study, soil tests were performed at the Middle East Technical University, Soil Mechanics Laboratory of Civil Engineering Department. Chemical analysis of Soma fly ash was carried out at Mineral Research and Exploration laboratory (Maden Tetkik Arama, MTA, Ankara, Turkey). Preliminary and additional CBR tests were performed at the General Directorate of State Highways.

1.4 Report Organization

The thesis is divided into five chapters:

- Chapter 1 gives a brief introduction about the scope and the research program.
- Chapter 2 discusses the background and the previous studies on soft soil stabilization by using fly ash.
- Chapter 3 includes a description of the materials used, testing and the analysis performed in the study.
- Chapter 4 discusses the results obtained from the laboratory experiments.
- Finally, Chapter 5 includes conclusions and recommendations for further research.

CHAPTER 2

BACKGROUND AND LITERATURE SEARCH

2.1 Background

Construction of highways and runways over soft soils is one of the most common civil engineering problems in many parts of the world. The general and conventional approach to construct highway or runway on soft soils is to remove the soft soil and then replace it with a stronger material such as crushed rock. The high cost of replacement causes related administrations to evaluate alternative methods of construction on soft soils and new stabilization techniques. One method is to use fly ash as a stabilizing agent (Şenol et al., 2006). Fly ash usage including stabilization also considers many but mainly environmental concerns. They can be summarized as follows (www.undeerc.org):

- Decrease in the demand for landfill space,
- Conservation of natural resources,
- Cleaner and safer environment,
- Reduced carbon dioxide emissions,
- Significant economic savings for end users,
- Boost in economic development.

2.2 Soft Soil

Soft soils generally show low strength and high compressibility. Normally, due to varying climatic conditions, both physical and engineering properties (namely void ratio, water content, grain size distribution, compressibility, permeability and strength) show a consequential variation. Furthermore, they display low permeability, low compactness, and consequently poor quality for any construction over them.

If a pavement is to be constructed on soft soil, some problems may arise during or after construction. The subbase/base layer may sink into the soft soil, horizontal and vertical movement of the subbase/base layer may occur, as a result rutting can take place. These factors simply result in disturbance to the traffic. Some problematic cases are shown in Figure 2.1 and Figure 2.2.

Bearing capacity of soils is expressed by soaked CBR and UCS values. International Civil Aviation Organization (ICAO), the top worldwide aviation authority, classifies subgrade strengths in terms of CBR as listed in Table 2.1.

Figure 2.1 Construction work on a soft soil

Figure 2.2 A truck sinking into a soft soil

Table 2.1 Subgrade strength designations (ICAO, 2009)

Code	Designation	CBR (%)	Representative CBR values (%)
A	High	CBR > 13	15
B	Medium	8 < CBR ≤ 13	10
C	Low	4 < CBR ≤ 8	6
D	Ultra Low	CBR ≤ 4	3

The general classification of clays on the basis of unconfined compressive strength (UCS) is tabulated in Table 2.2.

Table 2.2 Consistency and UCS of clays (Das, 1997)

Consistency	UCS (kPa)
Very soft	0 – 24
Soft	24 – 48
Medium	48 – 96
Stiff	96 – 192
Very stiff	192 – 383
Hard	> 383

Subgrades having CBR values smaller than 8 and UCS values smaller than 48 kPa are considered as soft soil and need to be stabilized especially in pavement applications.

2.3 Fly Ash

2.3.1 Production and Consumption

Increasing demand of energy has resulted in worldwide consumption of approximately 2.2 billion tons of coal for electricity generation in 2001. In Turkey, 54.9 million tons of coal was consumed in thermal power plants in 2006.

Consumption of coal for electricity generation leads to coal combustion products (CCP) in large quantities. According to production and usage statistics made by American Coal Ash Association (ACAA), the total production of CCPs in 2009 is 122.2 million tons (ACAA, 2009).

Fly ash, a well-known CCP, is produced from combustion of pulverized coal. The worldwide production of fly ash is estimated to be 600 million tons per year (Türker et al., 2003). In Turkey, 13 million tons of fly ash is annually produced due to burning of lignite type coal in thermal power plants in order to generate electricity (Aruntaş, 2006). Fly ash is utilized in many ways such as cement and concrete admixture, flowable and structural fill, embankment, cover material, waste stabilization/solidification, pavement applications such as base and subbase, lightweight aggregate production and underground void filling (Scheetz, 1998). In many industrialized countries, high volume of fly ash is used in many areas.

Table 2.3 shows the ratio of fly ash utilization in some industrialized countries (Aruntaş, 2006). Table 2.4 and 2.5 give the production and utilization of fly ash in the United States of America (USA) and Europe, respectively (ACAA, 2009).

Table 2.3 Fly ash utilization in some industrialized countries (Aruntaş, 2006)

Country	Utilization (%)
Netherlands	100
Germany	95
Belgium	95
United Kingdom	50
China	40
USA	32

2.3.2 General Description

Fly ash is a finely graded residue resulting from the combustion of pulverized coal in a coal-fired boiler and transported by flue gases especially in electricity generating thermal power plants.

During the combustion process, mineral residue hardens and eventually forms ash. Coarse ash particles not lifted by flue gases referred to as bottom ash. The lighter and finer ash particles remain suspended in the flue gases, called fly ash.

Table 2.4 Fly ash production and utilization in USA (ACAA, 2009)

Total Fly Ash Produced (2009) (Short tons)	63,000,000	
Total Fly Ash Used (2009) (Short tons)	24,716,665	
Usage to Production Rate	39.20%	
Usage	(Short tons)	%
Concrete Concrete Products Grout	9,796,483	39.64
Blended Cement Raw Feed for Clinker	2,435,904	9.86
Flowable Fill	264,611	1.07
Structural Fills Embankments	4,646,626	18.80
Base Subbase	198,507	0.80
Soil Modification Stabilization	670,035	2.71
Blasting Grit Roofing Granules	47,710	0.19
Mining Applications	2,148,171	8.69
Waste Stabilization Solidification	3,515,289	14.22
Agriculture	102,908	0.42
Aggregate	87,317	0.35
Miscellaneous Other	803,104	3.25
	Total	100.00

Table 2.5 Fly ash production and utilization in Europe (ACAA, 2009)

Total Fly Ash Produced (2008) (Short tons)	37,476,000	
Total Fly Ash Used (2008) (Short tons)	17,692,000	
Use to Production Rate	47.21%	
Usage	(Short tons)	%
Cement raw material	3,863,000	21.83
Blended cement	2,460,000	13.90
Concrete addition	5,760,000	32.56
Aerated concrete blocks	663,000	3.75
Non-aerated concrete blocks	311,000	1.76
Bricks + ceramics	93,000	0.53
Grouting	346,000	1.96
Asphalt filler	95,000	0.54
Subgrade stabilisation	128,000	0.72
Pavement base course	3,000	0.01
General engineering fill	1,556,000	8.79
Structural fill	1,841,000	10.41
Soil amendment	40,000	0.23
Infill	446,000	2.52
Other uses	87,000	0.49
	Total	100.00

According to the American Coal Ash Association (ACAA), the production and disposal ratios of fly ash and bottom ash are approximately 80/20 by the total weight.

A typical pulverized coal combustion system is shown in Figure 2.3 (www.undeerc.org).

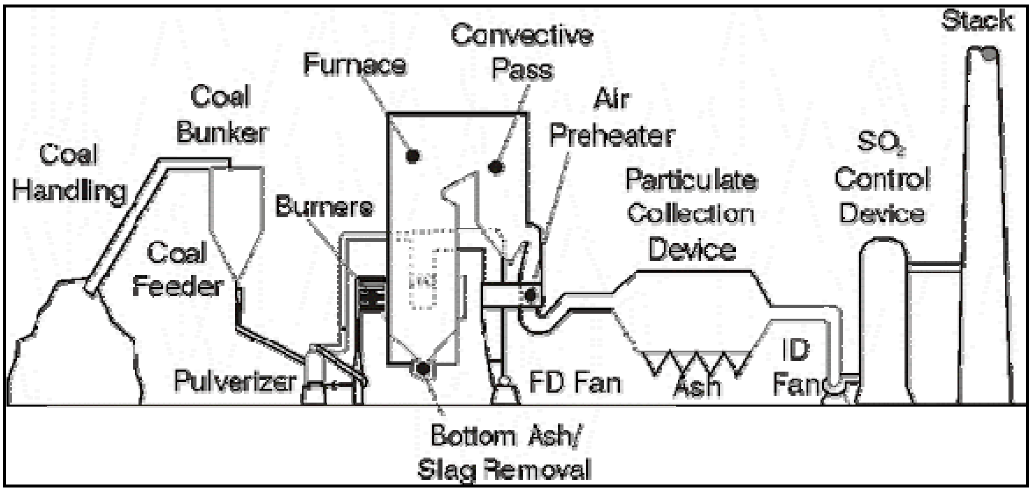


Figure 2.3 Pulverized coal combustion system (www.undeerc.org)

Fly ash is collected by means of particulate emission control devices such as electrostatic precipitators, filter fabric baghouses or mechanical collection devices as cyclones (www.fhwa.dot.gov). Particles are generally in the form of spheres of silicon, aluminum and iron oxides. Particle size ranges from 0.01 μm to 100 μm (Chang et al., 1977).

2.3.3 Classification

Utilization of fly ash has led to international standards, specifications and practices for classification and usage. According to ASTM C 618, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete” classification, fly ashes are classified as either Class F or Class C.

Class F fly ash has pozzolanic properties whereas Class C fly ash has both pozzolanic and cementitious properties. ASTM C 618 standard specification defines the required chemical composition of Class F and Class C fly ashes (Table 2.6).

Table 2.6 Chemical requirements of fly ashes (ASTM, 2008)

Chemical Composition	Class F	Class C
Minimum (SiO_2 + Al_2O_3 + Fe_2O_3), %	70	50
Maximum SO_3, %	5	5
Maximum moisture content, %	3	3
Maximum loss on ignition, %	6	6

Class C fly ash is generally obtained from by-product of burning lignite or subbituminous coal in power plants. They consist primarily of calcium alumino-sulfate glass, as well as quartz, tricalcium aluminate, and free lime (CaO).

Class C fly ash is also referred to as high calcium fly ash because it typically contains more than 10 percent CaO. The high CaO content mainly contributes to self-cementing property in the presence of water.

Class F fly ash is formed during burning of bituminous and anthracite coals. It consists primarily of alumino-silicate glass, with quartz, mullite, and magnetite. Class F fly ash typically has less than 10 percent CaO. It requires additional lime or cement for more effective pozzolanic property.

2.3.4 Physical Properties of Fly Ash

Fly ash consists of fine, powder formed particles that are predominantly spherical in shape. The spheres are whether hollow or solid, and have an amorphous structure in nature (Figure 2.4). The particle size distribution of most bituminous coal fly ashes is generally similar to that of silt (less than 0.075 mm or No. 200 sieve).

Although subbituminous coal fly ashes are also silt-sized, they are generally slightly coarser than bituminous coal fly ashes (Clarke, 1993). The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area (measured by the Blaine air permeability method) may range from 170 to 1,000 m^2/kg (Naik and Singh, 1995).

For each power plant and coal source, color of fly ash is usually consistent. Depending on its chemical and mineral constituents, fly ash can be tan to dark gray in color (Figure 2.5). Lighter colors may represent high lime and low carbon content whereas dark gray to black color may result from high unburned carbon content.

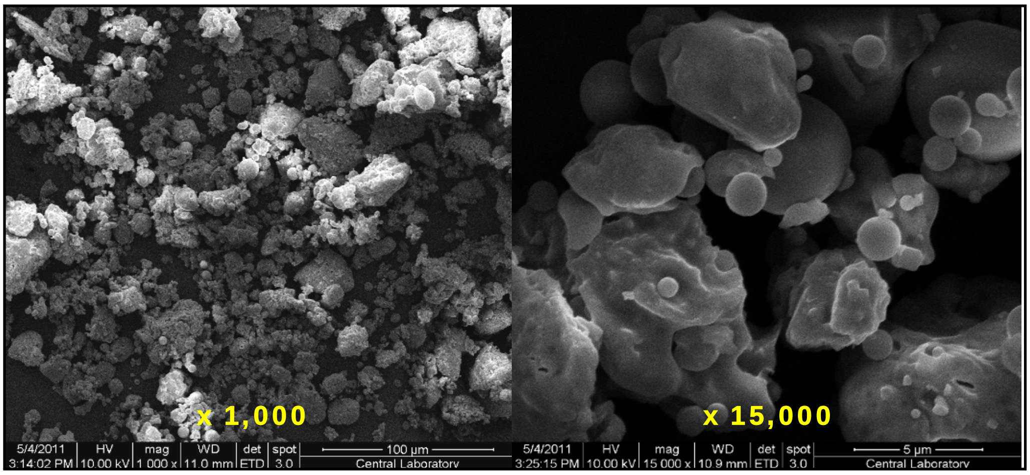


Figure 2.4 Scanning electron microscope images of Soma fly ash

Figure 2.5 Typical colors of fly ashes

2.3.5 Chemical Properties of Fly Ash

The type of coal burned in thermal power plant, handling process and storage techniques used have great effects on the chemical properties of fly ash.

There are basically four types of coal. They are anthracite, bituminous, subbituminous, and lignite. Each type of coal varies in terms of its calorific value, color, chemical composition, ash content, carbon content and geological origin. Some typical properties of coal types are summarized in Table 2.7. In addition, fly ash is sometimes classified according to the type of coal burnt.

Table 2.7 Typical properties of different coal types

Coal Type	Color	Calorific Value (Btu/lb)	Carbon Content (%)
Lignite	Brownish Black	4,000–8,000	25–32
Subbituminous	Black	8,000–13,000	35–45
Bituminous	Dark Black	10,500–15,000	45–85
Antrachite	Jet Black	> 15,000	85–95

The main components of fly ash from bituminous coal are silica, alumina, iron oxide, and calcium with varying amounts of carbon, as measured by the loss on ignition (LOI).

Fly ash produced from combustion of lignite and subbituminous coal is characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as lower carbon content, compared with bituminous coal fly ash (Meyers, 1976). Very little anthracite coal is burned in utility boilers, so there are only small amounts of anthracite coal fly ash.

Table 2.8 compares the range of the chemical constituents of various coal types. It is clear from Table 2.8 that lignite and subbituminous coal fly ashes have a higher calcium oxide content and lower loss on ignition than fly ash from bituminous coal. Lignite and subbituminous coal fly ashes may have a higher concentration of sulfate compounds than bituminous coal fly ashes.

The main difference between Class F and Class C fly ash is in the amount of calcium, silica, alumina, and iron content in the ash (ASTM, 2008). In Class F fly ash, calcium content typically ranges from 1 to 12 percent, mostly in the form of calcium hydroxide, calcium sulfate, and glassy components in combination with silica and alumina.

Table 2.8 Chemical composition of fly ashes produced from different coal types (percent by weight)

Component	Bituminous	Subbituminous	Lignite
SiO_2	20-60	40-60	15-45
Al_2O_3	4-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4

In contrast, Class C fly ash may have reported calcium oxide contents as high as 30 to 40 percent (McKerall et al., 1982).

Another difference between Class F and Class C is the amount of alkalis (combined sodium and potassium) and sulfates (SO_4). They are generally higher in the Class C fly ashes than in the Class F fly ashes.

2.3.6 Hydration of Fly Ash

Hydration of fly ash is defined as formation of cementitious material by the reaction of CaO with the pozzolans (SiO_2, Al_2O_3, Fe_2O_3) in the presence of water.

The hydrated calcium silicate gel or calcium aluminate gel cementitious material can bind inert material together. The pozzolanic reactions are shown in Figure 2.6 (TRB, 1987).

$$CaO + H_2O \rightarrow Ca(OH)_2$$

$$Ca(OH)_2 \rightarrow Ca^{++} + 2(OH)^-$$

$$Ca^{++} + 2(OH)^- + \underset{\text{silica}}{SiO_2} \rightarrow \underset{\text{gel}}{CSH}$$

$$Ca^{++} + 2(OH)^- + \underset{\text{alumina}}{Al_2O_3} \rightarrow \underset{\text{gel}}{CAH}$$

Figure 2.6 Hydration of fly ash (TRB, 1987)

For Class C fly ash, the calcium oxide (lime) of the fly ash can react with the pozzolans, namely siliceous and aluminous materials of the fly ash itself. Since the lime content of Class F fly ash is relatively low, addition of lime is necessary for hydration reaction with the pozzolans of the fly ash. For lime stabilization of soils, pozzolanic reactions depend on the siliceous and aluminous materials provided by the soil.

Hydration of tricalcium aluminate provides one of the primary cementitious products in many ashes. The rapid rate of hydration results in the rapid set of these materials.

This is the reason why delay in compaction results in lower strengths of the fly ash stabilized soils (TRB, 1987). Since the hydration of fly ash is very complex in nature, the stabilization must be based on the physical properties of the fly ash stabilized soil. The stabilization can not be predicted based on the chemical composition of the fly ash.

2.4 Previous Studies on Soil Stabilization with Fly Ash

A variety of laboratory and field studies have shown that cementitious, namely Class C fly ashes are very effective in improving the geotechnical and engineering properties of soft and/or expansive soils (Bergeson et al., 1985, Ferguson, 1993, Turner, 1997, Misra, 1998, Puppala and Musenda, 2000, Çokça, 2001, Edil et al., 2002, Bin-Shafique et al., 2004, Şenol et al., 2006). The fly ash-soil mixture is typically strong and stiff and provides necessary support as a subbase. In most subgrade applications, fly ash is used to stabilize soft soils so that a stable working platform is provided for construction equipment (Ferguson, 1993).

Reducing plasticity and shrink-swell potential of fine-grained soils is also a common objective (Misra, 1998, Bin-Shafique et al., 2004, Edil et al., 2006).

Since strength and stiffness of soft soils are the main concerns, mixture of soil, fly ash, and molding water content for stabilization is usually selected as a basis on which provides maximum strength and stiffness (Çokça, 2001, Şenol et al., 2003). Similarly, mixture is selected for expansive soil based on which provides minimum shrink-swell potential. In all cases, the strength and stiffness is measured either just after compaction or after a predetermined curing period.

Some of the relevant previous studies in soil stabilization by fly ash and lime are as follows (sorted by date):

Çokça (2001) studied stabilization of an expansive soil by using high-calcium and low-calcium Class C fly ashes from the Soma and Tunçbilek thermal power plants, in Turkey. Soma and Tunçbilek fly ashes were introduced up to 25% by weight of dry soil. Based on the experimental studies of the research:

- Plasticity index, activity, and swelling potential of the specimens decrease with increasing amount of stabilizer and curing period.
- Addition of 20% fly ash decreases the swelling potential to nearly the swelling potential obtained with 8% lime addition. The decrease in swelling potential from 20-25% fly ash addition is slight.
- The optimum fly ash content is nearly 20%.

- The decrease in swelling potential due to curing can be attributed to time-dependent pozzolanic activity and self-hardening property (formation of cementitious compounds) of fly ashes.
- On the basis of the study both high-calcium and low-calcium Class C fly ashes can be offered as alternative effective stabilizing agents for improvement of expansive soils.
- The use of Soma and Tunçbilek fly ashes as stabilizing agents can be economical compared with lime or cement in areas near the thermal power plants that produce fly ashes.
- Utilization of fly ash in soil stabilization has the advantage of reusing an industrial waste (CCP) without negatively affecting the environment.

Prabakar et al. (2004) studied the influence of fly ash on strength behavior. They discovered that addition of fly ash reduces the dry density of the soil due to the low specific gravity and unit weight of soil. The reduction in dry density can be in the order of 15–20%. The void ratios and porosity varies by the increasing amount of fly ash in soils. By adding fly ash up to 46%, the void ratios of soils can be increased by 25%. Based on the experimental studies of the research:

- The shear strength of fly ash mixed soil is improved. The shear strength increases non-linearly with increase in fly ash content. The increase in the fly ash content lacks to interlock the soil particles due to which soil-fiber particles failed to act as a single coherent matrix. The increase in fly ash content increases the value of cohesion and the variation is linear.

- CBR value of soil can be improved by the addition of fly ash as compared to the pure soil which would be beneficial especially for pavement. It is noticed that the shear strength and the angle of internal friction of soil admixed with fly ash gives a better strength.
- Introduction of fly ash into soil also reduces swelling. Swelling is reduced by increasing the amount of fly ash in the mixture. Further increasing amount of fly ash in soils leads to further reduction in swelling.
- It can be concluded that fly ash may be effectively utilized in soil to get improvement in shear strength, cohesion and thus improvement in the bearing capacity. Fly ash addition into soil can also be effectively used as the base materials for the roads, back filling, and improvement of soil bearing capacity of any structure.

Arora et al. (2005) studied the suitability of using Class F fly ash-amended soils as highway base materials since roadways have a high potential for high-volume utilization of the fly ash stabilized soils. Based on the research:

- As known, Class F fly ash cannot be used alone in soil stabilization applications as it is not self-cementing, with stabilizing agent, an activator such as Portland cement or lime added to produce cementitious products often called pozzolan stabilized mixtures.
- Unconfined compression, California bearing ratio, and resilient modulus tests were conducted on soil–fly ash mixtures prepared with cement and lime as activators.

- The effect of fines content, curing period, molding water content, compactive effort, cohesion, and cement or lime addition on geotechnical properties of Class F fly ash-amended highway bases were investigated. Mixtures with 40% Class F fly ash and sandy soil with 6-30% cohesionless fines were prepared. Three different molding water contents optimum, 4% wet of optimum, and 4% dry of optimum and two different compactive energies (standard and modified Proctor) were studied.
- Unconfined compression (q_u), CBR, and resilient modulus (M_R) tests were conducted to investigate the suitability of the mixtures as highway base materials. The base thicknesses were calculated for different mixture designs using their corresponding q_u, CBR and M_R values.
- In the field, by compacting the soil using higher compactive efforts increases the strength. Irrespective of molding water contents, the strength also increases with increase in curing time for the specimens.
- The highest strength was observed at 90 days. The test results shows that the water content at compaction can affect the q_u of the mixture design considerably. The performance of the fly ash, soil, and cement mixtures can be significantly increased by preventing the intrusion of excess water in the construction site.
- The variation of q_u with varying amounts of cohesionless fines is not consistent. On the other hand, addition of 10% kaolinite generally increases the strength of a mixture compacted at optimum moisture content.

- For cement-treated specimens, the q_u of 7 day cured specimens increases with increasing number of freeze-thaw cycles. The increase in strength with the number of cycles is more prominent for mixtures that contained 7% cement than for mixtures with 4% and 5 % cement.
- CBR, q_u and M_R increases with increasing cement content. However, the rate of increase decreases beyond 5% cement content.
- Lime treatment has a detrimental effect on the mixture designs. An increase in lime content decreases the q_u of the specimens for both 7 and 28 days old specimens.

Şenol et al. (2006) studied stabilization of soft subgrades by using various fly ashes. The objective of the research was to investigate the improvement in engineering properties of soft subgrades such as unconfined compressive strength and CBR. Soil–fly ash mixtures were prepared at fly ash contents of 10–20% with the specimens compacted at the optimum water content and about 7% wet of optimum. Unconfined compression strength and CBR tests were then conducted on specimens. The results are given as:

- The fly ash stabilization increases both the unconfined compressive strength and the CBR values substantially for the mixtures tested and have the potential to be suggested as an alternative for soft subgrade improvement of highway construction.

- The research shows that stabilizing the soft subgrade at specified water contents and minimizing compaction delay in the construction site can maximize the strength of fly ash-stabilized soils.

Edil et al. (2006) conducted a laboratory study where soil–fly ash mixtures were prepared at fly ash contents of 10–30% to evaluate how addition of fly ash can improve the CBR and resilient modulus (M_R) of wet and soft fine-grained subgrade soils. Specimens were prepared at optimum water content, 7% wet of optimum which simulates the possible in-situ condition, and 9–18% wet of optimum simulating a very wet condition. Based on the investigation, the observations and conclusions are as follows:

- CBR of soil–fly ash mixtures generally increases with increase in the fly ash content and decreases with increasing compaction water content. Adding 10 and 18% fly ash to fine-grained soils compacted at 7% wet of optimum water content (the typical in-situ condition), results in CBR value increase by a factor of 4 and 8, respectively. The CBR increases by a greater factor when fly ash is added to a wetter or more plastic fine-grained soil.
- Soil–fly ash mixtures prepared with 10% fly ash and fine-grained soil compacted at 7% wet of optimum (the typical in-situ condition) typically will have lower resilient modulus than soil alone compacted at optimum water content.

- However, when the fly ash content is on the order of 18%, the resilient modulus typically will be higher (30% higher, in the study) than the resilient modulus of soil alone compacted at optimum water content. Larger increases in resilient modulus typically should be expected for wetter or more plastic fine-grained soils; however, stabilization with fly ash results in comparable final CBR and M_R regardless of soil type.
- The effect of curing time on resilient modulus was evaluated using one type soil and two types of fly ashes. Between 7 and 14 days, the resilient modulus increases modestly. However, between 14 and 56 days, the resilient modulus increases by 20–50%. Thus, fly ash stabilized subgrades should stiffen over time, resulting in increased pavement support.
- The presence of 10% organic matter in one of the soils inhibits stabilization by most of the fly ashes. Soil–fly ash mixtures prepared with this soil typically has much lower CBR and M_R than obtained for inorganic soils.
- In some cases, the M_R is not measurable. However, a modest degree of stabilization is achieved for this soil with one of the off-specification fly ashes (a fly ash with high carbon content and a high CaO/SiO_2 ratio). The mechanism making the off-specification fly ash effective in stabilizing organic soils needs further study.

CHAPTER 3

EXPERIMENTAL STUDY AND RESULTS

3.1 Scope

The aim of the experimental study is to investigate the effects of the addition of self-cementing Class C fly ash on some of the geotechnical properties such as Atterberg limits, specific gravity, sieve analysis, modified Proctor compaction characteristics and bearing capacity (CBR and UCS) of a soft soil. The effect of curing period on CBR and UCS of fly ash stabilized samples are also investigated.

For comparison purposes, hydrated lime is used as an alternative stabilizing agent in UCS tests.

3.2 Materials

Soft Soil: In the beginning of the study, the predetermined soil was tested whether it is soft or not. For this reason, CBR tests were performed on compacted samples at General Directorate of State Highways and METU Soil Mechanics laboratories.

Soaked CBR results were calculated as 3.3 and 3.7, respectively. It was then concluded that the predetermined soil was soft according to ICAO subgrade strength designation.

Soft soil samples were obtained from Elmadağ Province nearby Ankara-Samsun State Highway in KM: 48+500. The sampling site is shown in Figure 3.1.

Figure 3.1 Site of soft soil sampling

Soil sampling was performed according to the TS 1901 "Methods for Boring and Obtaining Disturbed and Undisturbed Samples for Civil Engineering Purposes".

Laboratory tests were performed on Elmadağ soft soil at METU Civil Engineering Department Soil Mechanics Laboratory. The results are tabulated in Table 3.1.

Table 3.1 Laboratory test results of Elmadağ soft soil

Test	Characteristic	Unit	Result
Sieve Analysis	Sand	%	34.1
	Fines	%	65.9
Atterberg Limits	Liquid limit (LL)	%	27
	Plastic limit (PL)	%	19
	Plasticity index (PI)	%	8
Soil Classification	USCS group symbol	-	CL
Specific Gravity	G_s	-	2.77
Modified Proctor Compaction	Optimum moisture content (OMC) (w_{opt})	%	7.63
	Maximum dry density (MDD) (γ_{dmax})	g/cm^3	2.188
California Bearing Ratio (Compacted & Unstabilized)	CBR (Sample 1 - 2)	%	3.0 - 2.9
	Swell (Sample 1 - 2)	%	5.0 - 5.1

Table 3.1 indicates that Elmadağ soil is a soft soil since soaked CBR value is smaller than 4. It is classified as low plastic silty clay (CL) according to Unified Soil Classification System.

Fly Ash: Self-cementing Class C fly ash was obtained from Soma Thermal Power Plant. Its specific gravity is 2.23 and it is light gray in color (Figure 3.2). Fly ash was passed through No. 4 sieve before usage.

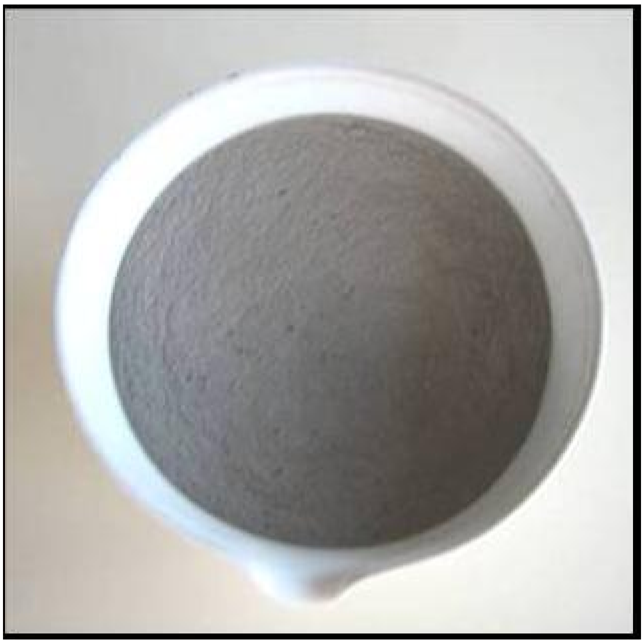


Figure 3.2 Soma fly ash

Scanning Electron Microscope (SEM) image of Soma fly ash is shown in Figure 3.3 with the magnification factors of 1,000 and 10,000, respectively.

Chemical analysis of the fly ash was carried out at Mineral Research and Exploration laboratory (Maden Tetkik Arama, MTA, Ankara, Turkey).

The chemical composition is tabulated in Table 3.2, whereas analysis report is given in Appendix A.

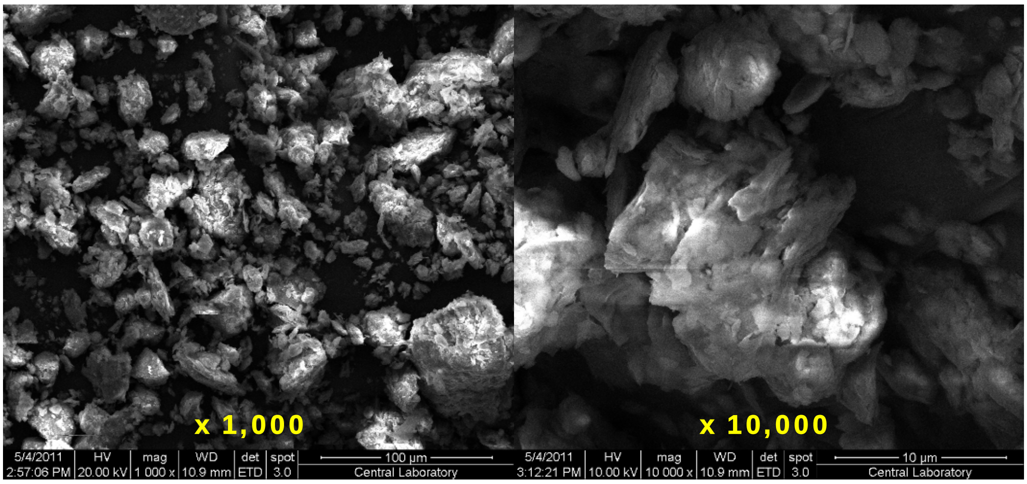


Figure 3.3 Scanning Electron Microscope images of soft soil

Table 3.2 Chemical composition of Soma fly ash

Component	Weight (%)
SiO_2	48.20
Al_2O_3	22.30
Fe_2O_3	5.30
(S + A + F)	75.80
CaO	15.80
MgO	1.20
Na_2O	0.50
K_2O	1.20
TiO_2	0.80
P_2O_5	0.20

Hydrated Lime: Commercial hydrated lime (BAŞTAŞ Lime) was used in the study. The chemical composition of hydrated lime is tabulated in Table 3.3.

Table 3.3 Chemical analysis of hydrated lime

Component	Weight (%)
SiO_2	0.58
Al_2O_3	0.38
Fe_2O_3	0.11
CaO	67.76
MgO	2.20
LOI	26.39

3.3. Sample Preparation

The soft soil, fly ash and hydrated lime used in the study are designated as SOS, FA, and L, respectively. The mix design of the materials designated such as “5% FA” implies that the sample consists of 95% soft soil and 5% fly ash by dry weight of the total sample.

Sample preparation process is shown in Figure 3.4 whereas the whole sample designation used in the research study and bearing tests performed are tabulated in Table 3.4.

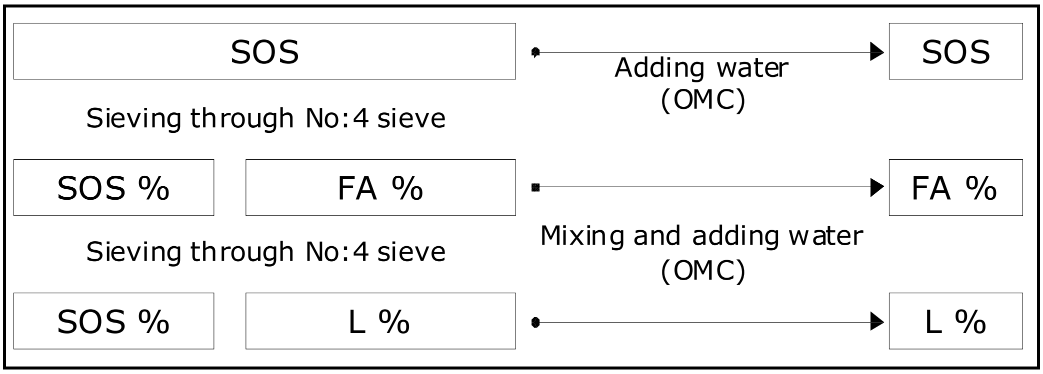


Figure 3.4 Sample preparation

Table 3.4 Sample designations and bearing tests performed

Sample No	Mix Design	Designation	CBR	UCS
1	100% Soft Soil	SOS	+	+
2	97% Soft Soil + 3% FA	3%FA	+	+
3	95% Soft Soil + 5% FA	5%FA	+	+
4	93% Soft Soil + 7% FA	7%FA	+	+
5	90% Soft Soil + 10% FA	10%FA	+	+
6	97% Soft Soil + 3% L	3%L	-	+
7	95% Soft Soil + 5% L	5%L	-	+
8	93% Soft Soil + 7% L	7%L	-	+

\+ Performed

\- Not performed

For compaction and bearing capacity tests, disturbed samples of soft soil were air-dried (Figure 3.5). After air-drying, samples were grounded so that they could pass through No. 4 sieve (Figure 3.6).

Each sample was prepared by mixing a calculated amount of stabilizing agent with SOS to obtain a sample with predetermined percentage of stabilizing agent which varied from 0 up to 10 percent (by dry weight of the total sample).

The predetermined amounts of soft soil and stabilizing agent, namely fly ash, were mixed manually and also by using a dry and clean trowel. Special care was taken during mixing process to ensure uniform distribution of fly ash and water.

In modified Proctor compaction tests, samples were prepared individually for altering compaction water content. This was due to possibility of grain size alteration and cementing effect of stabilizing agent on soft soil.

For index properties of samples such as Atterberg limits, sieve analysis, and modified Proctor compaction, the effect of curing would not be required.

In literature it is also mentioned that compaction delay after mixing fly ash with soil results in substantial loose in strength gain (Figure 3.7).

Figure 3.5 Air-drying of soft soil

Figure 3.6 Grounded soft soil

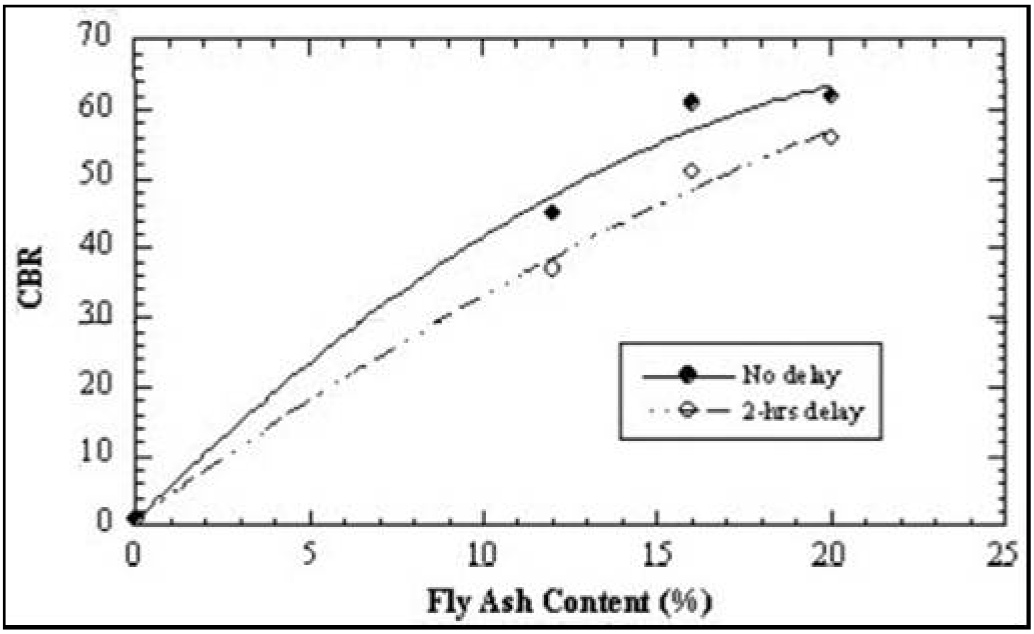


Figure 3.7 Strength loose due to compaction delay
(Şenol et al., 2003)

For the soaked CBR tests on cured samples, the samples which were prepared according to the above procedure were compacted in CBR molds and then taken to humidity room. During curing special care was given to prevent loss of moisture. The samples were set to cure in the humidity room for 7 and 28 days (Figure 3.8). The curing temperature and relative humidity in the humidity room were approximately 20°C and 99%, respectively.

After 7 and 28 days, the cured samples were taken out of the humidity room and soaked in water for 4 days in order to perform soaked CBR tests (Figure 3.9).

Figure 3.8 Curing in humidity room

Figure 3.9 Soaking in constant level of water

3.4 Test Procedures and Results

3.4.1 Particle Size Analysis

Wet sieving procedure was preferred. 500 g of sample was used in each test. The effect of curing on sieve analysis was not investigated. Therefore 24 hours soaked soft soil samples were mixed with predetermined amounts of fly ash and then the samples were sieved. The percent fines of samples obtained from wet sieve analysis are tabulated in Table 3.5. Particle size distributions of samples are shown in Figure 3.10, whereas particle size analysis test reports are provided in Appendix B.

Table 3.5 Percent fines of samples

Sample	Fines (%)
SOS	65.9
3%FA	60.8
5%FA	55.3
7%FA	51.6
10%FA	50.2

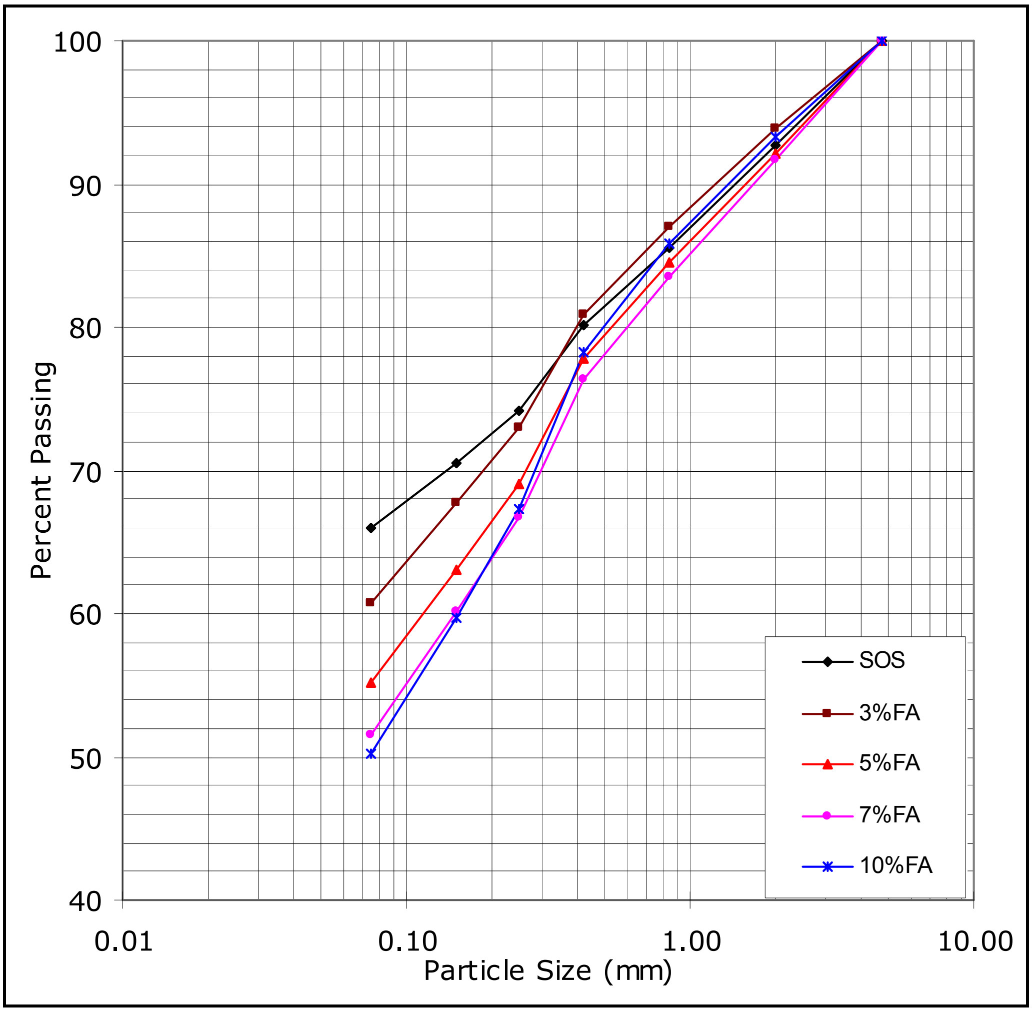


Figure 3.10 Particle size distributions of samples

3.4.2 Atterberg Limits

The Atterberg limits tests were carried out on uncured (0 day cured) samples according to ASTM D 4318 "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils". The results obtained are tabulated in Table 3.6.

Table 3.6 Atterberg limits of samples

Sample	LL (%)	PL (%)	PI (%)
SOS	23	11	12
3%FA	25	12	13
5%FA	26	12	14
7%FA	30	14	16
10%FA	29	14	15

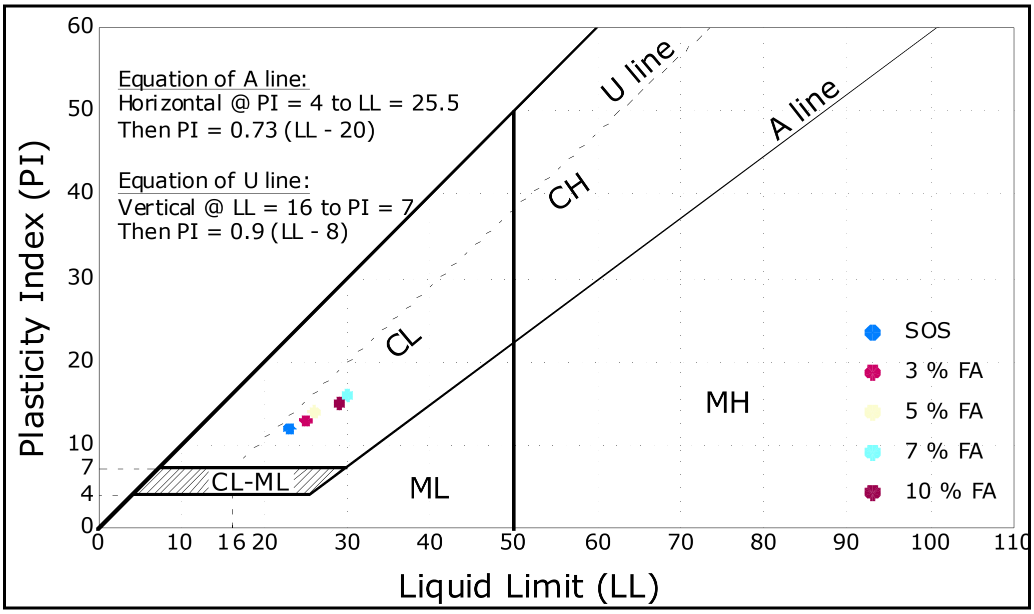


Figure 3.11 Plasticity chart for samples

3.4.3. Soil Classification

Using Atterberg limits and particle size analysis, the group symbol, i.e., soil type, of the samples were determined according to ASTM D 2487 "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)". The results obtained are tabulated in Table 3.7.

Table 3.7 Soil classification of samples

Sample	Soil Classification
SOS	CL
3%FA	CL
5%FA	CL
7%FA	CL
10%FA	CL

3.4.4. Modified Proctor Compaction

The modified Proctor compaction tests were carried out on uncured samples according to Method A of ASTM D 1557 "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3(2,700 kN-m/m^3))".

2,500 g of total samples were used in each test. The results of modified Proctor compaction tests were to be used in sample preparation for the bearing tests.

Bearing tests were predetermined to be performed on samples prepared at the optimum moisture content and compacted to the maximum dry density. As a result, special care was taken in modified Proctor compaction tests. The results are tabulated in Table 3.8.

Samples compacted at different moisture contents for a predetermined percentage of fly ash is shown in Figure 3.12.

Table 3.8 Compaction characteristics of samples

Sample	Maximum Dry Density (g/cm^3)	Optimum Moisture Content (%)
SOS	2.188	7.63
3%FA	2.172	7.42
5%FA	2.157	7.20
7%FA	2.145	7.80
10%FA	2.100	8.34

Figure 3.12 Specimens compacted at different moisture contents

3.4.5 California Bearing Ratio

The California Bearing Ratio (CBR) test is a load test performed under uniform pressure. It is defined as the determination of bearing ratio of soil sample by means of the relationship between load and penetration while penetration piston is forced into the soil sample with a uniform rate of 1.27 mm/min. Typical CBR values for different soil types are given in Table 3.9 (USAEWES, 1957).

The apparatus needed for the test defined by ASTM D 1883 "Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils" is as follows:

- Loading Machine

For measurable CBR values greater than 50, the minimum loading capacity of loading machine should be 44.5 kN.

Table 3.9 Typical CBR values for different soil types (USAEWES, 1957)

Soil Type	Soil Classification	Typical CBR (%)
Coarse-Grained Soils (More than 50% retained on No. 200 sieve)	GW	40–80
	GP	30–60
	GM	20–60
	GC	20–40
	SW	20–40
	SP	10–40
	SM	10–40
	SC	5–20
Fine-Grained Soils (50% or more retained on No. 200 sieve)	ML	≤15
	CL	≤15
	OL	≤5
	MH	≤10
	CH	≤15
	OH	≤5

The machine shall be equipped with a movable head or base that travels at a non-pulsating (uniform) rate of 1.27 mm/min. The movement of head or base is used in forcing the penetration piston into the soil sample. The loading machine used in CBR tests performed in this study is MATEST CBR Tester S211-10. It is shown in Figure 3.13.

Figure 3.13 MATEST CBR Tester S211-10

- Penetration Piston

A metal piston having a diameter of 49.63 mm is required during penetration into the soil sample.

- Load and Penetration Measuring Devices

Two mechanical dial indicator (or electronic displacement transducer) are needed to measure the amount of the load applied on soil sample and penetration.

- Mold

The mold is a rigid metal cylinder with an inside diameter of 152.4 mm, a height of 177.8 mm and a volume of 2,124 cm^3 with a metal extension collar and a metal base plate. Metal base plate has at least twenty eight 1.59 mm diameter holes uniformly spaced over the plate within the inside circumference of the mold. A typical mold and other apparatus are shown in Figure 3.14.

- Rammer

A rammer as specified in ASTM D 1557 for modified compaction of the soil sample in a 152.4 mm diameter mold. If a mechanical rammer is used it must be equipped with a circular foot, and when so equipped, must provide a means for distributing the rammer blows uniformly over the surface of the soil sample. The mechanical rammer used in the study is shown in Figure 3.15.

Figure 3.14 Miscellaneous apparatus used in CBR tests

Figure 3.15 Mechanical rammer

- Expansion - Measuring Apparatus

Expansion - measuring apparatus consists of an adjustable metal stem and a perforated metal plate having at least forty-two holes uniformly spaced over the plate and a metal support for the dial gage measuring the amount of swell during soaking. Generally a mechanical dial gage capable of reading to 0.025 mm with a range of 5 mm minimum is needed. The expansion measuring apparatus shall not weigh more than 1.27 kg.

- Weights

One or two annular metal weights having a total mass of 4.54 kg with a central hole through which the penetration piston passes during loading.

<u>Summary of CBR test method performed in this study (Including test specimen preparation and bearing test) is as follows:</u>

- The soil sample is compacted at the optimum moisture content determined previously in accordance with ASTM D 1557.

- A moisture content determination is performed in order to check whether the moisture content of the soil sample is within the ±0.5% of its optimum water content.

- The mold (with extension collar attached) is clamped to the base plate. The spacer disk is inserted above the base plate and a disk of filter paper is placed on top of the spacer disk.

- The soil sample is compacted into the mold.

- The extension collar is removed and compacted soil sample is trimmed by means of a straightedge.

- If any hole on the surface of the soil sample develops during trimming, smaller size of material is used for patching.

- Perforated base plate and spacer disk are removed and the mass of mold + compacted soil sample is recorded.

- Another disk of filter paper is placed on the perforated base plate. The mold is then inverted and the perforated base plate is clamped to the mold with compacted soil sample in contact with the filter paper.

- Surcharge weights are placed on the perforated plate and adjustable stem assembly. Then the whole assembly is carefully lowered onto the compacted soil sample in the mold.

- Mold + compacted soil sample + surcharge weights are immersed in water. Initial measurement for swell is taken and the soil sample is allowed to soak for 96 hours.

- A constant water level and free access of water to the top and bottom of soil sample by means of holes is maintained.

- After 96 hours, final swell measurement is taken and swell is calculated as a percentage of the initial height of the soil sample.
- Free water is removed and the soil sample is allowed to drain downward for 15 minutes.

- The surcharge weights, perforated plate, and filter paper are removed and the mass is recorded.

- Surcharge weights are placed onto the soil sample and the penetration piston is seated with the smallest possible load.

- Then load is applied on the penetration piston so that the rate of penetration is approximately 1.27 mm/min.

- The load readings at penetrations of 0.64 mm, 1.27 mm, 1.91 mm, 2.54 mm, 3.18 mm, 3.81 mm, 4.45 mm, 5.08 mm, 7.62 mm, 10.16 mm and 12.70 mm are recorded.

- The compacted soil is then removed from the mold and the water content of the top 25.4 mm layer is determined. A typical loaded CBR specimen is shown in Figure 3.16.

Figure 3.16 A typical loaded CBR specimen

The calculation of CBR value is as follows:

- The load readings are converted to the stresses by dividing them into the cross-sectional area of the penetration piston.

- Stress - penetration curve is plotted. A typical curve is shown in Figure 3.17.

- If it is needed, the curve is corrected for concave upward shape or surface irregularities.

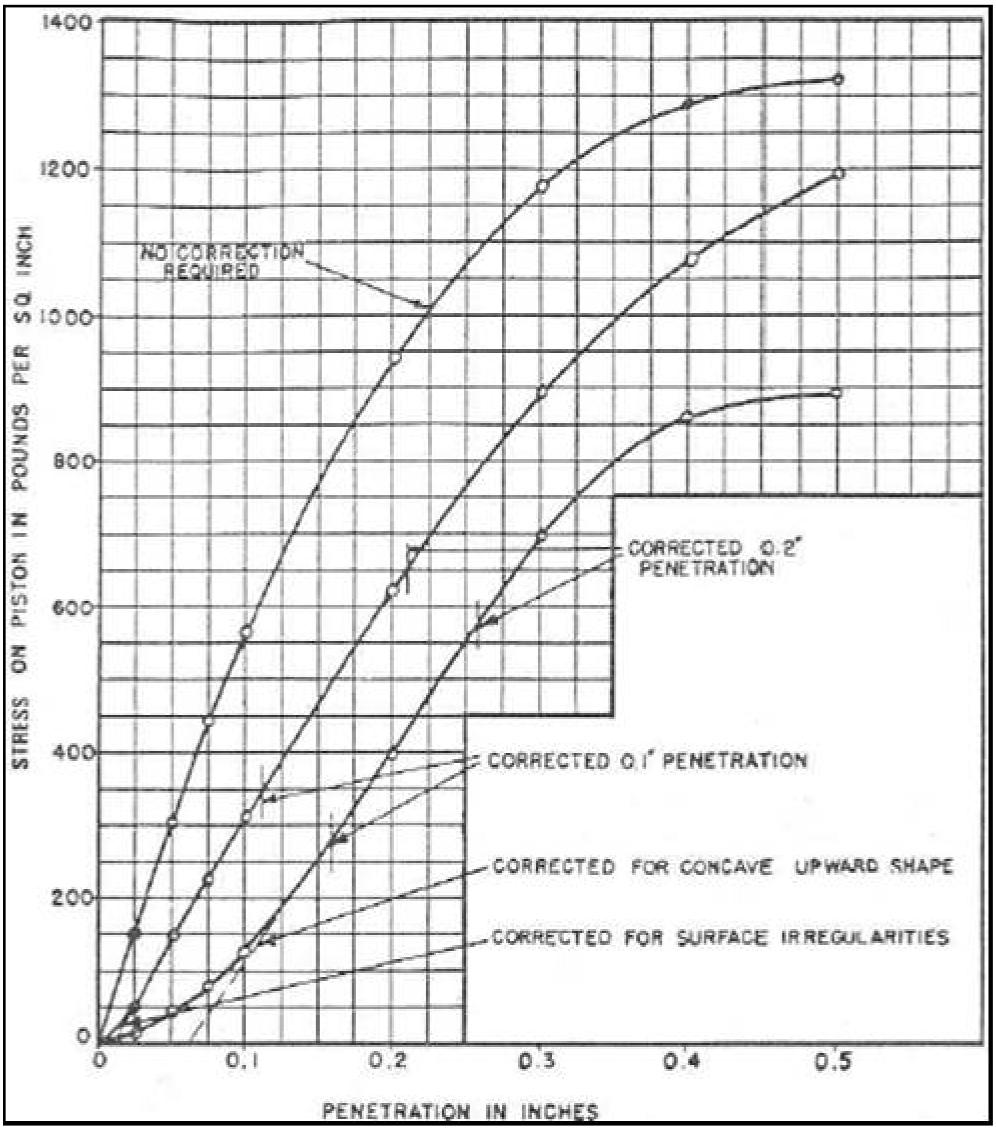


Figure 3.17 Typical stress - penetration curve (ASTM, 2007)

- The bearing ratio reported is normally the one at 2.54 mm penetration. If the CBR at 5.08 mm penetration is greater than the one at 2.54 mm, then the test is rerun. If this test again gives a similar result, then the CBR is reported as the one at 5.08 mm penetration.

The average results of CBR tests carried out in this study are tabulated in Table 3.10, whereas the test forms are provided in Appendix C.

Table 3.10 Average CBR and swell of samples

Soaking	4 days					
Curing	0 days		7 days		28 days	
Sample	CBR_{ave}	$Swell_{ave}$	CBR_{ave}	$Swell_{ave}$	CBR_{ave}	$Swell_{ave}$
SOS	3.0	5.1	N/A	N/A	N/A	N/A
3 % FA	5.0	4.8	7.8	3.5	9.4	2.9
5 % FA	6.2	5.2	11.9	3.1	20.1	2.3
7 % FA	6.2	5.1	17.2	3.2	55.5	1.1
10 % FA	6.8	4.5	85.9	0.7	114.5 *	0.7
15 % FA	22.3	4.4	162.0 *	0.1	N/A	N/A
20 % FA	41.6	3.1	246.0 *	0.1	N/A	N/A

* Perfomed at General Directorate of State Highways laboratory

At the beginning of the experimental study, stabilized samples with 15 percent and 20 percent fly ash were also decided to be investigated in terms of bearing capacity improvement. It is a clear outcome from Table 3.10 that 15%FA and 20%FA samples (7 days cured) have CBR much greater than 100. For this reason, 15%FA and 20%FA samples were not investigated and discussed more in the research study.

3.4.6 Unconfined Compressive Strength

The Unconfined Compressive Strength (UCS) test is an unconsolidated and undrained load test performed for determining the unconfined compressive strength of cohesive soil samples where the lateral confining pressure is equal to zero during the test.

UCS is the compressive stress at which an unconfined cylindrical soil sample fails in a load test. UCS is taken as the maximum load attained per unit area during loading, or the load per unit area at 15% axial strain, whichever is secured first.

For UCS test specimens, the shear strength is calculated to be half of the compressive stress at failure.

Summary of the test procedure defined by ASTM D 2166 "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil" is as follows:

- Prepare specimens having a minimum diameter of 30 mm, and height-to-diameter ratio between 2 and 2.5.

- Place the specimen in the loading device (Figure 3.18) and make necessary adjustments.

Figure 3.18 Wykeham Farrance Tritech 10 Test Machine

- Load the specimen so as to produce an axial strain at a rate of 1/2 to 2 % per minute until the load values decrease with increasing strain, or until 15 % strain is reached.

- Record load, deformation, and time values at sufficient intervals to define the shape of the stress-strain curve.

- Determine the water content of the test specimen using the entire specimen.

- Calculate the axial strain, the average cross-sectional area, and the compressive stress for a given applied load.

- Plot a graph showing the relationship between compressive stress and axial strain.

- Select the maximum value of compressive stress, or the compressive stress at 15 % axial strain.

The UCS tests were performed on both unstabilized, fly ash stabilized, and hydrated lime stabilized samples. In sample preparation for UCS tests, a condition similar to soaked CBR case was aimed. Then the moisture contents obtained from soaked CBR tests and the maximum dry densities obtained from modified Proctor compaction tests were used to obtain bulk densities for compaction. Curing periods were chosen same as those for CBR tests.

The tests were carried out in general accordance with ASTM Standard D 2166. The average results of UCS tests carried out in this study are tabulated in Table 3.11.

3.4.7 SEM-EDX Analysis

Scanning Electron Microscope (SEM) technique coupled with Energy Dispersive X-Ray (EDX) is one of the best and most widely used methods to identify and characterize morphology and elemental constituents of fly ash particles. SEM-EDX analysis provides fast and accurate results on the microstructure and elemental composition of fly ashes.

Table 3.11 Average UCS of samples

Curing	0 days			7 days			28 days		
Sample	W_{design} (%)	C_{ave} (%)	UCS_{ave} (kPa)	W_{design} (%)	C_{ave} (%)	UCS_{ave} (kPa)	W_{design} (%)	C_{ave} (%)	UCS_{ave} (kPa)
SOS	15	88	47	N/A	N/A	N/A	N/A	N/A	N/A
3 % FA	16	84	51	15	85	73	15	87	112
5 % FA	17	84	55	15	87	85	15	88	134
7 % FA	21	79	24	16	86	95	13	88	333
10 % FA	26	75	6	15	87	389	14	88	642
3 % L	16	84	78	15	87	198	15	87	290
5 % L	17	84	74	15	88	208	15	86	251
7 % L	21	78	36	16	86	271	13	84	230

W_{design} : Design water content obtained from soaked CBR tests for stabilized and unstabilized samples

C_{ave}:Average percent of compaction for UCS test samples

SEM examines external microstructure of materials such as metals, rocks, and biological specimens.

In SEM analysis, valuable information about morphology and composition of material is obtained by bombarding the specimen with a scanning beam of electrons and then collecting slow secondary electrons that the specimen generates.

These electrons are collected, amplified and displayed on a cathode ray tube. The electron beam and the cathode ray tube scan synchronously so that an image of the surface of the specimen is formed. SEM images are taken at a very slow rate of scan in order to capture greater resolution.

EDX is an analytical technique used for the elemental analysis or chemical characterization of a material. It is one of the variants of X-ray Fluorescence Spectroscopy and most commonly found on SEM systems. The main principal related to characterization capability is the unique atomic structure of each element allowing X-rays that are characteristic of an element's atomic structure to be identified uniquely from one another.

In this study, SEM-EDX analysis was used to describe the change in microstructure for unstabilized and stabilized samples with curing effect. SEM-EDX analysis was performed at METU Central Laboratory by using QUANTA 400F Field Emission Scanning Electron Microscope (High Resolution) and images were recorded to reveal the microstructure of samples.

Critical samples were chosen as SOS, FA, 3%FA (0, 7, and 28 days of curing), and 10%FA (0, 7, and 28 days of curing). A total number of 8 samples were investigated (Figure 3.19). Stabilized samples were prepared by compacting at the optimum moisture contents and then curing for predetermined periods.

During SEM-EDX analysis, voltage was selected as of 10 kV and magnification factors ranging between 200 and 60.000 was used. SEM images of 3%FA and 10%FA with different curing periods are shown in Figure 3.20 and 3.21, respectively.

EDX analysis gives information for the upper few micrometers of the surface of the samples. Atomic percentages of a randomly selected point on the surface of fly ash and soft soil were calculated (Figure 3.22 and 3.23) during SEM-EDX analysis.

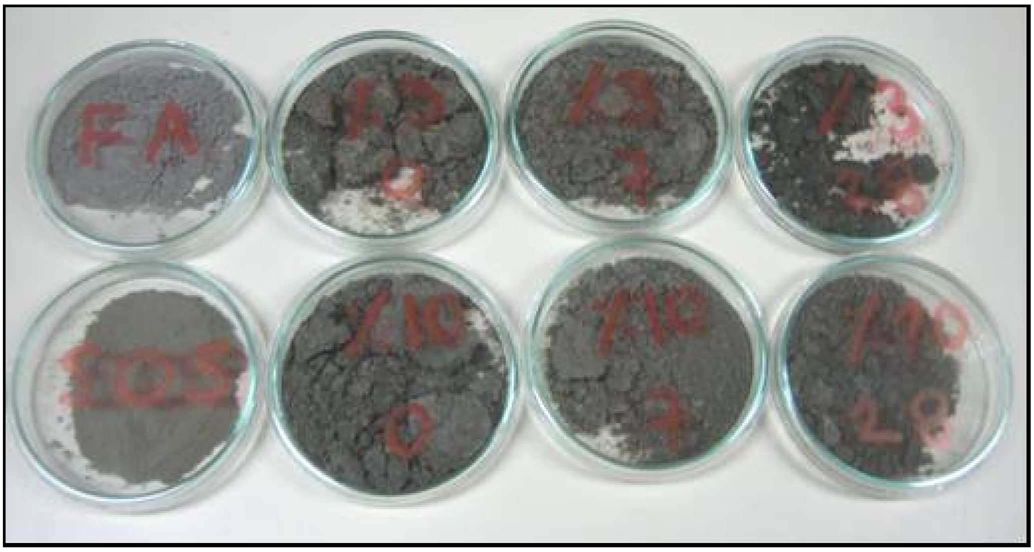


Figure 3.19 Samples used in SEM-EDX analysis

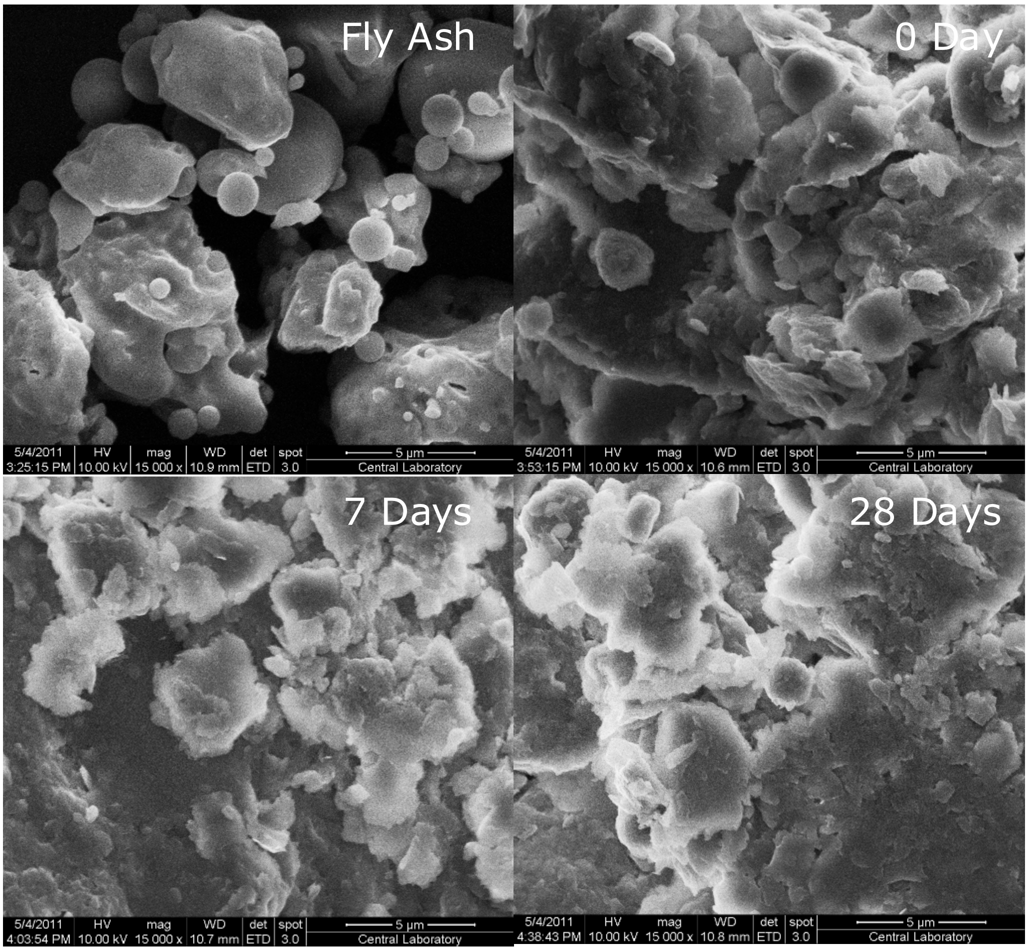


Figure 3.20 SEM images of FA and 3%FA (cured)

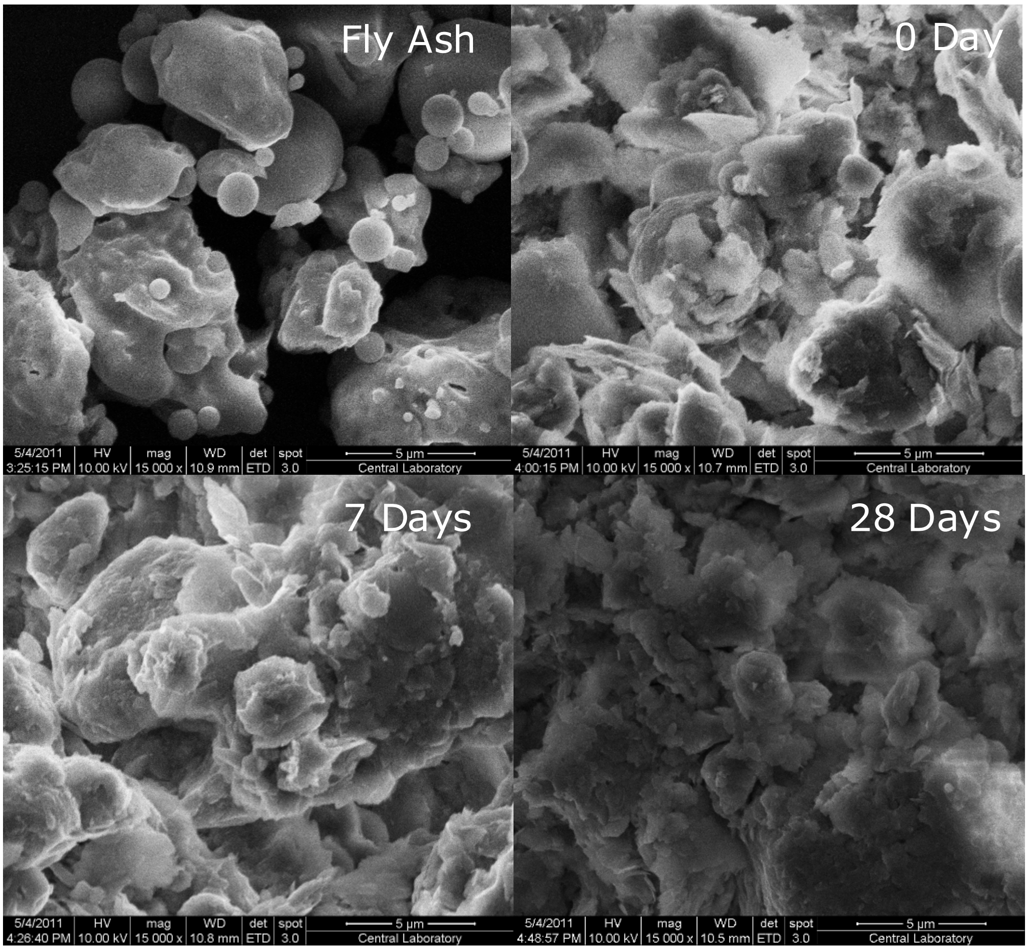
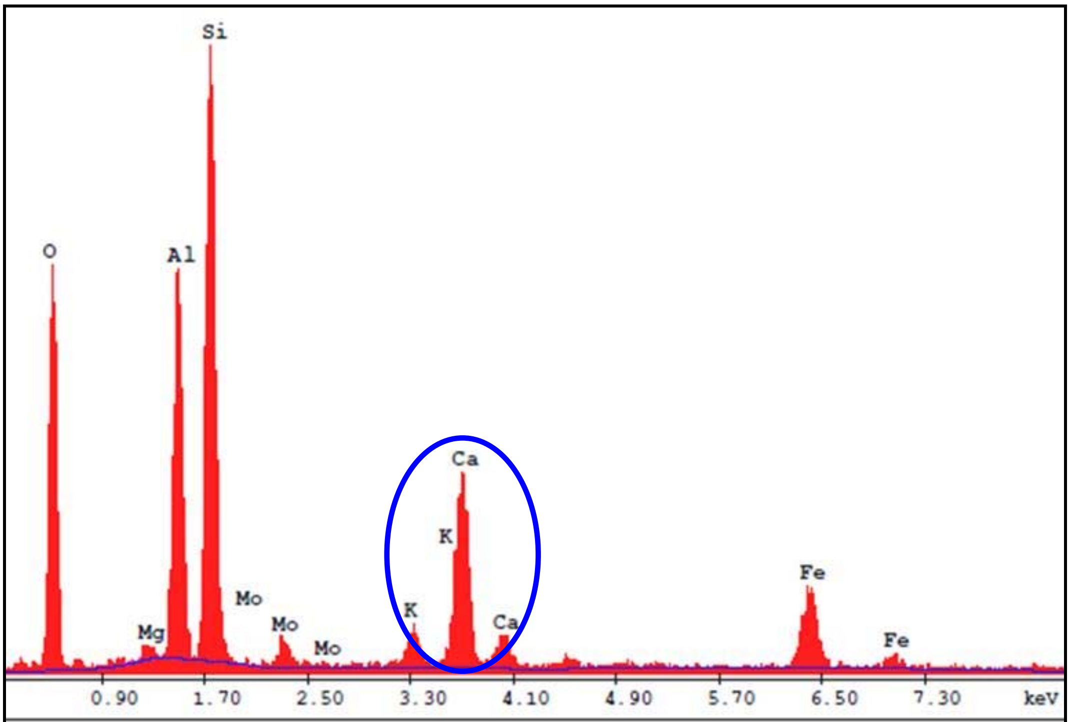


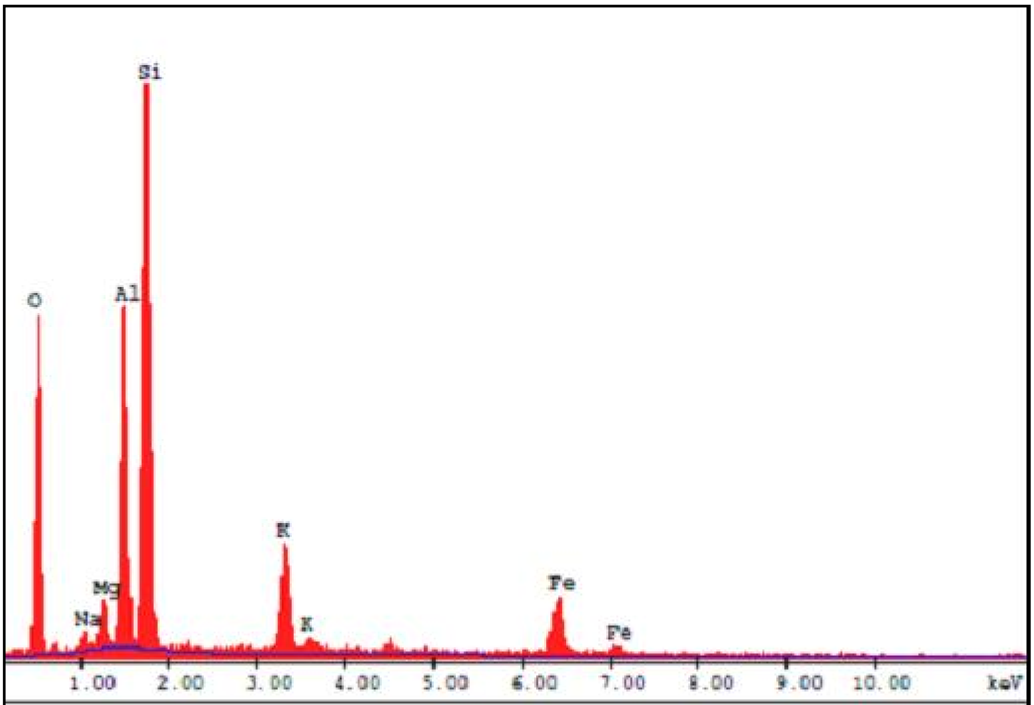
Figure 3.21 SEM images of FA and 10%FA (cured)



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
O K	45.87	62.75	0.1033	1.0324	0.2181	1.0006
MgK	0.61	0.55	0.0021	0.9953	0.3459	1.0091
AlK	13.22	10.73	0.0614	0.9670	0.4753	1.0100
SiK	23.57	18.37	0.1093	0.9962	0.4646	1.0020
MoL	2.15	0.49	0.0127	0.8418	0.7002	1.0036
K K	1.32	0.74	0.0098	0.9461	0.7751	1.0148
CaK	7.63	4.17	0.0616	0.9681	0.8314	1.0034
FeK	5.61	2.20	0.0492	0.8947	0.9785	1.0000
Total	100.00	100.00				

Figure 3.22 EDX diagram of Soma fly ash



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
O K	42.11	57.20	0.1080	1.0316	0.2485	1.0007
NaK	1.30	1.23	0.0034	0.9691	0.2677	1.0058
MgK	2.85	2.55	0.0108	0.9945	0.3757	1.0104
AlK	15.14	12.19	0.0714	0.9663	0.4825	1.0111
SiK	28.47	22.03	0.1278	0.9954	0.4505	1.0010
K K	5.16	2.87	0.0373	0.9445	0.7629	1.0020
FeK	4.96	1.93	0.0439	0.8937	0.9886	1.0000
Total	100.00	100.00				

Figure 3.23 EDX diagram of Elmadağ soft soil

CHAPTER 4

DISCUSSION OF TEST RESULTS

4.1 Particle Size Analysis

Referring to Figure 4.1, percentage of fines decreases gradually and the sample becomes coarser as fly ash content increases. The reason may be flocculation and agglomeration of particles which is also seen in SEM images for stabilized samples. In fact, addition of fly ash did not alter the soil classification. The classification of Elmadağ soft soil remains as CL after adding fly ash up to 10%.

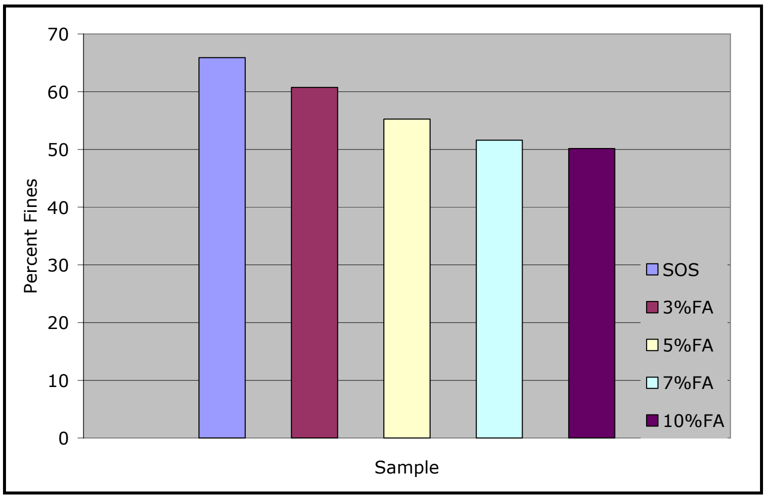


Figure 4.1 Percent fines of samples

4.2 Atterberg Limits

It is clear from Figure 4.2 that plasticity index (PI) values do not change significantly for all stabilized samples. PI values are 12 and 15 for soft soil and 10%FA sample, respectively. Fly ash addition with no curing up to 10 percent is not effective for Elmadağ soft soil concerning plasticity point of view.

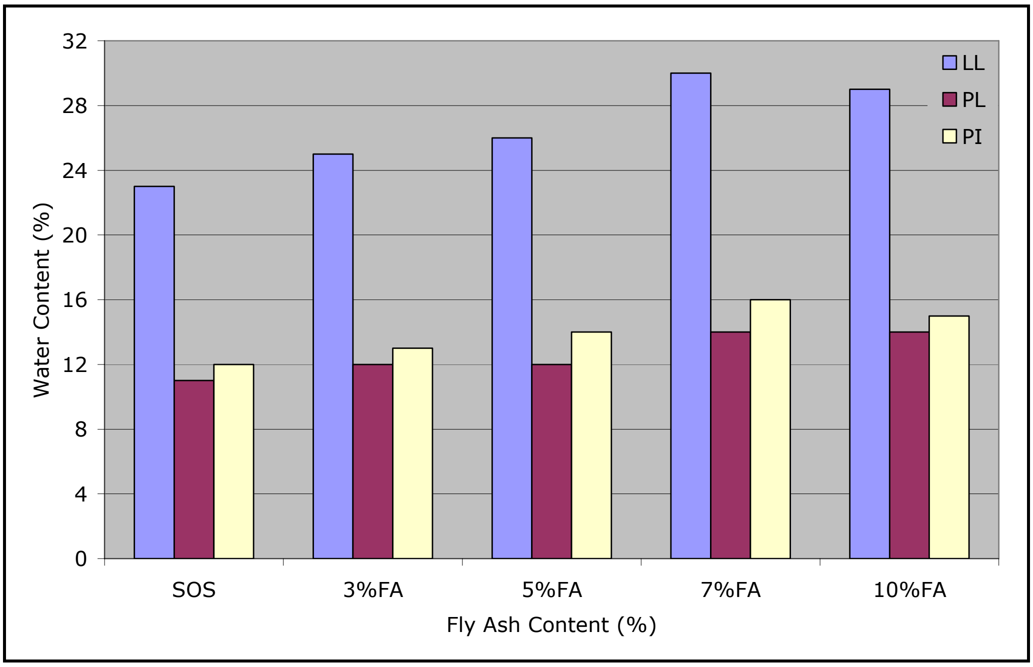


Figure 4.2 Atterberg limits of samples

4.3 Compaction Characteristics

Bell-shaped compaction curves corresponding to modified Proctor effort are shown in Figure 4.3.

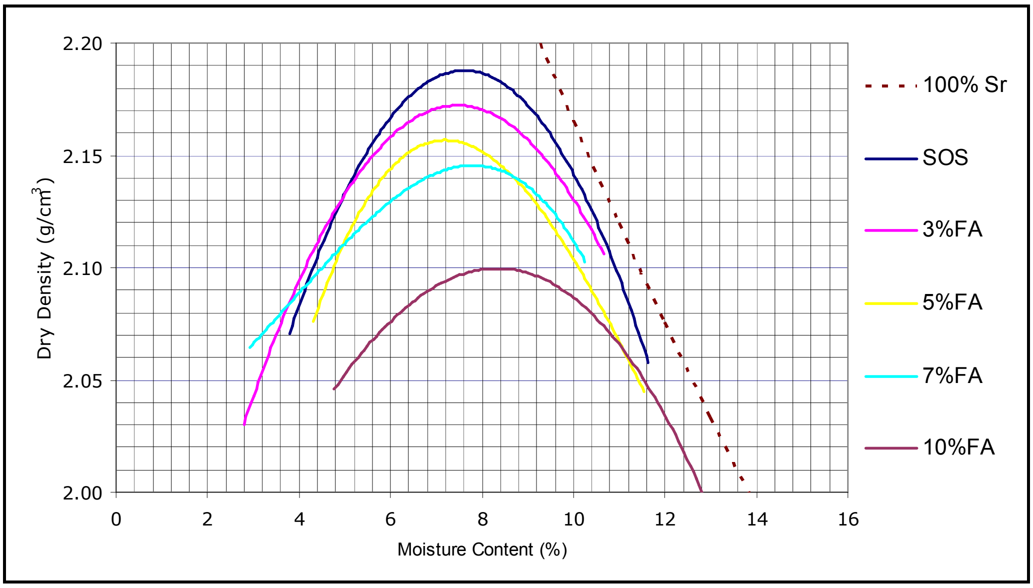


Figure 4.3 Compaction curves for soft soil and fly ash stabilized samples

Fly ash is a lightweight and fine material in the form of powder. Therefore the maximum dry density of soft soil decreases slightly with the addition of fly ash, whatever the mix-design is.

On the other hand, the optimum moisture content varies between 7.20 and 8.34 percent with the addition of fly ash up to 10 percent.

4.4 California Bearing Ratio

The variation in soaked CBR and swell values based on the results of CBR tests performed are shown in Figure 4.4 and 4.5.

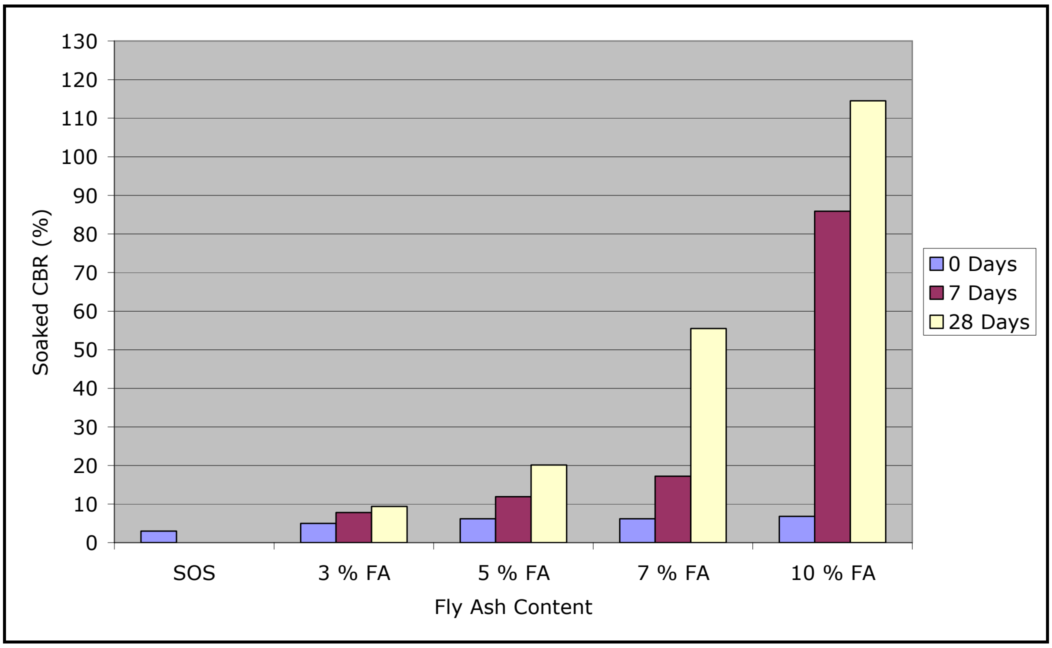


Figure 4.4 Soaked CBR of soft soil and fly ash stabilized samples (cured)

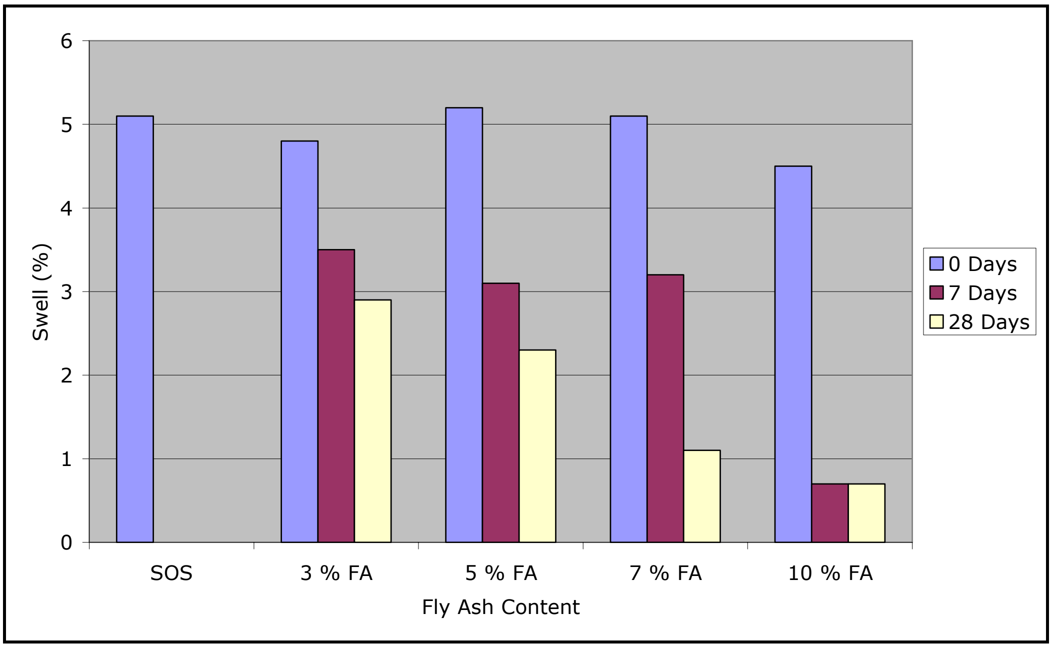


Figure 4.5 Swell of soft soil and fly ash stabilized samples (cured)

The CBR of soft soil compacted to the maximum dry density at its optimum moisture content is approximately 3.0 which implies that the soil is “poor” or “ultra low in strength.

Referring to Figure 4.4, soaking just after compaction slightly increases CBR of samples (with the addition of fly ash). Although the increase is clear it is not very effective from engineering point of view. Referring to Figure 4.5, swell percentages of the samples do not vary considerably without curing. They are almost 5 percent for predetermined amounts of stabilizing agent.

For 7 days cured samples, there is a considerable amount of increase in soaked CBR values. The bearing ratios were increased up to 7.8, 11.9, 17.2, and 85.9 for fly ash contents as 3%, 5%, 7%, and 10%, respectively (Figure 4.4). The swell percentages are approximately 3 percent for fly ash stabilized samples (except 10%FA). Addition of 10% fly ash causes considerable decrease in swell potential. The swell percentage is smaller than 1 percent for 10%FA sample.

For 28 days cured samples, the bearing ratios were increased up to 9.4, 20.1, 55.5, and 114.5, for 3%FA, 5%FA, 7%FA, and 10%FA, respectively. The swell potential is much smaller for all samples compared especially to 0 days cured samples.

4.5 Unconfined Compressive Strength

Since a modified Proctor compaction effort was supplied and there was a volume change in soaked CBR samples due to swell 100% compaction was not attained. But except for 0 day cured samples, a compaction degree of 86% ± 2% was obtained as compaction water contents do not differ so much for 7 and 28 days cured samples.

Referring to Figure 4.6, for 0 days of curing condition, there is a slight increase in UCS values up to 5%FA. But for 7%FA and 10%FA, there is a substantial decrease. The reason most probably related to high compaction water content and low compaction characteristics.

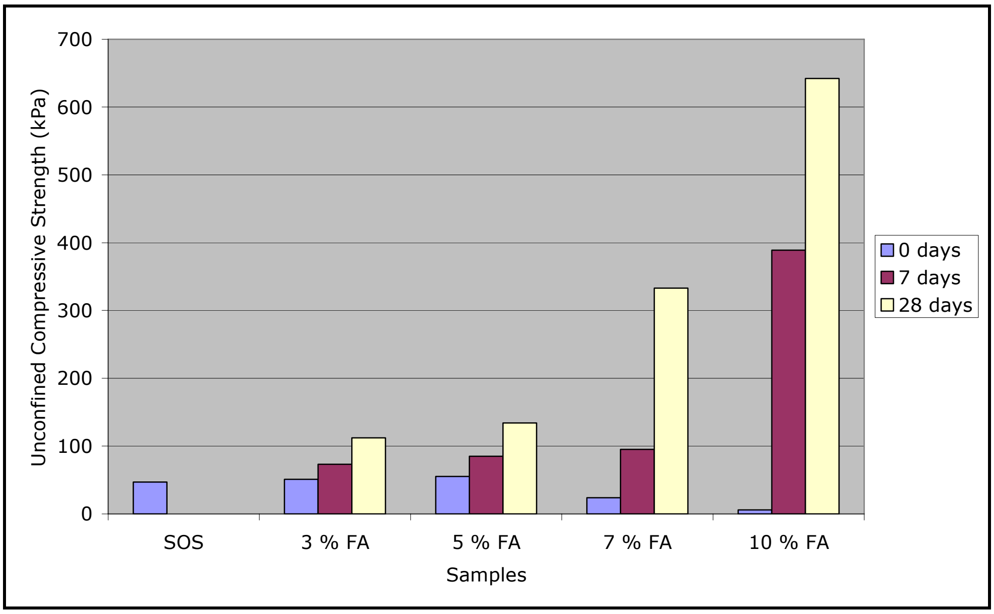


Figure 4.6 UCS of soft soil and fly ash stabilized samples (cured)

For 7 days cured samples, strength gain is clear and the most substantial strength gain is observed for 10%FA sample. Compacted and unstabilized soft soil sample has UCS value of 47 kPa. When 10 percent of fly ash is added and sample is cured for 7 days, UCS value increases up to 389 kPa.

The strength gain is much more valuable for 7%FA and 10%FA samples under 28 days of curing period. In this case UCS values increase up to 333 kPa and 642 kPa, respectively.

Hydrated lime, a well-known stabilizing agent, was used for comparison purpose. Referring to Figure 4.7, it is clear that the stabilizing effect of lime shows a similar behavior with respect to fly ash stabilized samples. Since the compaction water contents are high, UCS values show substantial decrease for lime stabilized samples (0 days cured samples). Similar to fly ash stabilized samples under 7 days of curing, UCS values increase with increasing lime content.

But for 28 days cured samples UCS values decrease with increasing lime content. Further tests on hydrated lime stabilized samples (28 days cured) should be performed in order to verify stabilization characteristics.

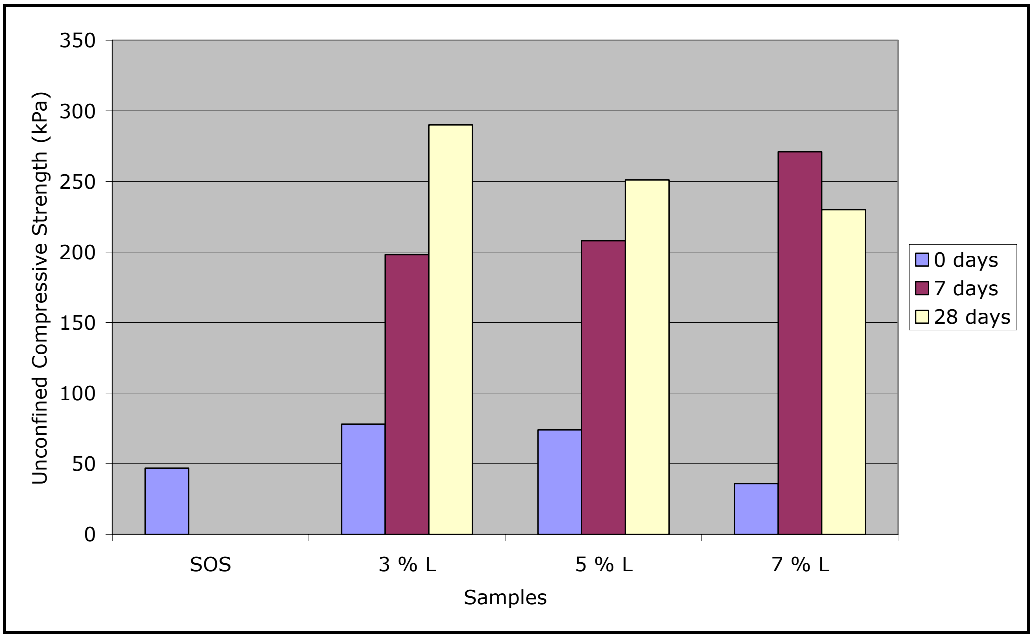


Figure 4.7 UCS of soft soil and hydrated lime stabilized samples (cured)

4.6 SEM-EDX Analysis

SEM-EDX analysis provided fast and accurate results of the microstructure and elemental composition of fly ash and soft soil. In addition, SEM images were taken for fly ash stabilized samples. EDX data indicated that fly ash particles contain O, Mg, Al, Si, Mo, K, Ca, and Fe. Besides, Elmadağ soft soil contains O, Na, Mg, Al, Si, K, and Fe. Existence of potassium content and flake like microstructure show that the main clay mineral in the composition of soft soil is most probably illite. The illites are the only minerals commonly found in the clay size fraction of soils that contain potassium in their structure (Mitchell, 1993).

Referring to Figures 3.20 and 3.21 SEM images indicated that the microstructures of stabilized samples changed due to stabilization process (cementation) and developed with long-term curing.

4.7 Evaluation of Fly Ash Stabilization

Stabilization is recommended for soft soils having undesirable characteristics such as low bearing capacity, high swell and excessive plasticity.

For soils having CBR, swell, and PI characteristics as tabulated in Table 4.1 stabilization is required according to Technical Specification on Highways (Karayolu Teknik Şartnamesi, KTŞ) published by General Directorate of State Highways (Karayolları Genel Müdürlüğü, KGM, Ankara, Turkey). For comparison purpose, characteristics of Elmadağ soft soil are also given in the same table.

Table 4.1 Soil characteristics for stabilization (KTŞ, 2006)

Characteristic	KTŞ	Soft Soil (Elmadağ)	Condition
CBR (%)	< 10.0	3.0	Satisfied
Swell (%)	> 3.0	5.1	Satisfied
PI (%)	≥ 10	12	Satisfied

For design purposes some required characteristics after stabilization are defined by related authorities in pavement applications such as highways and runways. Required characteristics defined by KTŞ (for highways) and by UFC (for runways) are summarized in Table 4.2.

Table 4.2 Required characteristics for pavement layers

Characteristic	Application – Technical Specification			
	Highway - KTŞ			Runway - UFC
Layer	Fill	Grade Section	Subbase	Subbase
CBR (%)	≥ 15	≥ 20	≥ 50	≥ 30
Swell (%)	< 2.0	< 1.0	< 0.5	N/A
LL (%)	< 40	< 30	< 25	≤ 25
PI (%)	< 20	< 10	< 6	≤ 5

The comparison of LL and PI results with pavement layer requirements for highways and runways defined by KTŞ and UFC is tabulated in Table 4.3.

The comparison of CBR and swell results (obtained from soaked CBR tests) with pavement layer requirements defined by KTŞ and UFC are tabulated in Tables 4.4, 4.5, 4.6, and 4.7.

Table 4.3 Comparison of LL and PI for highway and runway requirements (no curing)

Sample	Plasticity		Highway - KTŞ						Runway - UFC	
	LL (%)	PI (%)	Fill		Grade Section		Subbase		Subbase	
			LL	PI	LL	PI	LL	PI	LL	PI
SOS	23	12								
3 % FA	25	13								
5 % FA	26	14								
7 % FA	30	16								
10 % FA	29	15								

Not satisfied

Satisfied

Table 4.4 Comparison of CBR-swell for highway fill layer

Soaking	4 days					
Curing	0 day		7 days		28 days	
Sample	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$
SOS	3.0	5.1	N/A	N/A	N/A	N/A
3 % FA	5.0	4.8	7.8	3.5	9.4	2.9
5 % FA	6.2	5.2	11.9	3.1	20.1	2.3
7 % FA	6.2	5.1	17.2	3.2	55.5	1.1
10 % FA	6.8	4.5	85.9	0.7	114.5	0.7
15 % FA	22.3	4.4	162.0	0.1	N/A	N/A
20 % FA	41.6	3.1	246.0	0.1	N/A	N/A

Not satisfied

Satisfied

Highway fill layer: It is clear from Table 4.3 that all samples satisfy plasticity requirements. According to Table 4.4 CBR and swell requirements are satisfied by 10%FA sample (7 days cured), 7 %FA (28 days cured), and 10%FA (28 days cured).

Table 4.5 Comparison of CBR-swell for highway grade section

Soaking	4 days					
Curing	0 day		7 days		28 days	
Sample	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$
SOS	3.0	5.1	N/A	N/A	N/A	N/A
3 % FA	5.0	4.8	7.8	3.5	9.4	2.9
5 % FA	6.2	5.2	11.9	3.1	20.1	2.3
7 % FA	6.2	5.1	17.2	3.2	55.5	1.1
10 % FA	6.8	4.5	85.9	0.7	114.5	0.7
15 % FA	22.3	4.4	162.0	0.1	N/A	N/A
20 % FA	41.6	3.1	246.0	0.1	N/A	N/A

Not satisfied (orange)
Satisfied (green)

Highway grade section:

It is clear from Table 4.3 that although all samples satisfy LL requirements PI requirement is not satisfied in any case.

According to Table 4.5 CBR and swell requirements are satisfied by 10%FA sample (7 days cured) and 10%FA (28 days cured) at the same time.

Table 4.6 Comparison of CBR-swell for highway subbase layer

Soaking	4 days					
Curing	0 day		7 days		28 days	
Sample	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$
SOS	3.0	5.1	N/A	N/A	N/A	N/A
3 % FA	5.0	4.8	7.8	3.5	9.4	2.9
5 % FA	6.2	5.2	11.9	3.1	20.1	2.3
7 % FA	6.2	5.1	17.2	3.2	55.5	1.1
10 % FA	6.8	4.5	85.9	0.7	114.5	0.7
15 % FA	22.3	4.4	162.0	0.1	N/A	N/A
20 % FA	41.6	3.1	246.0	0.1	N/A	N/A

Not satisfied

Satisfied

Highway subbase layer:

It can generally be concluded from Table 4.3 that plasticity requirements are not satisfied. According to Table 4.6 although CBR requirement is only satisfied by 10%FA sample (7 days cured), 7%FA (28 days cured), and 10%FA (28 days cured) samples swell requirement is not satisfied.

Table 4.7 Comparison of CBR-swell for runway subbase layer

Soaking	4 days					
Curing	0 day		7 days		28 days	
Sample	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$	CBR $_{ave}$	Swell $_{ave}$
SOS	3.0	5.1	N/A	N/A	N/A	N/A
3 % FA	5.0	4.8	7.8	3.5	9.4	2.9
5 % FA	6.2	5.2	11.9	3.1	20.1	2.3
7 % FA	6.2	5.1	17.2	3.2	55.5	1.1
10 % FA	6.8	4.5	85.9	0.7	114.5	0.7
15 % FA	22.3	4.4	162.0	0.1	N/A	N/A
20 % FA	41.6	3.1	246.0	0.1	N/A	N/A

Orange	Not satisfied
Green	Satisfied
Cyan	Not required

Runway subbase layer: Similar to highway subbase layer, it can generally be concluded from Table 4.3 that plasticity requirements are not satisfied. According to Table 4.7 CBR requirement is only satisfied by 10%FA sample (7 days cured), 7%FA (28 days cured), and 10%FA (28 days cured) samples. It can be noted that swell is not a requirement according to UFC specification.

CHAPTER 5

CONCLUSIONS

This research investigated the effect of fly ash addition on some geotechnical properties of Elmadağ soft soil. Fly ash was introduced as stabilizing agent from 0 up to 10% by dry weight of soft soil. Hydrated lime was also used for comparison purpose in Unconfined Compressive Strength tests.

According to the results of the experiments performed at Middle East Technical University Soil Mechanics Laboratory, the conclusions are as follows:

1. Soil classification remains same as CL although percent of fines decreases with increasing fly ash content.

2. Addition of fly ash does not change the plasticity of Elmadağ soft soil significantly.

3. Maximum dry density obtained from modified Proctor test decreases with increasing fly ash content.

4. There is no consistent variation in optimum moisture content with increasing fly ash content.

5. CBR of Elmadağ soft soil increases as the fly ash content increases. Effect of fly ash addition as stabilizing agent is very positive.

6. Addition of fly ash does not change swell of 0 day cured & stabilized samples significantly. It remains approximately same as Elmadağ soft soil. But as curing is applied, i.e., 7 and 28 days, swell decreases significantly. It is smaller than 1 percent for 10%FA sample with 7 and 28 days of curing.

7. Substantial CBR improvement is gained by adding 7% or more fly ash to Elmadağ soft soil.

8. Increase in fly ash content does not increase unconfined compressive strength of 0 day cured samples due to higher compaction moisture content. As compaction moisture content increases unconfined compressive strength of 0 day cured samples decreases although fly ash content increases.

9. For 7 and 28 days cured and fly ash stabilized samples, effect of curing on unconfined compressive strength of samples is positive. The general tendency of bearing capacity improvement is similar to CBR improvement behavior.

10. Increase in hydrated lime content does not change unconfined compressive strength of 0 day cured samples consistently.

11. For 7 days cured and hydrated lime stabilized samples, effect of curing on unconfined compressive strength of samples is positive. But for 28 days cured samples there is decrease in unconfined compressive strength of hydrated lime stabilized samples.

12. The governing clay mineral in Elmadağ soft soil is illite due to existence of potassium ions detected in SEM-EDX analysis. The microstructure of fly ash stabilized and cured samples are very different than fly ash and soft soil.

13. Improvement of bearing capacity of Elmadağ soft soil is possible by the addition of fly ash. 7% or more fly ash addition with curing is very effective in terms of CBR, swell, and unconfined compressive strength.

14. Degree of stabilization is directly related to proper curing conditions. Thus, special care in terms of curing should be taken at the construction site for desired stabilization characteristics. Otherwise it is not possible to obtain similar bearing capacity improvement as obtained in laboratory conditions.

REFERENCES

American Coal Ash Association, ACAA, www.acaa-usa.org, last visited on January 2011.

Arora, S., Aydilek, A. H.,” Class F Fly-Ash-Amended Soils as Highway Base Materials”, Journal of Materials in Civil Engineering, Nov/Dec 2005, pp. 640-649.

Aruntaş, H. Y., “The Potential of Fly Ash Usage in Construction Sector”, Journal of Faculty of Engineering and Architecture of Gazi University, 2006, vol. 21, no. 1, pp. 193-203.

ASTM C 618, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete”, 2008.

ASTM D 1557, “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3(2,700 kN-m/m3))”, 2009.

ASTM D 1883, “Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils”, 2007.

ASTM D 2166, “Standard Test Method for Unconfined Compressive Strength of Cohesive Soil”, 2006.

ASTM D 2487, “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)”, 2010.

ASTM D 4318, “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils”, 2010.
Bergeson, K. L., Pitt, J. M., Demirel T., “Increasing Cementitious Products of a Class C Fly Ash”, Transport Res. Rec., 1985, 998:41

Bin-Shafique, M. S., Edil, T. B., Benson, C. H., and Şenol A., “Incorporated Fly Ash Stabilized Subbase into Pavement Design- A Case Study”, Geotechnical Engineering, 2004, Vol. 157 GE4, pp. 239-249.

Chang, A. C., Lund J. L., Page, L. A., Warneke, E. J., “Physical Properties of Fly Ash Amended Soils”, J. Environ. Qual., 1977, pp. 267-270.

Clarke, J. L., “Structural Lightweight Aggregate Concrete”, Blackie Academic and Professional, 1993, Berkshire.

Çokça, E., “Use of Class C Fly Ashes for the Stabilization of an Expansive Soil”, Journal of Geotechnical and Geo-environmental Engineering”, 2001,127, No.7, pp. 568-573.

Das, B. M., “Advanced Soil Mechanics”, Taylor and Francis Publishers, 1997.

Edil, T. B., Benson, C. H., Bin-Shafique, M. S., Tanyu, B. F., Kim, W., Şenol, A., “Field Evaluation of Construction Alternatives for Roadway over Soft Subgrade”, Transportation Research Record, 2002, 1786, TRB, National Research Council, Washington, DC, pp. 36-48.

Edil, T. B., Acosta, H. A., Benson C. H., “Stabilizing Soft Fine-Graded Soils with Fly Ash”, Journal of Materials in Civil Engineering, 2006, 18:2, pp. 283-294.

Ferguson, G., “Use of self-Cementing Fly Ash as a Soil Stabilizing Agent”, Fly Ash for Soil Improvement, 1993, GSP No. 36, ASCE, Reston, VA, pp. 1-14.

Federal Highway Administration, www.fhwa.dot.gov, last visited on February 2011.

ICAO, International Civil Aviation Organization, Annex 14 to the Convention on International Civil Aviation, Aerodromes, Volume I, “Aerodrome Design and Operations, Fifth Edition”, 2009, Montreal, Quebec, Canada.

Energy & Environmental Research Center, www.undeerc.org, last visited on January 2011.

Lee, S. W., Fishman, K. L., “Resilient and Plastic Behavior of Classifier Tailings and Fly Ash Mixtures”, Transport Res. Rec., October 1993,1418:51–9.

McKerall, W. C., W.B. Ledbetter and D.J. Teague, “Analysis of Fly Ashes Produced in Texas”, Texas Transportation Institute, Research Report No. 240-1, 1982, Texas A&M University, College Station.

Meyers, J. F., Pichumani, R., Kapples, B. S., “Fly Ash: A Highway Construction Material”, Federal Highway Administration, Report No. FHWA-IP-76-16, 1976, Washington, D.C.

Misra, A. “Stabilization Characteristics of Clays Using Class C Fly Ash”, Transportation Research Record 1611, 1998, TRB, National Research Council, Washington, D. C., pp. 46-54.

Mitchell, J. K., “Fundamentals of Soil Behavior”, John Wiley & Sons, 1993.

Naik, T.R., Singh, S.S., "Fly Ash Generation and Utilization- An Overview", Proceedings of Workshop on Flowable Slurry Containing Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, 1995, Vol. 1, pp. 1-32, Milwaukee, Wisconsin.

Prabakar J., Dendorkar, N., Morchhale, R. K, "Influence of Fly Ash Strength Behavior of Typical Soils", Construction and Building Materials 18, 2004, pp. 263-267.

Puppala, A. J., Musenda, C., "Effect of Fiber Reinforcement on Strength and Volume Change in Expansive Soils", Transportation Res. Rec. 1736., 2000, No. 00-0716.

Scheetz, B. E., Earle, R., "Utilization of Fly Ash", Current Opinion in Solid State & Materials Science, 1998, Vol. 3, pp. 510-520.

SEAS Soma Electricity Production and Trade Company, www.seas.gov.tr, last visited on May 2011.

Şenol, A., Edil, T. B. Bin-Shafique, M. S., Acosta, H., Benson, C. H., "Soft Subgrades' Stabilization by Using Various Fly Ashes", Resources, Conservation and Recycling, April 2006, v 46, n 4, pp. 365-76.

Şenol, A., Bin-Shafique, M. S., Edil, T. B. and Benson, C. H., "Use of Class C Fly Ash for the Stabilization of Soft Subgrade", ARI, The Bulletin of the İstanbul Technical University, 2003, Vol.53, pp. 89-95.

Technical Specification on Highways, General Directorate of State Highways, 2006, Ankara

TRB, Lime Stabilization: Reactions, Properties, Design, and Construction, State of the Art Report 5. Transportation Research Board, National Research Council, Washington, D.C., 1987.

TS 1901, "Methods for Boring and Obtaining Disturbed and Undisturbed Samples for Civil Engineering Purposes", 1975.

Turner, J.P. , "Evaluation of Western Coal Fly Ashes for Stabilization of Low-Volume Roads", ASTM Special Technical Publication, 1997, 1275, Conshohocken, PA, USA: ASTM; pp. 157-171.

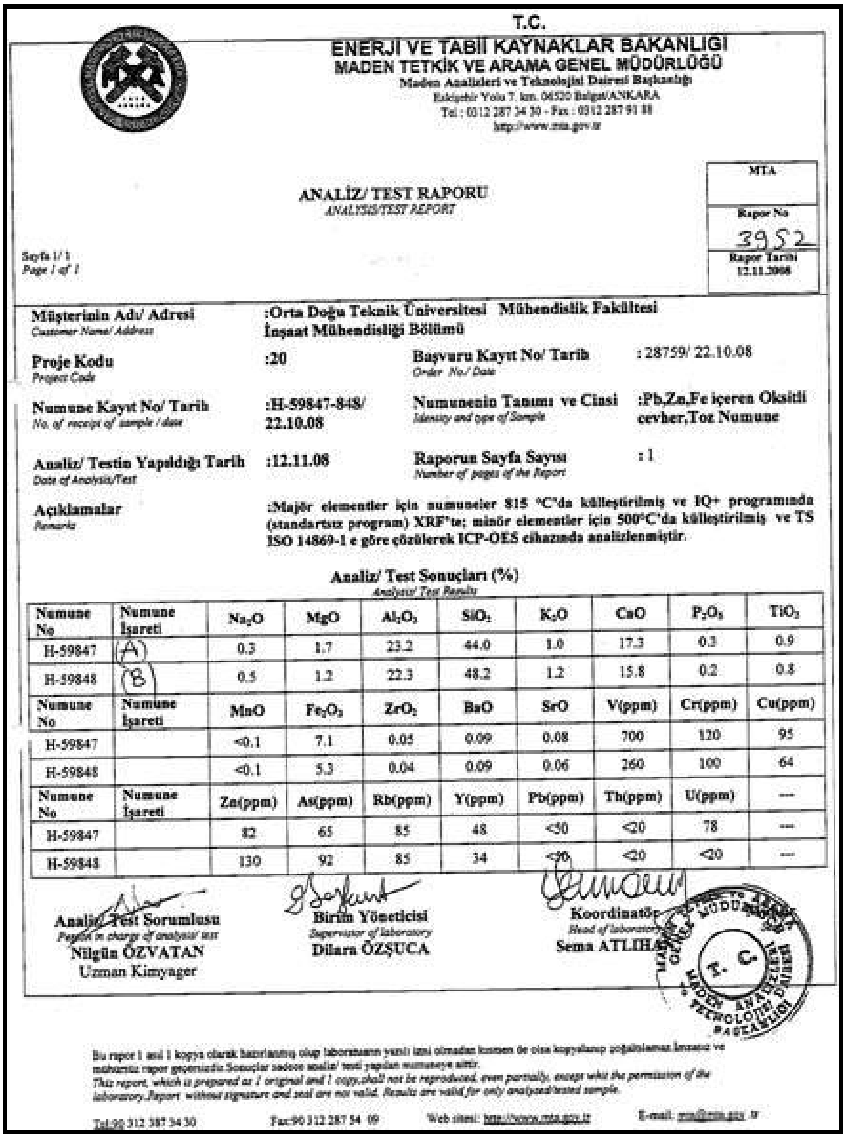
Türker, P., Erdoğan, B., Katnaş, F., and Yeğinobalı, A., "Türkiye'deki Uçucu Küllerin Sınıflandırılması ve Özellikleri", Türkiye Çimento Müstahsilleri Birliği, 2003.

UFC, "Pavement Design For Airfields", 3-260-02, Washington, D.C., 2001.

USAEWES, "The Unified Soil Classification System", Technical Memorandum No. 3-357, Appendix B, Characteristics of Soil Groups Pertaining to Roads and Airfields, 1957.

APPENDIX A

SOMA FLY ASH ANALYSIS REPORT



T.C.

ENERJİ VE TABİİ KAYNAKLAR BAKANLIĞI

MADEN TETKİK VE ARAMA GENEL MÜDÜRLÜĞÜ

Maden Analizleri ve Teknolojisi Dairesi Başkanlığı

Eskişehir Yolu 7. km. 06520 Balgat/ANKARA

Tel : 0312 287 34 30 - Fax : 0312 287 91 88

http://www.mta.gov.tr

MTA

Rapor No: 3952

Rapor Tarihi: 12.11.2008

ANALİZ/ TEST RAPORU

ANALYSIS/TEST REPORT

Sayfa 1/1
Page 1 of 1

Müşterinin Adı/ Adresi *Customer Name/ Address*	:Orta Doğu Teknik Üniversitesi Mühendislik Fakültesi İnşaat Mühendisliği Bölümü		
Proje Kodu *Project Code*	:20	**Başvuru Kayıt No/ Tarih** *Order No/ Date*	: 28759/ 22.10.08
Numune Kayıt No/ Tarih *No. of receipt of sample / date*	:H-59847-848/ 22.10.08	**Numunenin Tanımı ve Cinsi** *Identity and type of Sample*	:Pb,Zn,Fe içeren Oksitli cevher,Toz Numune
Analiz/ Testin Yapıldığı Tarih *Date of Analysis/Test*	:12.11.08	**Raporun Sayfa Sayısı** *Number of pages of the Report*	: 1

Açıklamalar *Remarks*: Majör elementler için numuneler 815 °C'da külleştirilmiş ve IQ+ programında (standartsız program) XRF'te; minör elementler için 500°C'da külleştirilmiş ve TS ISO 14869-1 e göre çözülerek ICP-OES cihazında analizlenmiştir.

Analiz/ Test Sonuçları (%)
Analysis/ Test Results

Numune No	Numune İşareti	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	P_2O_5	TiO_2
H-59847	(A)	0.3	1.7	23.2	44.0	1.0	17.3	0.3	0.9
H-59848	(B)	0.5	1.2	22.3	48.2	1.2	15.8	0.2	0.8

Numune No	Numune İşareti	MnO	Fe_2O_3	ZrO_2	BaO	SrO	V(ppm)	Cr(ppm)	Cu(ppm)
H-59847		<0.1	7.1	0.05	0.09	0.08	700	120	95
H-59848		<0.1	5.3	0.04	0.09	0.06	260	100	64

Numune No	Numune İşareti	Zn(ppm)	As(ppm)	Rb(ppm)	Y(ppm)	Pb(ppm)	Th(ppm)	U(ppm)	---
H-59847		82	65	85	48	<50	<20	78	---
H-59848		130	92	85	34	<50	<20	<20	---

Analiz/ Test Sorumlusu	**Birim Yöneticisi**	**Koordinatör**
Person in charge of analysis/ test	*Supervisor of laboratory*	*Head of laboratory*
Nilgün ÖZVATAN	Dilara ÖZŞUCA	Sema ATLIHAN
Uzman Kimyager		

Bu rapor 1 asıl 1 kopya olarak hazırlanmış olup laboratuvarın yazılı izni olmadan kısmen de olsa kopyalanıp çoğaltılamaz. İmzasız ve mühürsüz rapor geçersizdir. Sonuçlar sadece analiz/ testi yapılan numuneye aittir.

This report, which is prepared as 1 original and 1 copy, shall not be reproduced, even partially, except with the permission of the laboratory. Report without signature and seal are not valid. Results are valid for only analyzed/tested sample.

Tel:90 312 287 34 30 Fax:90 312 287 54 09 Web sitesi: http://www.mta.gov.tr E-mail: mta@mta.gov.tr

Figure A-1: Analysis report of Soma fly ash

APPENDIX B

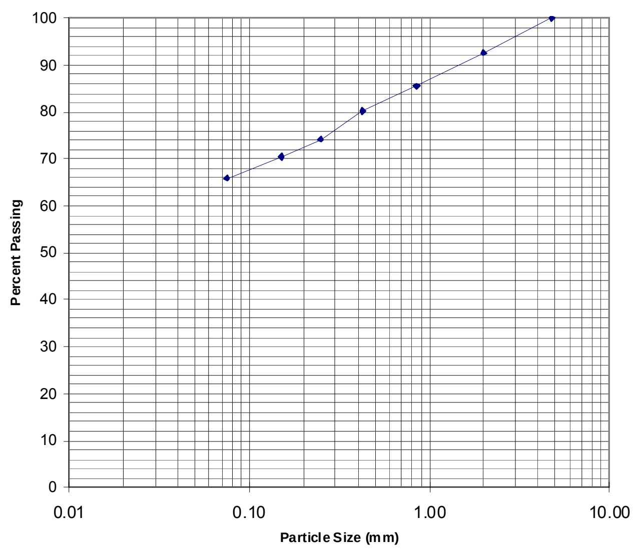
PARTICLE SIZE ANALYSIS

Table B-1: Particle size analysis test (SOS)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
PARTICLE SIZE ANALYSIS TEST

General information about sample and test procedure			
Location	Elmadağ/Ankara	Test date	01.02.2011
Sample name	SOS	Tested by	Murat Aziz ÖZDEMİR
Mass of sample, (g)	500.0 Dry	Soil classification	CL
Condition of sample	Soaked - Wet		

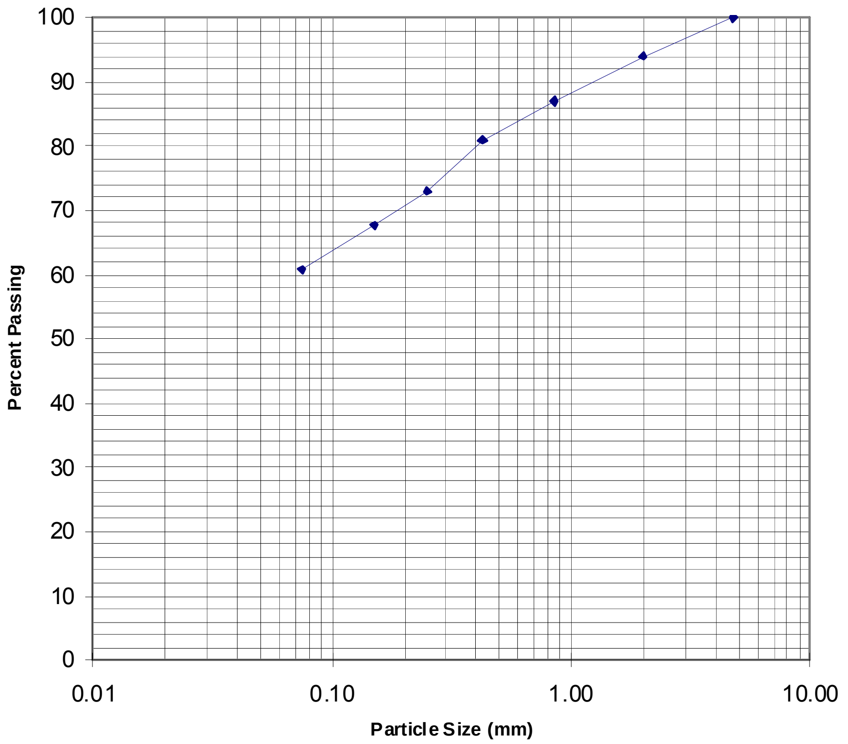
ASTM test sieves	Sieve openings (mm)	Mass retained (g)	Cumulative mass retained (g)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
No. 4	4.750	0.0	0.0	0.0	100.0
No. 10	2.000	36.8	36.8	7.4	92.6
No. 20	0.850	35.5	72.3	14.5	85.5
No. 40	0.425	26.6	99.0	19.8	80.2
No. 60	0.250	30.0	129.0	25.8	74.2
No. 100	0.150	18.5	147.4	29.5	70.5
No. 200	0.075	23.0	170.4	34.1	65.9
Total		170.4			



Summary of test results			
Sand content	Passing No. 4 & retained on No. 200	%	34.1
Fines content	Passing No. 200	%	65.9

Table B-2: Particle size analysis test (3%FA)

MIDDLE EAST TECHNICAL UNIVERSITY SOIL MECHANICS LABORATORY PARTICLE SIZE ANALYSIS TEST					
General information about sample and test procedure					
Location	Elmadağ/Ankara		Test date	01.02.2011	
Sample name	3%FA		Tested by	Murat Aziz ÖZDEMİR	
Mass of sample, (g)	500.0 Dry		Soil classification		CL
Condition of sample	Soaked - Wet				
ASTM test sieves	**Sieve openings (mm)**	**Mass retained (g)**	**Cumulative mass retained (g)**	**Cumulative percentage retained (%)**	**Cumulative percentage passing (%)**
No. 4	4.750	0.0	0.0	0.0	100.0
No. 10	2.000	30.3	30.3	6.1	93.9
No. 20	0.850	34.7	65.0	13.0	87.0
No. 40	0.425	30.8	95.8	19.2	80.8
No. 60	0.250	39.2	134.9	27.0	73.0
No. 100	0.150	26.3	161.3	32.3	67.8
No. 200	0.075	35.0	196.2	39.2	60.8
Total		196.2			



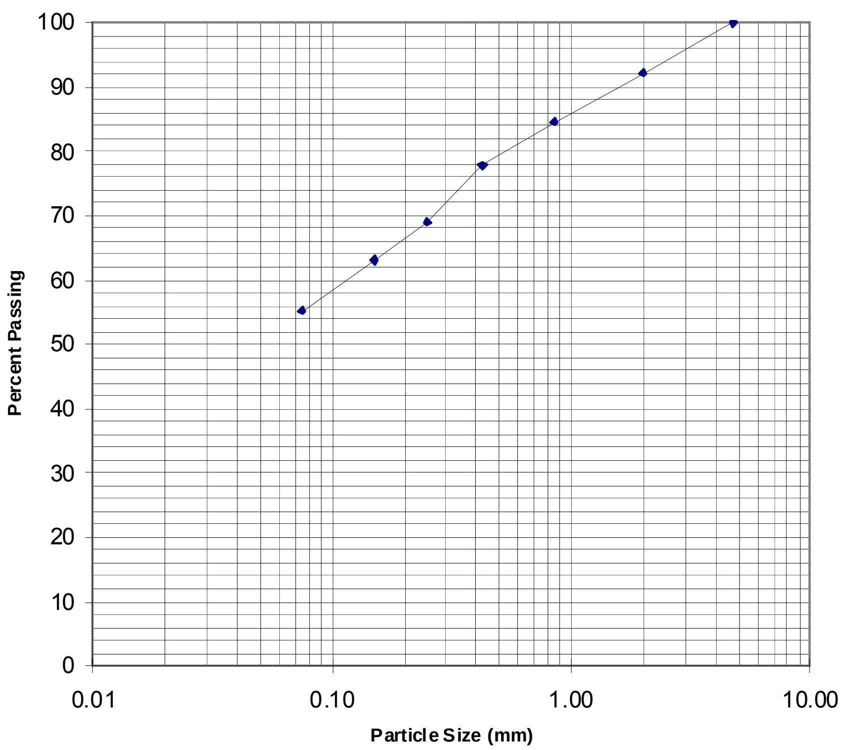
Summary of test results			
Sand content	Passing No. 4 & retained on No. 200	%	39.2
Fines content	Passing No. 200	%	60.8

Table B-3: Particle size analysis test (5%FA)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
PARTICLE SIZE ANALYSIS TEST

General information about sample and test procedure			
Location	Elmadağ/Ankara	Test date	01.02.2011
Sample name	5%FA	Tested by	Murat Aziz ÖZDEMİR
Mass of sample, (g)	500.0 Dry	Soil classification	CL
Condition of sample	Soaked - Wet		

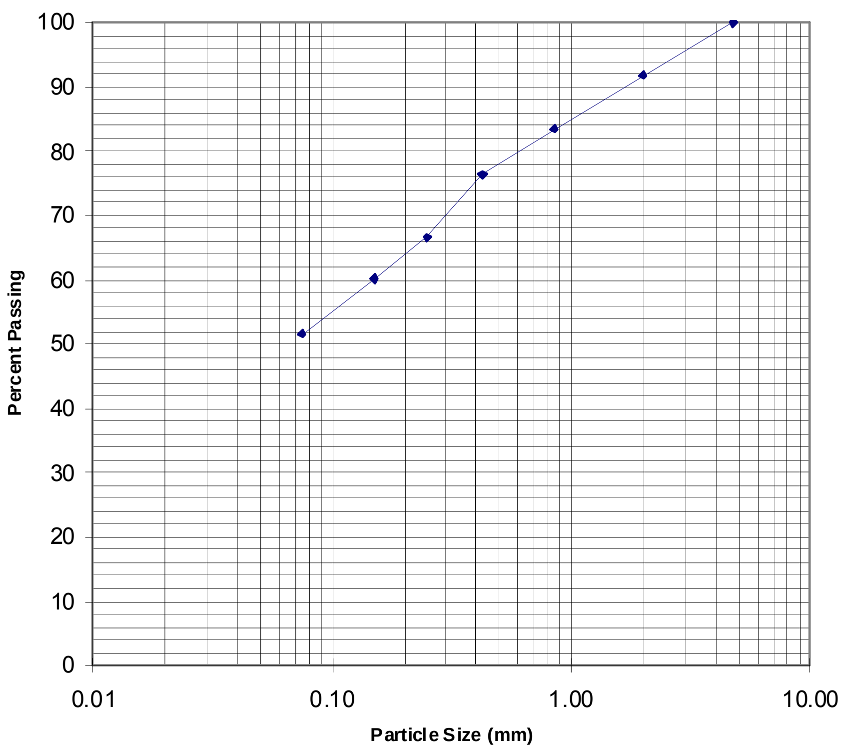
ASTM test sieves	Sieve openings (mm)	Mass retained (g)	Cumulative mass retained (g)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
No. 4	4.750	0.0	0.0	0.0	100.0
No. 10	2.000	39.1	39.1	7.8	92.2
No. 20	0.850	38.3	77.4	15.5	84.5
No. 40	0.425	33.5	110.9	22.2	77.8
No. 60	0.250	44.1	155.0	31.0	69.0
No. 100	0.150	29.7	184.7	36.9	63.1
No. 200	0.075	39.1	223.8	44.8	55.3
Total		223.8			



Summary of test results			
Sand content	Passing No. 4 & retained on No. 200	%	44.8
Fines content	Passing No. 200	%	55.3

Table B-4: Particle size analysis test (7%FA)

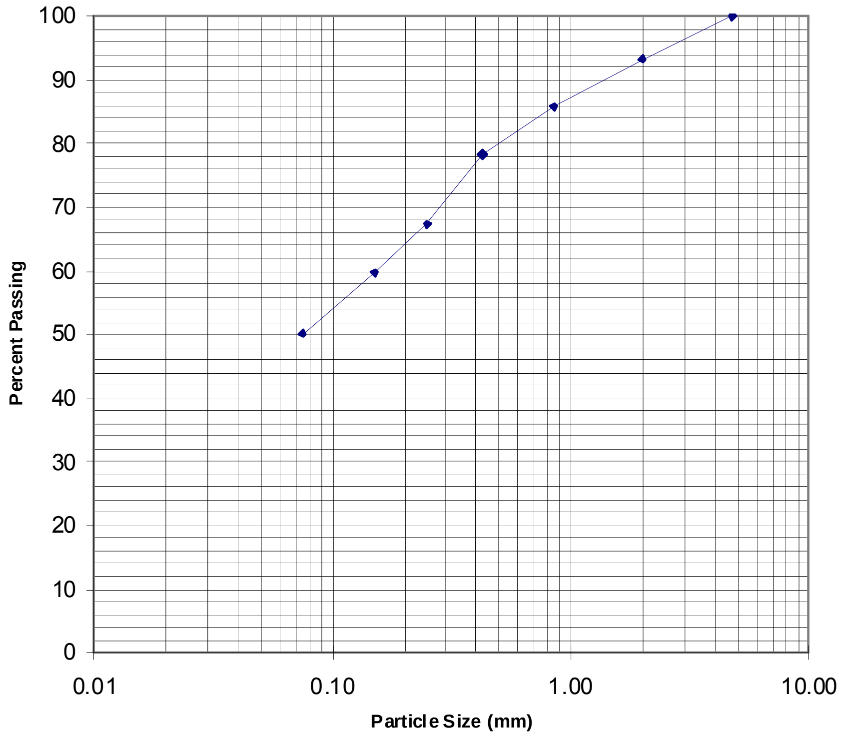
MIDDLE EAST TECHNICAL UNIVERSITY SOIL MECHANICS LABORATORY PARTICLE SIZE ANALYSIS TEST					
General information about sample and test procedure					
Location	Elmadağ/Ankara		Test date	01.02.2011	
Sample name	7%FA		Tested by	Murat Aziz ÖZDEMİR	
Mass of sample, (g)	500.0 Dry		Soil classification		CL
Condition of sample	Soaked - Wet				
ASTM test sieves	**Sieve openings (mm)**	**Mass retained (g)**	**Cumulative mass retained (g)**	**Cumulative percentage retained (%)**	**Cumulative percentage passing (%)**
No. 4	4.750	0.0	0.0	0.0	100.0
No. 10	2.000	41.6	41.6	8.3	91.7
No. 20	0.850	40.9	82.5	16.5	83.5
No. 40	0.425	35.6	118.1	23.6	76.4
No. 60	0.250	48.6	166.7	33.3	66.7
No. 100	0.150	32.3	199.0	39.8	60.2
No. 200	0.075	43.1	242.1	48.4	51.6
Total		242.1			



Summary of test results			
Sand content	Passing No. 4 & retained on No. 200	%	48.4
Fines content	Passing No. 200	%	51.6

Table B-5: Particle size analysis test (10%FA)

MIDDLE EAST TECHNICAL UNIVERSITY SOIL MECHANICS LABORATORY PARTICLE SIZE ANALYSIS TEST					
General information about sample and test procedure					
Location	Elmadağ/Ankara		Test date	01.02.2011	
Sample name	10%FA		Tested by	Murat Aziz ÖZDEMİR	
Mass of sample, (g)	500.0 Dry		Soil classification		CL
Condition of sample	Soaked - Wet				
ASTM test sieves	**Sieve openings (mm)**	**Mass retained (g)**	**Cumulative mass retained (g)**	**Cumulative percentage retained (%)**	**Cumulative percentage passing (%)**
No. 4	4.750	0.0	0.0	0.0	100.0
No. 10	2.000	33.4	33.4	6.7	93.3
No. 20	0.850	37.4	70.8	14.2	85.9
No. 40	0.425	37.8	108.5	21.7	78.3
No. 60	0.250	55.1	163.6	32.7	67.3
No. 100	0.150	37.7	201.3	40.3	59.7
No. 200	0.075	47.9	249.3	49.9	50.2
Total		249.3			



Summary of test results			
Sand content	Passing No. 4 & retained on No. 200	%	49.9
Fines content	Passing No. 200	%	50.2

APPENDIX C

CALIFORNIA BEARING RATIO (CBR)

Table C-1: CBR test (SOS, 0+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

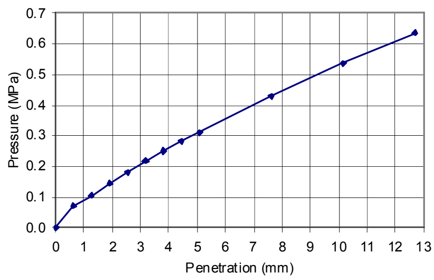
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	0% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.188	Condition of sample	Soaked
Optimum moisture content, (%)	7.63	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.11.2010
Initial height of sample, (mm)	116	End date	27.11.2010
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,165	12,385
Mass of mould + base, W_1, (g)	7,250	7,250
Mass of compacted specimen, $W_2 - W_1$, (g)	4,915	5,135
Bulk density, ρ = ($W_2 - W_1$) / V, (g/cm^3)	2.314	2.418
Dry density, ρ_d = 1000 / 100 + m, (g/cm^3)	2.147	2.107
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	362.00	268.20
Mass of container + dry soil, W_1, (g)	345.10	238.77
Mass of container, W_3, (g)	127.59	39.26
Mass of moisture, ($W_2 - W_1$), (g)	16.90	29.43
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.77	14.75

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		141	0.073		
1.27		206	0.106		
1.91		281	0.145		
2.54	6.9	353	0.182		2.6
3.18		422	0.218		
3.81		485	0.251		
4.45		545	0.282		
5.08	10.3	604	0.312		3.0
7.62		832	0.430		
10.16		1,041	0.538		
12.70		1,233	0.637		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	10	5.0
1	226	
2	411	
3	523	
4	596	

CBR (%)

3.0

Table C-2: CBR test (SOS, 0+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	0% FA / #3	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.188	Condition of sample	Soaked
Optimum moisture content, (%)	7.63	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.11.2010
Initial height of sample, (mm)	116	End date	27.11.2010
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

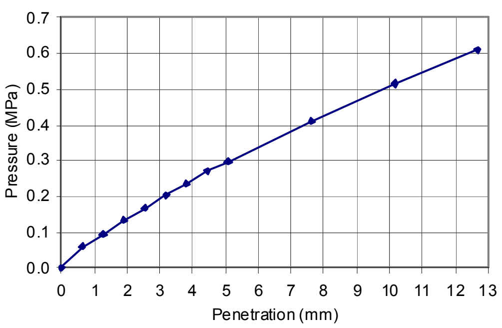
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,905	13,099
Mass of mould + base, W_1, (g)	7,956	7,956
Mass of compacted specimen, $W_2 - W_1$, (g)	4,949	5,143
Bulk density, $0 = (W_2 - W_1) / V$, (g/cm^3)	2.330	2.421
Dry density, $0_d = 1000 / 100 + m$, (g/cm^3)	2.162	2.109

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	136.24	252.83
Mass of container + dry soil, W_1, (g)	128.98	225.01
Mass of container, W_3, (g)	35.49	36.75
Mass of moisture, $(W_2 - W_1)$, (g)	7.26	27.82
Moisture content, $m = (W_2 - W_1) / (W_1 - W_3) \times 100$, (%)	7.77	14.78

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		117	0.060		
1.27		183	0.095		
1.91		257	0.133		
2.54	6.9	326	0.168		2.4
3.18		392	0.203		
3.81		454	0.235		
4.45		525	0.271		
5.08	10.3	577	0.298		2.9
7.62		796	0.411		
10.16		999	0.516		
12.70		1,182	0.611		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	5.1
1	183	
2	337	
3	435	
4	590	

CBR (%)

2.9

Table C-3: CBR test (3%FA, 0+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	3% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.01.2011
Initial height of sample, (mm)	116	End date	27.01.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

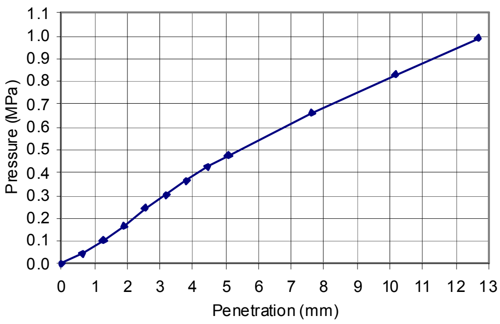
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,780	13,016
Mass of mould + base, W_1, (g)	7,940	7,940
Mass of compacted specimen, W_2 - W_1, (g)	4,840	5,076
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.279	2.390
Dry density, 2_d = 1002/ 100 + m, (g/cm^3)	2.123	2.061

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	565.15	609.03
Mass of container + dry soil, W_1, (g)	535.87	558.38
Mass of container, W_3, (g)	138.13	241.46
Mass of moisture, (W_2 - W_1), (g)	29.28	50.65
Moisture content, m = (W_2 - W_1)/ (W_1 - W_3) x 100, (%)	7.36	15.98

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		90	0.047		
1.27		200	0.103		
1.91		326	0.168		
2.54	6.9	473	0.244	0.287	4.2
3.18		586	0.303		
3.81		706	0.365		
4.45		826	0.427		
5.08	10.3	925	0.478	0.505	4.9
7.62		1,284	0.664		
10.16		1,607	0.830		
12.70		1,921	0.993		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	4.7
1	459	
2	531	
3	540	
4	544	

CBR (%)

4.9

Table C-4: CBR test (3%FA, 0+4 Days, Sample 2)

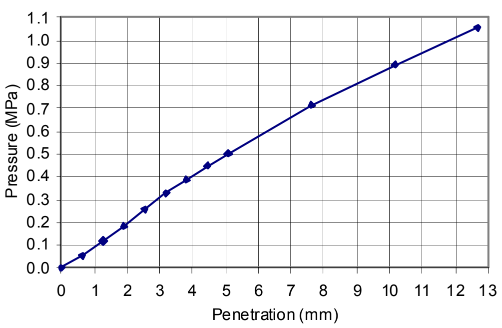
MIDDLE EAST TECHNICAL UNIVERSITY SOIL MECHANICS LABORATORY CALIFORNIA BEARING RATIO TEST			
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	3% FA / #2	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	31.03.2011
Initial height of sample, (mm)	116	End date	04.04.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	12,415	12,612
Mass of mould + base, W_1, (g)	7,619	7,619
Mass of compacted specimen, W_2 - W_1, (g)	4,796	4,993
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.258	2.351
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.105	2.026
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	287.31	505.06
Mass of container + dry soil, W_1, (g)	270.22	468.71
Mass of container, W_3, (g)	35.49	241.81
Mass of moisture, (W_2 - W_1), (g)	17.09	36.35
Moisture content, m = (W_2 - W_1) / (W_1 - W_3) x 100, (%)	7.28	16.02

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		101	0.052		
1.27		228	0.118		
1.91		356	0.184		
2.54	6.9	503	0.260	0.291	4.2
3.18		636	0.329		
3.81		751	0.388		
4.45		873	0.451		
5.08	10.3	975	0.504	0.528	5.1
7.62		1,387	0.717		
10.16		1,726	0.892		
12.70		2,047	1.058		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	4.9
1	471	
2	554	
3	567	
4	572	

CBR (%)

5.1

Table C-5: CBR test (5%FA, 0+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	5% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	15.12.2010
Initial height of sample, (mm)	116	End date	19.12.2010
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

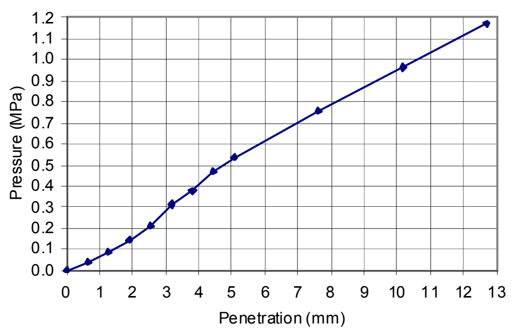
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	11,923	12,165
Mass of mould + base, W_1, (g)	7,188	7,188
Mass of compacted specimen, W_2 - W_1, (g)	4,735	4,977
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.229	2.343
Dry density, 2_d = 1002/ 100 + m, (g/cm^3)	2.079	1.999

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	482.61	200.08
Mass of container + dry soil, W_1, (g)	458.68	175.31
Mass of container, W_3, (g)	128.36	31.41
Mass of moisture, (W_2 - W_1), (g)	23.93	24.77
Moisture content, m = (W_2 - W_1)/ (W_1 - W_3) x 100, (%)	7.24	17.21

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		75	0.039		
1.27		162	0.084		
1.91		274	0.142		
2.54	6.9	407	0.210	0.375	5.4
3.18		604	0.312		
3.81		733	0.379		
4.45		904	0.467		
5.08	10.3	1,035	0.535	0.638	6.2
7.62		1,463	0.756		
10.16		1,867	0.965		
12.70		2,271	1.174		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	60	5.1
1	575	
2	619	
3	640	
4	650	

CBR (%)

6.2

Table C-6: CBR test (5%FA, 0+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

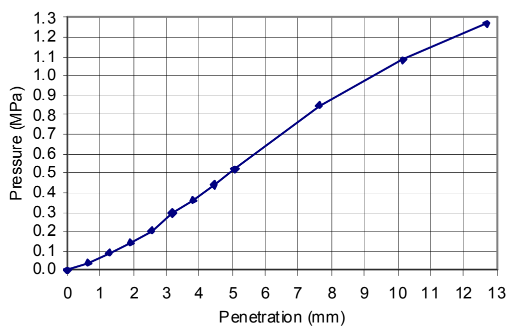
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	5% FA / #2	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	31.03.2011
Initial height of sample, (mm)	116	End date	04.04.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	11,950	12,169
Mass of mould + base, W_1, (g)	7,201	7,201
Mass of compacted specimen, $W_2 - W_1$, (g)	4,749	4,968
Bulk density, 2 = ($W_2 - W_1$) / V, (g/cm^3)	2.236	2.339
Dry density, 2_d = 1002/ 100 + m, (g/cm^3)	2.082	2.008
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	238.20	312.44
Mass of container + dry soil, W_1, (g)	224.53	273.58
Mass of container, W_3, (g)	39.26	37.81
Mass of moisture, ($W_2 - W_1$), (g)	13.67	38.86
Moisture content, m = ($W_2 - W_1$)/ ($W_1 - W_3$) x 100, (%)	7.38	16.48

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		71	0.037		
1.27		177	0.091		
1.91		274	0.142		
2.54	6.9	397	0.205	0.325	4.7
3.18		569	0.294		
3.81		698	0.361		
4.45		853	0.441		
5.08	10.3	1,009	0.521	0.624	6.1
7.62		1,638	0.847		
10.16		2,096	1.083		
12.70		2,456	1.269		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	41	5.3
1	533	
2	581	
3	609	
4	653	

CBR (%)

6.1

Table C-7: CBR test (7%FA, 0+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	7% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.01.2011
Initial height of sample, (mm)	116	End date	27.01.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

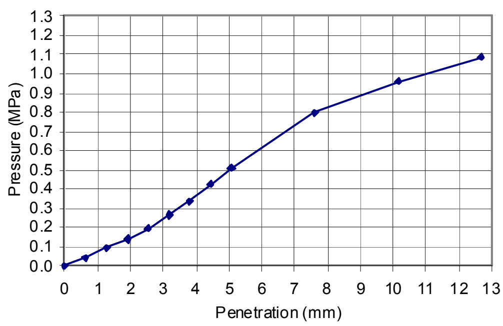
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,420	12,812
Mass of mould + base, W_1, (g)	7,720	7,720
Mass of compacted specimen, $W_2 - W_1$, (g)	4,700	5,092
Bulk density, 2 = ($W_2 - W_1$) / V, (g/cm^3)	2.213	2.397
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.059	1.987

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	470.18	827.06
Mass of container + dry soil, W_1, (g)	454.32	725.97
Mass of container, W_3, (g)	241.81	235.78
Mass of moisture, ($W_2 - W_1$), (g)	15.86	101.09
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.46	20.62

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		84	0.043		
1.27		183	0.095		
1.91		269	0.139		
2.54	6.9	381	0.197	0.330	4.8
3.18		513	0.265		
3.81		654	0.338		
4.45		824	0.426		
5.08	10.3	991	0.512	0.630	6.1
7.62		1,547	0.799		
10.16		1,855	0.959		
12.70		2,107	1.089		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	
1	394	
2	477	4.6
3	511	
4	532	

CBR (%)

6.1

Table C-8: CBR test (7%FA, 0+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	7% FA / #2	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	20.02.2011
Initial height of sample, (mm)	116	End date	24.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

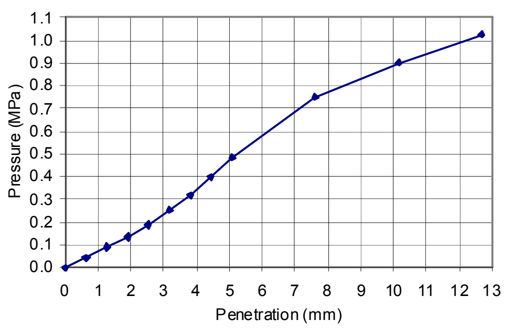
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	11,925	12,280
Mass of mould + base, W_1, (g)	7,355	7,355
Mass of compacted specimen, W_2 - W_1, (g)	4,570	4,925
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.152	2.319
Dry density, 2_d = 1002/ 100 + m, (g/cm^3)	2.002	1.902

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	580.74	782.61
Mass of container + dry soil, W_1, (g)	557.18	684.84
Mass of container, W_3, (g)	241.80	239.21
Mass of moisture, (W_2 - W_1), (g)	23.56	97.77
Moisture content, m = (W_2 - W_1)/ (W_1 - W_3) x 100, (%)	7.47	21.94

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		83	0.043		
1.27		175	0.090		
1.91		259	0.134		
2.54	6.9	364	0.188	0.345	5.0
3.18		488	0.252		
3.81		619	0.320		
4.45		771	0.398		
5.08	10.3	936	0.484	0.645	6.3
7.62		1,450	0.749		
10.16		1,746	0.902		
12.70		1,982	1.024		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	16	5.5
1	504	
2	583	
3	632	
4	651	

CBR (%)

6.3

Table C-9: CBR test (10%FA, 0+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	10% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.100	Condition of sample	Soaked
Optimum moisture content, (%)	8.34	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	15.12.2010
Initial height of sample, (mm)	116	End date	19.12.2010
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

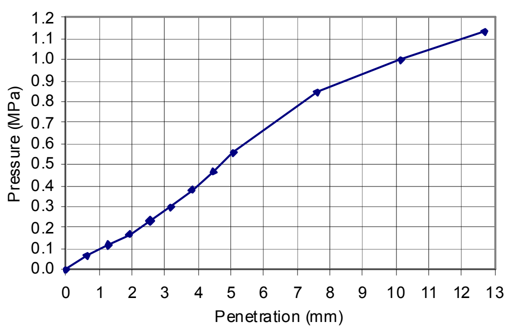
Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	12,037	12,349
Mass of mould + base, W_1, (g)	7,383	7,383
Mass of compacted specimen, W_2 - W_1, (g)	4,654	4,966
Bulk density, ρ = (W_2 - W_1) / V, (g/cm^3)	2.191	2.338
Dry density, ρ_d = 100ρ/ 100 + m, (g/cm^3)	2.021	1.865

Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	260.48	238.98
Mass of container + dry soil, W_1, (g)	243.26	198.03
Mass of container, W_3, (g)	38.18	36.75
Mass of moisture, (W_2 - W_1), (g)	17.22	40.95
Moisture content, m = (W_2 - W_1) / (W_1 - W_3) x 100, (%)	8.40	25.39

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		132	0.068		
1.27		230	0.119		
1.91		329	0.170		
2.54	6.9	452	0.234	0.385	5.6
3.18		580	0.300		
3.81		733	0.379		
4.45		904	0.467		
5.08	10.3	1,080	0.558	0.690	6.7
7.62		1,634	0.844		
10.16		1,930	0.997		
12.70		2,199	1.136		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	4.5
1	456	
2	501	
3	518	
4	527	

CBR (%)

6.7

Table C-10: CBR test (10%FA, 0+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	0 days
Sample name and number	10% FA / #2	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.100	Condition of sample	Soaked
Optimum moisture content, (%)	8.34	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	15.12.2010
Initial height of sample, (mm)	116	End date	19.12.2010
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

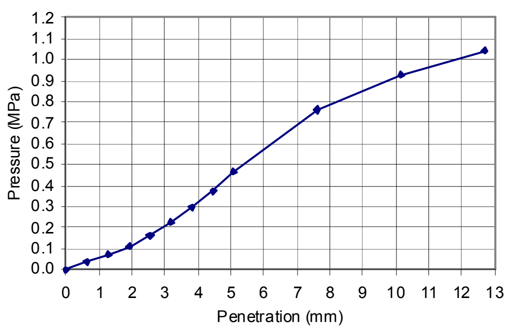
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,458	12,791
Mass of mould + base, W_1, (g)	7,712	7,712
Mass of compacted specimen, $W_2 - W_1$, (g)	4,746	5,079
Bulk density, ρ = ($W_2 - W_1$) / V, (g/cm^3)	2.234	2.391
Dry density, ρ_d = 100ρ / 100 + m, (g/cm^3)	2.066	1.896

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	255.65	198.65
Mass of container + dry soil, W_1, (g)	239.27	166.06
Mass of container, W_3, (g)	37.72	41.25
Mass of moisture, ($W_2 - W_1$), (g)	16.38	32.59
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	8.13	26.11

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		72	0.037		
1.27		144	0.074		
1.91		218	0.113		
2.54	6.9	320	0.165	0.410	5.9
3.18		437	0.226		
3.81		575	0.297		
4.45		725	0.375		
5.08	10.3	901	0.466	0.715	6.9
7.62		1,475	0.762		
10.16		1,795	0.928		
12.70		2,020	1.044		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	4.4
1	415	
2	477	
3	501	
4	518	

CBR (%)

6.9

Table C-11: CBR test (3%FA, 7+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	3% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.01.2011
Initial height of sample, (mm)	116	End date	03.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

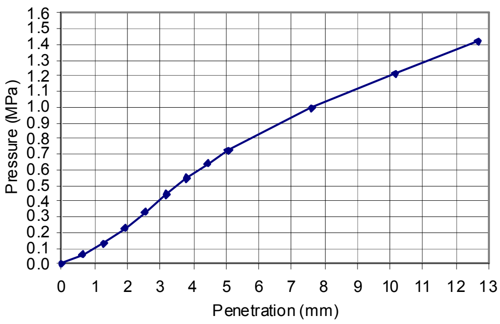
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	11,913	12,135
Mass of mould + base, W_1, (g)	7,200	7,200
Mass of compacted specimen, $W_2 - W_1$, (g)	4,713	4,935
Bulk density, $\rho = (W_2 - W_1) / V$, (g/cm^3)	2.219	2.323
Dry density, $\rho_d = 100\rho / 100 + m$, ($g/cm^3$)	2.063	2.022

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	407.91	533.22
Mass of container + dry soil, W_1, (g)	387.60	493.44
Mass of container, W_3, (g)	119.57	226.51
Mass of moisture, ($W_2 - W_1$), (g)	20.31	39.78
Moisture content, $m = (W_2 - W_1) / (W_1 - W_3) \times 100$, (%)	7.58	14.90

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		111	0.057		
1.27		254	0.131		
1.91		440	0.227		
2.54	6.9	640	0.331	0.405	5.9
3.18		856	0.442		
3.81		1,056	0.546		
4.45		1,239	0.640		
5.08	10.3	1,397	0.722	0.771	7.5
7.62		1,924	0.994		
10.16		2,352	1.216		
12.70		2,747	1.420		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	100	3.3
1	464	
2	477	
3	485	
4	488	

CBR (%)

7.5

Table C-12: CBR test (3%FA, 7+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	3% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.01.2011
Initial height of sample, (mm)	116	End date	03.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

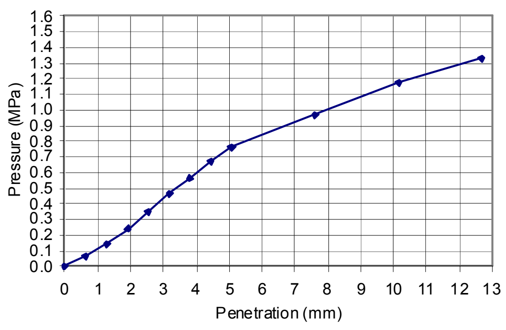
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	11,990	12,202
Mass of mould + base, W_1, (g)	7,200	7,200
Mass of compacted specimen, $W_2 - W_1$, (g)	4,790	5,002
Bulk density, $\rho = (W_2 - W_1) / V$, (g/cm^3)	2.255	2.355
Dry density, $\rho_d = 100\rho / 100 + m$, (g/cm^3)	2.095	2.056

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	259.26	688.63
Mass of container + dry soil, W_1, (g)	243.39	615.81
Mass of container, W_3, (g)	36.33	115.49
Mass of moisture, ($W_2 - W_1$), (g)	15.87	72.82
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.66	14.55

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		121	0.063		
1.27		279	0.144		
1.91		468	0.242		
2.54	6.9	674	0.348	0.435	6.3
3.18		899	0.465		
3.81		1,091	0.564		
4.45		1,301	0.672		
5.08	10.3	1,469	0.759	0.815	7.9
7.62		1,877	0.970		
10.16		2,279	1.178		
12.70		2,575	1.331		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	30	3.7
1	401	
2	427	
3	439	
4	455	

CBR (%)

7.9

Table C-13: CBR test (5%FA, 7+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	5% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	21.12.2010
Initial height of sample, (mm)	116	End date	01.01.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

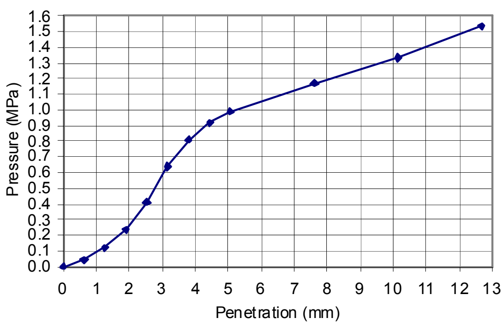
Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	11,934	12,185
Mass of mould + base, W_1, (g)	7,191	7,191
Mass of compacted specimen, W_2 - W_1, (g)	4,743	4,994
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.233	2.351
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.087	2.045

Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	242.42	651.28
Mass of container + dry soil, W_1, (g)	228.85	598.05
Mass of container, W_3, (g)	35.05	241.75
Mass of moisture, (W_2 - W_1), (g)	13.57	53.23
Moisture content, m = (W_2 - W_1) / (W_1 - W_3) x 100, (%)	7.00	14.94

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		81	0.042		
1.27		230	0.119		
1.91		461	0.238		
2.54	6.9	800	0.413	0.830	12.0
3.18		1,238	0.640		
3.81		1,565	0.809		
4.45		1,780	0.920		
5.08	10.3	1,918	0.991	1.080	10.5
7.62		2,262	1.169		
10.16		2,582	1.334		
12.70		2,980	1.540		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	716	3.0
1	1025	
2	1043	
3	1053	
4	1071	

CBR (%)

12.0

Table C-14: CBR test (5%FA, 7+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	5% FA / #2	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	23.03.2011
Initial height of sample, (mm)	116	End date	03.04.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

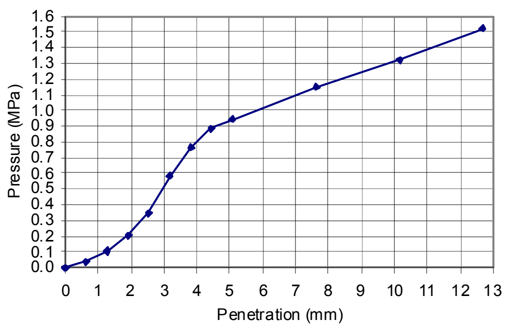
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,651	12,887
Mass of mould + base, W_1, (g)	7,930	7,930
Mass of compacted specimen, W_2 - W_1, (g)	4,721	4,957
Bulk density, 2 = (W_2 - W_1) / V, (g/cm^3)	2.223	2.334
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.073	2.021

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	236.24	291.22
Mass of container + dry soil, W_1, (g)	222.50	256.65
Mass of container, W_3, (g)	33.32	33.32
Mass of moisture, (W_2 - W_1), (g)	13.74	34.57
Moisture content, m = (W_2 - W_1) / (W_1 - W_3) x 100, (%)	7.26	15.48

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		77	0.040		
1.27		206	0.107		
1.91		401	0.207		
2.54	6.9	674	0.348	0.810	11.7
3.18		1,129	0.583		
3.81		1,482	0.766		
4.45		1,713	0.885		
5.08	10.3	1,824	0.943	1.065	10.3
7.62		2,221	1.148		
10.16		2,561	1.324		
12.70		2,945	1.522		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	27	3.2
1	309	
2	353	
3	391	
4	405	

CBR (%)

11.7

Table C-15: CBR test (7%FA, 7+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

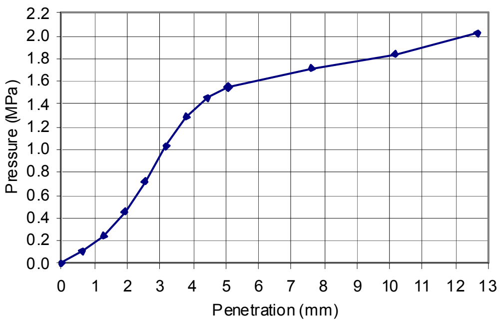
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	7% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	25.01.2011
Initial height of sample, (mm)	116	End date	05.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	11,864	12,099
Mass of mould + base, W_1, (g)	7,196	7,196
Mass of compacted specimen, $W_2 - W_1$, (g)	4,668	4,903
Bulk density, 2 = ($W_2 - W_1$) / V, (g/cm^3)	2.198	2.308
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.040	2.000
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	843.59	594.65
Mass of container + dry soil, W_1, (g)	799.94	545.56
Mass of container, W_3, (g)	235.79	226.84
Mass of moisture, ($W_2 - W_1$), (g)	43.65	49.09
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.74	15.40

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		209	0.108		
1.27		470	0.243		
1.91		883	0.456		
2.54	6.9	1,400	0.724	1.180	17.1
3.18		2,000	1.034		
3.81		2,490	1.287		
4.45		2,813	1.454		
5.08	10.3	3,001	1.551	1.620	15.7
7.62		3,315	1.713		
10.16		3,558	1.839		
12.70		3,920	2.026		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	21	3.1
1	313	
2	362	
3	379	
4	387	

CBR (%)

17.1

Table C-16: CBR test (7%FA, 7+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	7% FA / #2	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	20.02.2011
Initial height of sample, (mm)	116	End date	03.03.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

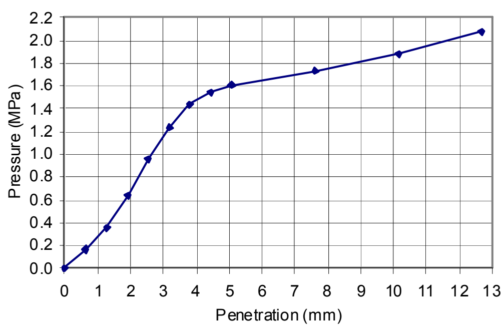
Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	11,817	12,058
Mass of mould + base, W_1, (g)	7,202	7,202
Mass of compacted specimen, $W_2 - W_1$, (g)	4,615	4,856
Bulk density, $\rho = (W_2 - W_1) / V$, (g/cm^3)	2.173	2.286
Dry density, $\rho_d = 100\rho / 100 + m$, ($g/cm^3$)	2.018	1.963

Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	666.66	855.33
Mass of container + dry soil, W_1, (g)	636.24	768.17
Mass of container, W_3, (g)	239.19	239.42
Mass of moisture, ($W_2 - W_1$), (g)	30.42	87.16
Moisture content, $m = (W_2 - W_1) / (W_1 - W_3) \times 100$, (%)	7.66	16.48

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		323	0.167		
1.27		691	0.357		
1.91		1,242	0.642		
2.54	6.9	1,855	0.959	1.190	17.2
3.18		2,397	1.239		
3.81		2,783	1.438		
4.45		2,998	1.549		
5.08	10.3	3,112	1.608	1.635	15.9
7.62		3,354	1.733		
10.16		3,639	1.881		
12.70		4,016	2.075		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	533	3.3
1	759	
2	871	
3	915	
4	922	

CBR (%)

17.2

Table C-17: CBR test (10%FA, 7+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

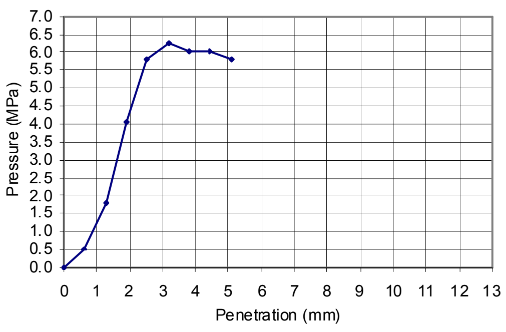
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	10% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.100	Condition of sample	Soaked
Optimum moisture content, (%)	8.34	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	21.12.2010
Initial height of sample, (mm)	116	End date	01.01.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	12,490	12,694
Mass of mould + base, W_1, (g)	7,705	7,705
Mass of compacted specimen, W_2 - W_1, (g)	4,785	4,989
Bulk density, б = (W_2 - W_1) / V, (g/cm^3)	2.253	2.349
Dry density, $б_d$ = 100б/ 100 + m, (g/cm^3)	2.079	2.056
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	244.32	725.37
Mass of container + dry soil, W_1, (g)	228.67	665.02
Mass of container, W_3, (g)	41.25	241.76
Mass of moisture, (W_2 - W_1), (g)	15.65	60.35
Moisture content, m = (W_2 - W_1)/ (W_1 - W_3) x 100, (%)	8.35	14.26

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		1,025	0.530		
1.27		3,450	1.783		
1.91		7,800	4.031		
2.54	6.9	11,250	5.814	6.191	89.7
3.18		12,050	6.227		
3.81		11,688	6.040		
4.45		11,685	6.039		
5.08	10.3	11,238	5.808		
7.62					
10.16					
12.70					

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	
1	66	
2	70	0.6
3	73	
4	74	

CBR (%)

89.7

Table C-18: CBR test (10%FA, 7+4 Days, Sample 2)

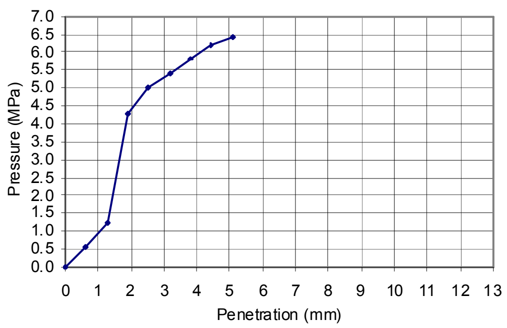
MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	7 days
Sample name and number	10% FA / #2	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.100	Condition of sample	Soaked
Optimum moisture content, (%)	8.34	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	10.01.2011
Initial height of sample, (mm)	116	End date	21.01.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,625	12,845
Mass of mould + base, W_1, (g)	7,940	7,940
Mass of compacted specimen, $W_2 - W_1$, (g)	4,685	4,905
Bulk density, 2 = ($W_2 - W_1$) / V, (g/cm^3)	2.206	2.309
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.045	2.002
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	325.34	477.73
Mass of container + dry soil, W_1, (g)	310.90	444.40
Mass of container, W_3, (g)	127.59	226.88
Mass of moisture, ($W_2 - W_1$), (g)	14.44	33.33
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.88	15.32

California Bearing Ratio determination					
Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		1,107	0.572		
1.27		2,337	1.208		
1.91		8,239	4.258		
2.54	6.9	9,715	5.021	5.667	82.1
3.18		10,500	5.426		
3.81		11,273	5.826		
4.45		12,000	6.202		
5.08	10.3	12,379	6.398		
7.62					
10.16					
12.70					

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	0	0.7
1	79	
2	84	
3	86	
4	87	

CBR (%)

82.1

Table C-19: CBR test (3%FA, 28+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	3% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	25.01.2011
Initial height of sample, (mm)	116	End date	26.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

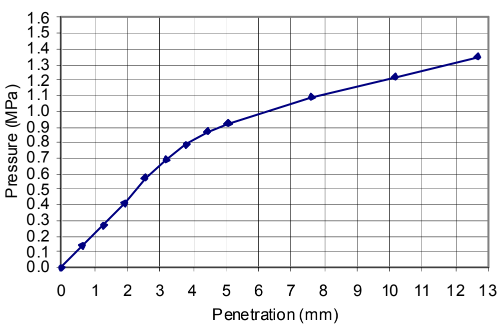
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,500	12,760
Mass of mould + base, W_1, (g)	7,655	7,655
Mass of compacted specimen, $W_2 - W_1$, (g)	4,845	5,105
Bulk density, 2 = ($W_2 - W_1$) / V, (g/cm^3)	2.281	2.403
Dry density, 2_d = 1002 / 100 + m, (g/cm^3)	2.122	2.087

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	593.65	708.86
Mass of container + dry soil, W_1, (g)	568.04	647.37
Mass of container, W_3, (g)	226.86	241.77
Mass of moisture, ($W_2 - W_1$), (g)	25.61	61.49
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)	7.51	15.16

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		268	0.139		
1.27		526	0.272		
1.91		793	0.410		
2.54	6.9	1,107	0.572	0.62	9.0
3.18		1,341	0.693		
3.81		1,526	0.789		
4.45		1,689	0.873		
5.08	10.3	1,786	0.923	0.94	9.2
7.62		2,110	1.090		
10.16		2,358	1.219		
12.70		2,606	1.347		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	240	3.3
1	616	
2	623	
3	628	
4	629	

CBR (%)

9.2

Table C-20: CBR test (3%FA, 28+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	3% FA / #2	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.172	Condition of sample	Soaked
Optimum moisture content, (%)	7.42	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	18.02.2011
Initial height of sample, (mm)	116	End date	20.03.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

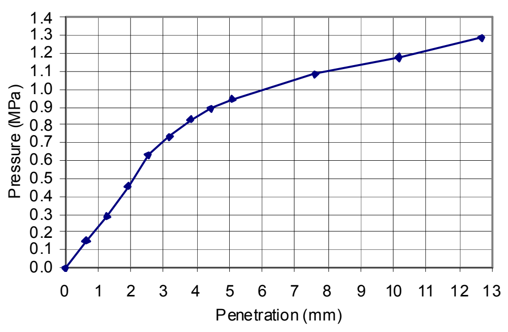
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,470	12,725
Mass of mould + base, W_1, (g)	7,655	7,655
Mass of compacted specimen, $W_2 - W_1$, (g)	4,815	5,070
Bulk density, $\rho = (W_2 - W_1) / V$, (g/cm^3)	2.267	2.387
Dry density, $\rho_d = 100\rho / 100 + m$, (g/cm^3)	2.105	2.082

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	218.32	508.16
Mass of container + dry soil, W_1, (g)	205.39	447.94
Mass of container, W_3, (g)	37.81	36.60
Mass of moisture, ($W_2 - W_1$), (g)	12.93	60.22
Moisture content, $m = (W_2 - W_1) / (W_1 - W_3) \times 100$, (%)	7.72	14.64

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		291	0.150		
1.27		558	0.288		
1.91		888	0.459		
2.54	6.9	1,225	0.633	0.665	9.6
3.18		1,422	0.735		
3.81		1,607	0.830		
4.45		1,723	0.890		
5.08	10.3	1,824	0.943	0.952	9.2
7.62		2,096	1.083		
10.16		2,279	1.178		
12.70		2,492	1.288		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	11	2.5
1	259	
2	286	
3	298	
4	307	

CBR (%)

9.6

Table C-21: CBR test (5%FA, 28+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	5% FA / #1	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	14.01.2011
Initial height of sample, (mm)	116	End date	15.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

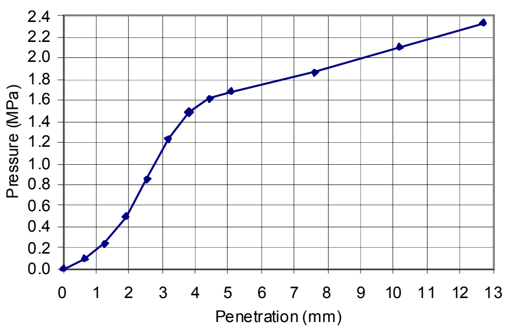
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,727	12,961
Mass of mould + base, W_1, (g)	7,997	7,997
Mass of compacted specimen, $W_2 - W_1$, (g)	4,730	4,964
Bulk density, $\delta = (W_2 - W_1) / V$, (g/cm^3)	2.227	2.337
Dry density, $\delta_d = 100\delta / 100 + m$, (g/cm^3)	2.086	2.037

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	654.85	627.03
Mass of container + dry soil, W_1, (g)	621.46	563.09
Mass of container, W_3, (g)	127.59	128.36
Mass of moisture, ($W_2 - W_1$), (g)	33.39	63.94
Moisture content, m = ($W_2 - W_1$)/ ($W_1 - W_3$) x 100, (%)	6.76	14.71

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		186	0.096		
1.27		464	0.240		
1.91		963	0.498		
2.54	6.9	1,655	0.855	1.370	19.9
3.18		2,388	1.234		
3.81		2,879	1.488		
4.45		3,130	1.618		
5.08	10.3	3,268	1.689	1.760	17.1
7.62		3,606	1.864		
10.16		4,078	2.107		
12.70		4,518	2.335		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	107	2.7
1	383	
2	408	
3	415	
4	419	

CBR (%)

19.9

Table C-22: CBR test (5%FA, 28+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

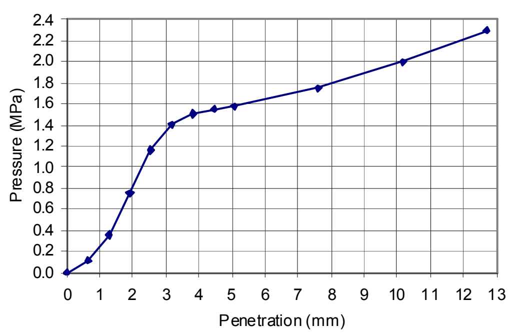
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	5% FA / #2	Standard	ASTM D1557& D1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.157	Condition of sample	Soaked
Optimum moisture content, (%)	7.20	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	14.01.2011
Initial height of sample, (mm)	116	End date	15.02.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

Dry density determination	**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)	11,871	12,101
Mass of mould + base, W_1, (g)	7,180	7,180
Mass of compacted specimen, $W_2 - W_1$, (g)	4,691	4,921
Bulk density, $\delta = (W_2 - W_1) / V$, (g/cm^3)	2.209	2.317
Dry density, $\delta_d = 100\delta / 100 + m$, (g/cm^3)	2.063	2.019
Moisture content determination	**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)	654.03	633.49
Mass of container + dry soil, W_1, (g)	619.09	568.50
Mass of container, W_3, (g)	126.83	127.59
Mass of moisture, $(W_2 - W_1)$, (g)	34.94	64.99
Moisture content, $m = (W_2 - W_1) / (W_1 - W_3) \times 100$, (%)	7.10	14.74

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		221	0.114		
1.27		688	0.356		
1.91		1,463	0.756		
2.54	6.9	2,244	1.160	1.400	20.3
3.18		2,720	1.406		
3.81		2,914	1.506		
4.45		2,992	1.546		
5.08	10.3	3,046	1.574	1.620	15.7
7.62		3,396	1.755		
10.16		3,860	1.995		
12.70		4,452	2.301		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	170	1.9
1	365	
2	380	
3	383	
4	387	

CBR (%)

20.3

Table C-23: CBR test (7%FA, 28+4 Days, Sample 1)

MIDDLE EAST TECHNICAL UNIVERSITY
SOIL MECHANICS LABORATORY
CALIFORNIA BEARING RATIO TEST

General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	7% FA / #1	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	30.01.2011
Initial height of sample, (mm)	116	End date	03.03.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR

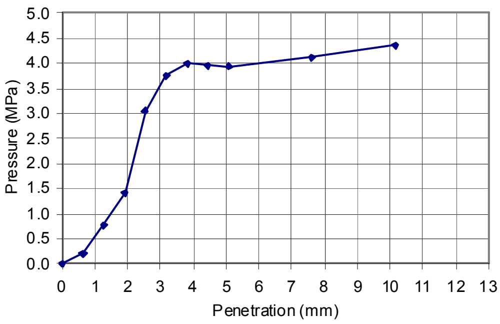
Dry density determination	Before soaking	After soaking
Mass of mould + base + soil, W_2, (g)	12,650	12,860
Mass of mould + base, W_1, (g)	7,940	7,940
Mass of compacted specimen, W_2 - W_1, (g)	4,710	4,920
Bulk density, γ = (W_2 - W_1) / V, (g/cm^3)	2.218	2.316
Dry density, γ_d = 100γ/ 100 + m, (g/cm^3)	2.065	2.041

Moisture content determination	Before soaking	After soaking
Mass of container + wet soil, W_2, (g)	522.03	632.59
Mass of container + dry soil, W_1, (g)	502.66	585.85
Mass of container, W_3, (g)	241.78	239.18
Mass of moisture, (W_2 - W_1), (g)	19.37	46.74
Moisture content, m = (W_2 - W_1)/ (W_1 - W_3) x 100, (%)	7.42	13.48

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		401	0.207		
1.27		1,498	0.774		
1.91		2,753	1.423		
2.54	6.9	5,907	3.053	3.980	57.7
3.18		7,249	3.746		
3.81		7,718	3.989		
4.45		7,652	3.955		
5.08	10.3	7,626	3.941	4.025	39.1
7.62		7,951	4.109		
10.16		8,436	4.360		
12.70					

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	80	0.8
1	157	
2	175	
3	176	
4	177	

CBR (%)

57.7

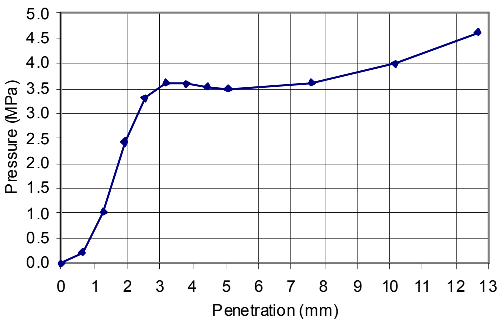
Table C-24: CBR test (7%FA, 28+4 Days, Sample 2)

MIDDLE EAST TECHNICAL UNIVERSITY SOIL MECHANICS LABORATORY CALIFORNIA BEARING RATIO TEST			
General information about specimen and test procedure			
Location	Elmadağ / Ankara	Curing period	28 days
Sample name and number	7% FA / #2	Standard	ASTM D 1557& D 1883
Soil classification	CL	Method of compaction	Modified
Maximum dry density, (g/cm^3)	2.145	Condition of sample	Soaked
Optimum moisture content, (%)	7.80	Surcharge, (kg)	4.54
Area of penetration piston, (mm^2)	1,935	Start date	16.02.2011
Initial height of sample, (mm)	116	End date	20.03.2011
Volume of mould, (cm^3)	2,124	Tested by	Murat Aziz ÖZDEMİR
Dry density determination		**Before soaking**	**After soaking**
Mass of mould + base + soil, W_2, (g)		12,695	12,900
Mass of mould + base, W_1, (g)		7,989	7,989
Mass of compacted specimen, $W_2 - W_1$, (g)		4,706	4,911
Bulk density, γ = ($W_2 - W_1$) / V, (g/cm^3)		2.216	2.312
Dry density, γ_d = 100γ / 100 + m, (g/cm^3)		2.052	2.042
Moisture content determination		**Before soaking**	**After soaking**
Mass of container + wet soil, W_2, (g)		713.54	682.85
Mass of container + dry soil, W_1, (g)		678.54	631.08
Mass of container, W_3, (g)		241.79	239.4
Mass of moisture, ($W_2 - W_1$), (g)		35.00	51.77
Moisture content, m = ($W_2 - W_1$) / ($W_1 - W_3$) x 100, (%)		8.01	13.22

California Bearing Ratio determination

Penetration	Standard pressure	Pressure reading		Corrected pressure	CBR
mm	MPa	N	MPa		%
0.00		0	0.000		
0.64		433	0.224		
1.27		1,981	1.024		
1.91		4,700	2.429		
2.54	6.9	6,415	3.315	3.675	53.3
3.18		7,007	3.621		
3.81		6,952	3.593		
4.45		6,848	3.539		
5.08	10.3	6,740	3.483	3.525	34.2
7.62		6,986	3.610		
10.16		7,742	4.001		
12.70		8,947	4.624		

Load - penetration curve



Swell during soaking

Days	Dial reading	Swell (%)
0	322	1.4
1	453	
2	465	
3	476	
4	485	

CBR (%)

53.3