

**A STUDY ON STRENGTH CHARACTERISTICS OF SUBGRADE SOIL
TREATED WITH FLY ASH AND ENSET FIBER; IN CASE OF TARCHA-
CHIDA ROAD SECTION, SOUTHERN ETHIOPIA**



Kefitawu Habitamu Kama

A Thesis Submitted to the Department of Civil Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in
Civil Engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

August, 2021

Adama, Ethiopia

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Advisor: Yadeta Chemdesa (PhD)

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APPROVAL OF MSc THESIS

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RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “*A Study on Strength Characteristics of Subgrade Soil Treated with Fly Ash and Enset Fiber; In Case of Tarcha-Chida Road Section, Southern Ethiopia*” prepared under my guidance by **Kefitawu Habitamu** submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Civil Engineering (Specialization in Geotechnical Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials;
amsl	Above Mean Sea Level;
CBR	California Bearing Ratio;
Cu	Undrained Cohesion;
EF	Enset Fiber;
ERA	Ethiopian Roads Authority;
ES	Expansive Soil;
FA	Fly Ash;
GI	Group Index;
IS	Indian Standard;
LL	Liquid Limit;
MDD	Maximum Dry Density;
NP	Non-Plastic;
OMC	Optimum Moisture Content;
PI	Plasticity Index;
PL	Plastic Limit;
St	Station;
TP	Test Pit;
UCS	Unconfined Compressive Strength;
USCS	Unified Soil Classification System;
WAC	Water Absorption Capacity;
%	Percent;
°C	Degree Centigrade;
g/cm ³	Gram per Centimeter Cube;
GPa	Giga Pascal;
Kg	Kilo gram;
kN/m ²	Kilo Newton per Meter Square;
kPa	Kilo Pascal;
mm	Millimeter;
MPa	Mega Pascal;
μm	Micrometer;

ABSTRACT

In Ethiopia, road pavement failure is becoming a common problem and major challenge. Such failures are most likely to happen due to expansive soil in the subgrade. This soil possesses low shear strength, high plasticity and compressibility. To improve the property of such soil; stabilization and/or reinforcement technique is commonly used. Stabilizing expansive soil with available waste materials and reinforcing it with discrete, randomly distributed natural fibers are recently getting more attention in geotechnical engineering. Fly ash is a waste material which remains after the combustion of coal. Enset fibers are natural fibers extracted from the pseudostem and leaf parts of enset plant. The soil in Tarcha-Chida road project site does not fulfill the subgrade soil requirements; and construction is going on by removing the existing soils and replacing them with selected materials which bring additional cost, may displace the people and change the landscape of the area. This study aimed to investigate the effect of fly ash and enset fiber on strength characteristics of expansive subgrade soil. The soil samples were collected from Tarcha-Chida road section. The experimental programs were carried out for soil alone, soil-fly ash and soil-fly ash-enset fiber mixes. Series of laboratory tests such as particle size distribution, Atterberg limits, specific gravity, free swell, free swell index, compaction, California bearing ratio (CBR) and unconfined compressive strength (UCS) tests were performed for soil alone and soil treated with fly ash. The percentage of fly ash by weight of dry soil is taken as 10%, 15%, 20% and 25%. The results show that fly ash reduces plasticity index, swelling and maximum dry density (MDD); and increase observed in optimum moisture content (OMC), CBR and UCS with increase in fly ash contents. A significant increase in CBR and UCS value is observed for addition of 20% of fly ash that is 3.77% and 177.75kPa respectively, and further addition of fly ash decreased the values. Optimum soil-fly ash mix (i.e. 80% soil and 20% fly ash) were reinforced randomly with enset fiber of 0.5%, 1%, 1.5% and 2% by weight of dry soil and length of 15mm and 20mm to investigate the effect of fiber on compaction, CBR and UCS. Coating the enset fiber with kerosene leads to reduction of water absorption capacity by 29%. The results on soil-fly ash-enset fiber show that MDD is decreased; and OMC, CBR and UCS are increased with increase in fiber content and length. The optimum CBR and UCS value obtained at 1.5% fiber content and 20mm fiber length was 6.38% and 231.5kPa respectively. Thus the optimum percentage of soil-fly ash-enset fiber mix is 78.5% soil, 20% fly ash and 1.5% enset fiber by weight. In general, this study showed that a combination of fly ash and enset fiber can be effectively used to improve the expansive subgrade soil.

Keywords: *Enset fiber, Expansive soil, Fly ash, California bearing ratio (CBR), Unconfined compressive strength (UCS)*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Expansive soils are the major problematic soils that show very strong swelling and shrinkage characteristics under changing moisture conditions. These soil increases in volume when it gains water resulting in loss of its strength and shrinks greatly on drying that develop cracks on surface. Expansive soils are not suitable for civil engineering constructions such as roads and light weight structures because such structures do not exert the necessary counter balance load to resist the expansion. These soil causes damage to engineering structures in the form of crack or differential settlement and causing billions of dollars in losses in many parts of the world, especially in places where there are significant climatic differences between the dry and rainy seasons (Nelson & Miller, 1992; Manjunath et al., 2013). Like many other countries, in Ethiopia lands that are fertile, suitable for agriculture, and covered by forest are heavily dominated with expansive soils.

For any structure or pavement, the stability depends on stability of foundation and/or subgrade. Expansive soil to be used as subgrade in pavement is known for its stability problem and need improvement. Improving the bearing capacity and shear strength of such soil can be accomplished through a variety of soil improvement techniques, such as soil stabilization and soil reinforcement. Soil stabilization is the process of improving the engineering properties of the soil, when the soil is not suitable for the intended purpose (Arora, 2003). For many years, road and geotechnical engineers have been using additives such as lime, cement and bitumen to improve the properties of the local soil. According to laboratory and field tests, use of such additives can increase the strength and stability of weak soils. However, in recent years, the cost of introducing these additives to soil has increased (Singh, 2020).

Recently, researchers focus more on the search for low cost and locally available waste materials such as bagasse ash, fly ash, rice husk ash, and so on as stabilizing agents for full or partial replacement of traditional stabilizers like cement and lime (Yadu et al., 2011; Ashango & Patra, 2016). In order to save natural resources for future generations, the use of locally available materials and waste material should be encouraged for sustainable development.

Coal fly ash is one of industrial waste material left after coal is combusted (burned), and it has been extensively used in embankment and highway construction (Singh & Arif, 2014).

Soil reinforcement is also one of ground improvement techniques in which tensile materials are introduced in to soil to increase its bearing capacity, to improve its stability, and to reduce settlements and lateral deformations. It can be achieved by either inserting continuous reinforcement inclusions (such as strip, bar, sheet, mat, or net) in a specific pattern inside a soil mass or by randomly mixing discontinuous fibers with a soil mass (Shukla et al., 2009). Soil reinforcement using natural fiber have attracted much attention as one of the emerging sustainable soil strengthening techniques in geotechnical engineering due to its advantages such as environmental friendliness, cost effectiveness, local availability, light weight, and no waste disposal problems. Use of natural fibers like sisal, kenaf, jute, coir, bamboo, etc. as soil reinforcement has been widely used in many countries such as India, Malaysia, Philippines, and Bangladesh (Muni et al., 2014).

In Ethiopia, a suitable plant with great potential to produce natural fiber is enset (i.e. enset fiber). However, soil reinforcement using this fiber for an alternative soil improvement is less explored. In addition, the combined effect of chemical admixture and natural fibers on soil properties is not well explored. Therefore, this study is aimed to investigate the effect of fly ash and enset fiber on strength characteristics of expansive subgrade soil.

1.2 Statement of the Problem

In Ethiopia, road pavement failure is becoming a common problem and major challenge that costs a lot of money, and in some cases, such failure occurs even before the completion of a project. For such failure the contributory factor is due to the presence of expansive soil in subgrade that causes persistent difficulties in construction and results in non-uniform settlement and cracking in pavement. The majority of the areas along the Tarcha-Chida road construction project are dominated by expansive soils. These soils are not suitable for road construction because of its expansiveness property when it gets contact with water. As a result of this problem the existing expansive soil is now being removed and replaced with selected material obtained from faraway. However, the excavation and production of selected borrow materials may cause displace of people and changed landscape of the area. Furthermore, excavation of expansive soil, as well as the search for and transportation of selected materials

result in additional cost and cause delay of construction. Therefore, to use the existing expansive soils for subgrade construction, economical soil treatment is needed.

1.3 Research Questions

- ✓ What effects have fly ash on expansive subgrade soil?
- ✓ What percentage of fly ash gives a better improvement of expansive soil?
- ✓ Are fly ash and enset fiber in combination has effect on strength characteristics of subgrade soil?
- ✓ Which combination by percentage for specific lengths of fiber with fly ash gives maximum strength of subgrade soil?

1.4 Objective of the Study

1.4.1 General objective

The general objective of this study is to investigate the combined effect of fly ash and enset fiber on strength characteristics of expansive subgrade soil.

1.4.2 Specific objectives

- ✓ To study the effect of fly ash on the properties of expansive subgrade soil using particle size, Atterberg limits, free swell, free swell index, compaction, CBR and UCS.
- ✓ To determine the optimum mix of fly ash for expansive soil stabilization.
- ✓ To study a combined effect of fly ash and enset fiber on compaction, CBR and UCS of subgrade soil.
- ✓ To determine the optimum mix related to fiber percentage at two specific lengths for soil-fly ash-fiber reinforcement.

1.5 Scope and Limitation of the Study

The scope of this study focuses on the addition of fly ash and enset fiber on expansive subgrade soils to enhance its engineering properties. The experimental program was carried out for soil alone, soil mix with fly ash, soil mix with optimum fly ash and enset fiber at different percentage and length. The index and engineering properties of soil for two test pits at 1m depth from Tarcha-Chida road was done by conducting grain size distribution, Atterberg limits, specific gravity, free swell, compaction, CBR and UCS. The stabilization of soil was carried out for only one test pit having low CBR and UCS value. Water absorption and specific gravity test were conducted for enset fiber and strength characteristics such as

compaction, CBR and UCS were conducted for soil-fly ash and soil-fly ash-fiber mixtures. The study was limited to physical properties of soil and stabilizers because there is lack of test equipments to determine their chemical composition.

1.6 Significance of the Study

It is known that expansive soil causes a significant damage to structures especially pavements and light buildings that are common problem to geotechnical engineers. To minimize their damages, expansive soils have been improved by different stabilization techniques. However, stabilization using waste materials such as fly ash that causes a problem due to its disposal and low cost natural fiber (enset fiber) available in Ethiopia are limited in study. Hence, this study gives a significant understanding of the effect of fly ash and enset fiber for improvement of the expansive soil. The study also contribute a significant benefit by utilizing waste and locally available natural material in to geotechnical engineering application as well reducing the waste disposal problems. Moreover, this study gives some insight for future researchers in the area of soil improvement especially using fly ash and natural fiber.

1.7 Organization of the Thesis

This report of the thesis consists of five chapters, each covering a specific topic of the thesis work. In the first Chapter background of the problem, objectives, research questions, scope and significance of the study are presented. Chapter two deals with a brief literature review about expansive soil, soil stabilization techniques and previous related works relevant to present study. Chapter three deals the description of study area, materials and methods used in the study. Chapter four presents the analysis, interpretation, discussion and comparison of laboratory test results. Chapter five consists of the conclusions and recommendations which are drawn from the research work. Finally, references and appendices are attached at the end of the thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1 Expansive Soils

Expansive soils are typically clayey soils that undergo large volume changes in direct response to changes in soil moisture. Expansive soil tends to swell (increase in volume) as the moisture content of the soil increases and shrink (decreases in volume) as the moisture content decreases. The amount and type of clay minerals in the soil, the arrangement and specific surface area of the clay particles, and the chemistry of the soil water surrounding those particles all affect the swelling capacity of the soil mass (Nelson & Miller, 1992). The active clay mineral called Montmorillonite, is responsible for shrink-swell property of expansive soil.

Expansive soil can be found anywhere in the world where climatic, geological and topographical conditions favored their formation. These soils are abundant in semi-arid and arid regions of tropical and temperate zones which the annual evaporation exceeds the precipitation (Chen, 1988). Expansive soil is widely distributed in the African continent, occurring in South Africa, Mozambique, Morocco, Ethiopia, Kenya, Ghana, Nigeria and so on. In other parts of the world, countries such as USA, Australia, Turkey, Argentina, Canada, Spain, Israel, Venezuela, and India have reported expansive soils (Teferra & Leikun, 1999).

Compared with any other natural hazards such as earthquakes and floods, expansive soil causes more damage to structures especially pavements and light buildings. According to reports, the damage caused by these soils has greatly increased the burden of natural disasters on the economies of countries where these soils have occurred significantly (Chen, 1988). Ethiopia is one of the countries where the existence and spatial distribution of expansive soil are considered as significant.

2.2 Source of Expansive Soil

The source of expansive soils is related to the combination of conditions and processes that lead to the formation of clay minerals with specific chemical composition when they contact with water. Clay mineralogy is determined by the composition of the parent material and the degree of physical and chemical weathering to which the materials are subjected. The parent material related to expansive soil is basic igneous rocks or sedimentary rocks. In basic igneous

rocks, they are formed by the decomposition of feldspar and pyroxene as well in sedimentary rocks they are composed of smectite (montmorillonite) which physically decompose to form expansive soils. The formation of montmorillonite was probably the weathering and erosion in the highlands, and that carried by streams to the coastal plains. The most important weathering process responsible for the formation of montmorillonite is the chemical weathering of parent rock mineral (Chen, 1988).

2.3 Mineralogy of Expansive Clay Soils

Expansive soils have very high clay content. Various clay minerals are formed by the stacking of basic sheet structures with different forms of bonding between the combined sheets. The three common types of clay minerals are Kaolinite, Illite and Montmorillonite (Teferra & Leikun, 1999).

Kaolinite - low degree of expansiveness

Illite - moderate degree of expansiveness

Montmorillonite - very high degree of expansiveness

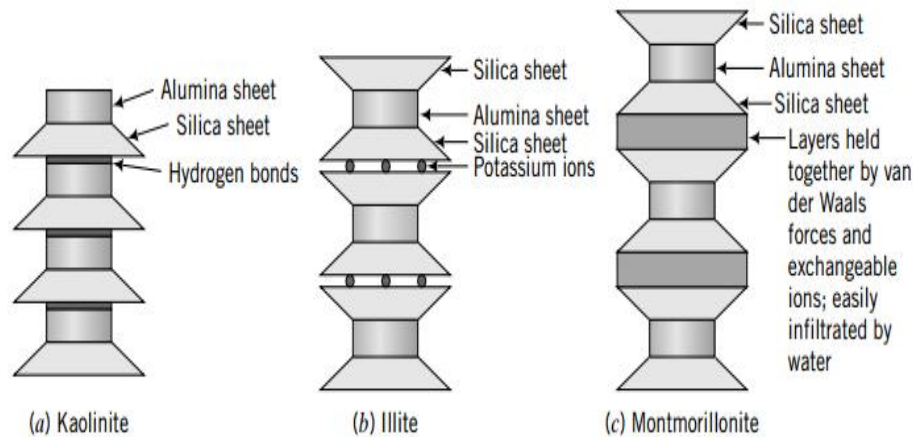


Figure 2.1 Schematic Representation of Clay Minerals (Budhu, 2007)

Kaolinite: it has a structural unit composed of alumina sheet joined to silica sheet and are bonded by hydrogen bonds. The bond that exists between the layers is very tight and hence it is difficult to separate the layers. As a result, kaolinite is relatively stable and water cannot penetrate between the layers. Consequently, kaolinite has low degree of expansiveness.

Montmorillonite: it is the most common type of all the clay minerals and is well known for its swelling properties. Its basic structure consists of an alumina sheet in between two silica sheets. The basic montmorillonite units are stacked one on top of the other, but the bond

between the individual units is relatively weak and water can easily penetrate between the sheets, and this cause them to separate and hence swell. Therefore, montmorillonite has very high degree of expansiveness.

Illite: has the same basic structure to that of montmorillonite. However, the basic illite units are bonded together by non-exchangeable potassium ions. Because of this, the illite units are reasonably stable so that mineral swelling is much smaller than montmorillonite. Hence, illite has moderate degree of expansiveness.

2.4 Identification of Expansive Soils

Identification of expansive soil usually consists of two important phases. The first is the visual/field identification and the second is sampling and measurement of material properties to be used as the basis for design.

2.4.1 Field identification

Expansive soils can be identified in the field through visual inspections. Some of the important field identification method that indicates the potential for expansive soils is as follows.

- ✓ They usually have black or gray color.
- ✓ When dry, the soils have cracks at the ground surface
- ✓ The wet samples of the soil are sticky and it will be relatively difficult to clean the soil from the hands.
- ✓ High dry strength and low moist strength.
- ✓ Appearance of cracks in nearby structures.

2.4.2 Laboratory identification

In general, there are three different methods of laboratory identification of expansive soils namely; mineralogical identification, indirect and direct methods.

A) Mineralogical identification

This method is used for identifying the mineralogy of clay particles such as characteristics crystal dimensions, characteristics reaction heat treatment, size and shape of clay particles and change deficiency and surface activity of clay particle. The various techniques under these methods are X-ray diffraction, differential thermal analysis, dye adsorption, chemical analysis and scanning electron microscope. But these methods are not suitable for routine tests because

they are time-consuming, require expensive test equipment, and the results can only be interpreted by specially trained technicians (Chen, 1988).

i) X-ray diffraction (XRD): is used to determine the proportion of the various minerals present in colloidal clay consists essentially by comparing the ratios of the intensities of diffraction lines from the different minerals with the intensities of lines from the standard substance (Chen, 1988). XRD is the most popular method, works on the principle that beams of X-rays diffracted from crystals are similar to light reflections from the crystal lattice planes. X-Ray analysis is well suited for identification of clay minerals because the wavelength of X-rays is of the same order of magnitude (about 10^{-9} mm) as the atomic plane spacing of these minute crystals. XRD allows us to determine the orientation of a single crystal or grain and to measure the size and shape of small crystalline regions (Nelson & Miller, 1992).

X-ray diffraction analysis has been a useful tool for quantitative analysis of clay minerals. This method is based on the relation between diffracted intensity and concentration of clay mineral. The contents of clay minerals are calculated by comparison with intensities yielded by standard samples with known components. The analytical uncertainties can be influenced by many factors, such as the choice of standard sample, the sample preparation technique, and the interference due to other minerals present in the sample (Hao et al., 2015). X-rays causes a constructive and destructive interference of the scattered X-ray beam, generating a unique diffraction pattern that presents several sharp spots, known as Bragg diffraction peaks. It provides information on structures, phases, preferred crystal orientations (texture), and other structural parameters, such as average grain size, crystallinity, strain, and crystal defects. The XRD pattern is the fingerprint of periodic atomic arrangements in a given material (Kaliva & Vamvakaki, 2020).

ii) Differential thermal analysis (DTA): is a thermoanalytic technique consists of simultaneously heating a sample of clay and an inert substance by recording any temperature difference between sample and reference. The resulting thermograms, which are plots of the temperature difference versus applied heat, are compared to those for pure minerals. Each mineral shows characteristic endothermic and exothermic reactions on the thermograms which can be detected relative to the inert reference (Nelson & Miller, 1992). A DTA consists of a sample holder, thermocouples, sample containers and a ceramic or metallic block; a furnace; a

temperature programmer; and a recording system. The key feature is the presence of two thermocouples connected to the voltmeter. One thermocouple is placed in an inert material such as Al_2O_3 , and the other is placed in a sample of the clay material. As the temperature is increased, there will be a brief deflection of the voltmeter if the sample is undergoing a phase transition. This occurs because the input of heat will raise the temperature of the inert substance, but be incorporated as latent heat in the material changing phase. It consists of inert environment with inert gases which will not react with sample and reference (Arens, 1951).

iii) Dye Adsorption: Dyestuffs and other reagents which exhibit characteristic colors when adsorbed by clay that have been used to identify clay. It is based on the assumption that dyes are taken up by adsorption which is a characteristic of surface and hence is a measure of the colloidal matter of the soil. When a clay sample has been pretreated with acid, the color assumed by the adsorbed dye depends on the base exchange capacity of the various clay minerals present. The presence of montmorillonite can be detected if its amount is greater than about 5 to 10 percent. The relatively simple testing procedure and speed of dye staining tests compared with X-ray diffraction and differential thermal analysis justify wider application of the color method (Chen, 1988).

iv) Chemical Analysis: it can be a valuable supplement to other methods such as X-ray analysis in identifying clays. In the montmorillonite group of clay minerals, chemical analysis can be used to determine the nature of isomorphism and to show the origin and location of the charge on the lattice. The isomorphism involves three basic variations in the substitution: the substitution of Al for Si in tetrahedral positions in the lattice; the substitution of Fe for Al in the octahedral coordination; and the substitution of Mg for Al in the octahedral positions (Chen, 1988).

v) Scanning electron microscope (SEM): it is a surface-imaging technique which generates high-resolution and high magnification images of a sample by scanning its surface with a focused electron beam. Electron microscopes have provided a means of directly observing the materials (clay particles). It is used to generate surface images of a sample on a microscopic level. It does this by scanning a sample with a beam of high energy electrons in an optical column. The electrons emitted by the beam then interact with the atomic structure of the sample and generate topographic images. Different types of electrons are produced from the

beam, secondary and backscattered (Velasco, 2013). If the microscope is equipped with X-ray capabilities, the device can generate information about the composition of structural elements and the specific locations of these elements. The main purpose of the microscopic examination is to determine mineralogic composition, texture, and internal structure (Chen, 1988).

B) Indirect method

In this method simple soil property tests can be used for the evaluation of swelling potential of expansive soils. Some of these tests are:

i) Atterberg limits

The Atterberg limit defines the moisture content boundaries between states of consistency of fine-grained soils. Here measurements of the plasticity index and liquid limit are commonly used to characterize soils and are useful indices for the identification of the swelling of expansive soils. The relation between the degree of expansion and the plasticity index is given in Table 2.1.

Table 2.1 Expansion potential of soils and plasticity index (Chen, 1988)

Plasticity Index (%)	Expansion Potential
0 - 15	Low
10 - 35	Medium
20 - 55	High
35 and Above	Very High

While it is true that high swelling soil will have a high index property, this is not true in reverse.

ii. Free swell tests

A free swell test involves putting a known volume of dry soil that has passed through a No. 40 (425µm) sieve into a graduated cylinder filled with water, and recording the swelling volume of material after the material settles at the bottom of a graduated cylinder, without any surcharge. The difference between the final volume and the initial volume, expressed as a percentage of the initial volume is a free swell value (Chen, 1988; Teferra & Leikun, 1999). The free swell of a soil is determined as:

$$\text{Free swell (\%)} = \frac{(\text{final volume}) - (\text{initial volume})}{(\text{initial volume})} \dots \dots \dots (2.1)$$

Experiments show that a good grade of high swelling commercial bentonite will have a free swell of from 1200 to 2000%. Soils having a free swell value as low as 100% can cause considerable damage to lightly weight structures, while soils having a free swell value below 50% can exhibit appreciable volume change even under very light loadings.

iii. Free swell index

Free swell index is one of the most commonly used simple tests to estimate the swelling potential of expansive clay. The procedure involves in taking two oven dried soil samples passing through a 425µm sieve and 10ml of each were placed separately in two 100ml graduated cylinder. One cylinder is filled with kerosene oil and the other filled with distilled water. Both of the samples are stirred and left undisturbed for a minimum of 24 hours after which the final volumes of soils in the cylinders are noted (Nelson et al., 2015). The free swell index is calculated as;

$$\text{Free swell (\%)} = \frac{(\text{final volume in water}) - (\text{final volume in kerosene})}{(\text{final volume in kerosene})} * 100\% \quad \dots \dots \dots (2.2)$$

The relation between the degree of expansion and free swell index is shown in Table 2.2.

Table 2.2 Expansion potential based on free swell index (Nelson et al., 2015)

Free Swell Index (%)	Expansion Potential
< 20	Low
20 - 35	Medium
35 - 50	High
> 50	Very High

iv. Free swell ratio test

To determine the swell property, Sridharan and Prakash (2000) proposed the free swell ratio method of characterizing the soil swelling. Free swell ratio is defined as the ratio of settled volume of 10ml oven dried soil passing through a 425µm sieve in distilled water to that of kerosene. The free swell ratio is calculated as;

$$\text{Free swell ratio} = \frac{(\text{final volume in water})}{(\text{final volume in kerosene})} \quad \dots \dots \dots (2.3)$$

The relation between the degree of expansion and free swell ratio is given in Table 2.3.

Table 2.3 Classification of soils based on free swell ratio (Sridharan & Prakash, 2000)

Free swell ratio	Soil Expansivity	Clay Type
< 1	Negligible	Non-Swelling
1.0 - 1.5	Low	Mixture of non-swelling and swelling
1.5 - 2.0	Moderate	Swelling
2.0 - 4.0	High	Swelling
> 4.0	Very high	Swelling

C) Direct method

These methods present the most useful data by direct measurement; which involves actual measurement of volume change in an odometer type testing (swell pressure test) apparatus. These tests are required to get measurable properties that can be used to predict or estimate the magnitude of volume change. To avoid erroneous conclusions, testing should be done on a variety of samples.

2.5 Soil Classification Method

2.5.1 General soil classification

Soil classification is the grouping of soils into different categories so that the soil in each category behaves similarly. It categorized soils into groups and subgroups based on engineering properties such grain size distribution, liquid limit, and plastic limit. The two major soil classification systems widely used are American Association of State Highway and Transportation Official (AASHTO) and the Unified Soil Classification System (USCS).

A) AASHTO classification system

AASHTO classification system is useful for classifying both coarse and fine grained soils for highway purpose. The particle size distribution and the plasticity characteristics are required to classify a soil in AASHTO. In these system the soils are divided in to seven types, designated as A-1 and A-7 are further subdivided in to two categories and the soil A-2 in to four categories. The soil with the lowest number is the most suitable for subgrade. For instance A-1 is better than the soil A-4. Soils rated A-6 or A-7 by AASHTO can be considered potentially expansive soil (Nelson & Miller, 1992).

Group index (GI) is an important parameter to evaluate the quality of soil as a highway subgrade material. It is given by the equation:

$$GI = (F_{200} - 35)[0.2 + 0.005(LL - 40)] + 0.01(F_{200} - 35)(PI - 10) \text{ ----- (2.4)}$$

Where F_{200} is percentages passing through sieve No.200 and LL & PI are liquid limit and plasticity index respectively.

B) Unified soil classification system (USCS)

The USCS is the most widely used system for determining the suitability of soils for general use based on particle size distribution and plasticity. According to this system the soils are classified into three major groups; coarse grained, fine grained and highly organic (peat). The soils are grouped as coarse grained, if more than 50% of the soil retained on No.200 (0.075mm) sieve and fine grained, if more than 50% of the soil passes No.200 sieve. The soils are represented by symbols such as, GW or SP, border line materials are represented by a double symbol as GW-GP.

The fine grained soils are divided into inorganic silts (M), inorganic clays (C), organic silts and clay (O). The soils are further divided into those having liquid limits lower than 50% (L), or higher (H). The distinction between the inorganic clay and silt is made by the basis of modified plasticity chart.

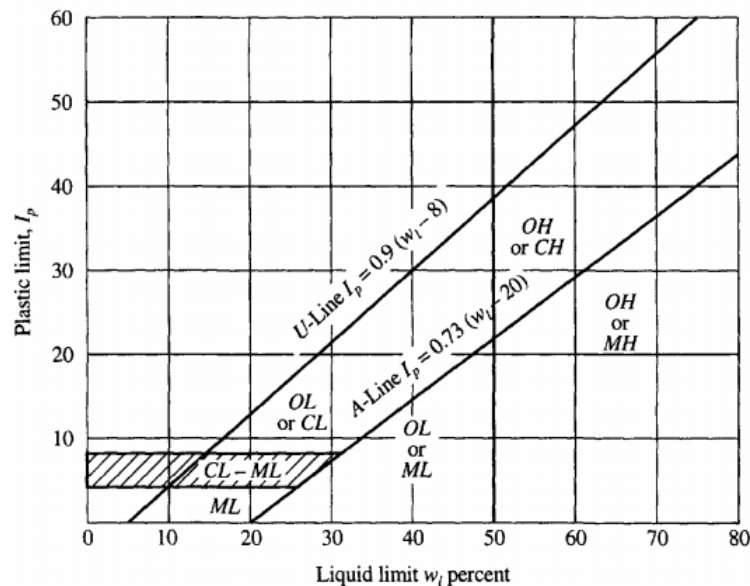


Figure 2.2 Plasticity chart for fine-grained soils (Murthy, 2002)

2.5.2 Classification specific to expansive soil

The parameters determined from expansive soil identification tests have been combined in a number of different classification scheme to provide a qualitative assessment of the degree of expansion. Unfortunately, there has no type evolved a standard classification procedure and a different scheme is used in practically at different location (Nelson & Miller, 1992). Classification based on indirect prediction of swell potential are discussed as follows:

a) Method of Chen

This method was proposed by Chen (1988) and presented a single index method for identifying expansive soil using only plasticity index as shown in Table 2.4.

Table 2.4 Relation between swelling potential and plasticity

Plasticity Index (%)	Swelling Potential
0 - 15	Low
10 - 35	Medium
20 - 55	High
35 and Above	Very High

b) Skempton method

Skempton (1953) observed plasticity index of a soil increase linearly with percentages of clay size fraction (percent finer than 2 μ m by weight) present. It is used as an index for identifying the swell potential of clay soil and expressed as:

$$\text{Activity (A)} = \frac{\text{Plasticity Index (PI)}}{\% \text{ of Clay size fraction by weight}} \dots \dots \dots (2.5)$$

Typical values of activities for clay minerals are given in the table below;

Table 2.5 Activity of clay minerals (Teferra & Leikun, 1999)

Activity	Types of clay minerals
< 0.75	Non active
0.75 - 1.25	Normally active
1.25 - 2.0	Active

c) USBR classification method

This method developed by Holtz and Gibbs (1956) which is based on the simultaneous consideration of colloid content < 0.001mm, plasticity index and shrinkage limit with observed volume change. The typical relationship of these properties with swelling potential is shown in Table 2.6.

Table 2.6 Classification of expansive soil based on USBR method (Chen, 1988)

Colloid content % < 0.001mm	Plasticity index	Shrinkage limit	Probable expansion %, total vol. change	Degree of expansion
> 28	> 35	< 11	> 30	Very high
20 - 13	25 - 41	7 - 12	20 - 30	High
13 - 23	15 - 28	10 - 16	10 - 30	Medium
> 15	< 18	> 15	< 10	Low

2.6 Soil Stabilization

Soil stabilization is a process of changing one or more soil characteristics to create an improved soil material in providing the desired engineering properties. The process may include blending of soil with two or more grains to achieve a desired gradation or mixing of commercially available additives such as cement, lime or bitumen that may alter the gradation, plasticity, or act as a binder for cementation of the soil (Guyer, 2011; Lim et al., 2014).

2.6.1 Method of soil stabilization

Stabilization is a process by which the property of soils are improved so as to meets the construction requirement. There are two broad categories of soil stabilization namely mechanical and chemical stabilization.

A) Mechanical stabilization

Mechanical stabilization is defined as a process of improving the quality of soil without changing the chemical properties of the soil. It is done by mixing two or more grades of soil to obtain the required specifications. It is the most widely used method where the material is made more stable by adjusting the particle size distribution. This type of stabilization includes: compaction, mixing or blending of two or more gradations, applying geo-reinforcement and mechanical remediation (Guyer, 2011).

B) Chemical stabilization

Chemical stabilization is a process in which different chemical or additive material is added to the soil. In this method, soil stabilization depends mainly on chemical reactions between stabilizers and soil minerals to achieve the desired property. Chemical stabilization involves mixing or injecting chemically active compounds (such as cement, lime, fly ash, sodium chloride or bitumen) into the soil to improve its stability, strength, and durability, or to control swelling and permeability (Lim et al., 2014). Some of chemical additives used for soil stabilization are as follows:

i) Cement stabilization

Cement stabilization is the most common method of stabilization with additives. Soil cement (mixture of soil and cement) has been used as foundation material in many projects, such as highway pavement, building pad, and slope protection of dams and embankments. Cement stabilization differs from other forms of chemical stabilization in such a way that structural strength is primarily gained from the cementing action rather than from internal friction, cohesion or chemical ion exchange of the materials. Almost all types of soils can be used for cement stabilization except highly organic soils or heavy clay soils (Teferra & Leikun, 1999).

ii) Lime stabilization

Three forms of lime are produced when limestone is broken. These are quick lime (CaO), hydrated lime ($\text{Ca}[\text{OH}]_2$) and hydrated lime slurry, all of them can be used to treat the soils. Lime has been known to reduce the swelling potential, liquid limit, plasticity index and it improves the workability and compaction of subgrade soils. In addition to being used alone, lime is also used with different admixtures; some of them are lime-fly ash, lime-cement, and lime-bitumen. In general, lime stabilization improves the strength, stiffness and durability of fine-grained soils (Arora, 2003).

iii) Fly ash stabilization

This method of stabilization is gaining more attention in recent times since it has wide spread availability to be used alone or with other cementitious additives. It is inexpensive and has a long history of use as an engineering material and has successfully employed in geotechnical application. Fly ash can improve the California bearing ratio (CBR) and unconfined compression strength (UCS) while lowering the liquid limit and plasticity index.

2.7 Coal Resource

Coal is a fossil fuel formed from peat and decayed plant materials found in prehistoric marshes. Coal is formed over hundreds of millions of years as the marsh humus degrades and gets buried beneath layers of sediments. Pressure and temperature increases compress the humus, reducing moisture content and other organics, and forming coal seams. Coal is a sedimentary rock that is mostly made up of carbon, hydrogen, oxygen, sulfur, and nitrogen.

2.7.1 Coal production and reserves

According to World Coal Association report in 2018, it is estimated that there are over 1.06 trillion tons of proven coal reserves worldwide and are heavily concentrated in just a few countries; such as United state of America (24%), Russia (15%), Australia (14%) and China (13%); which is enough to last more than 130 years at current production rate.

Now a day it is believed that in every continent except Antarctica fossil fuels are the major source of energy generation. In 2018 over 3,916 million tons of coal produced worldwide. China and United state (US) are the leading countries in the coal production and estimated about 1,829 and 364 million tons respectively. In Africa 92% of coal was produced in South Africa and quantitatively about 143 million tons of coal produced annually (BPstats, 2019).

2.7.2 Coal production in Ethiopia

Ethiopia has huge potential of coal resource at different places in the country. The country should focus more on the mining sector in order to fully utilize its coal potential and save foreign currency. Coal mining offers a variety of work opportunities. In addition to extraction services, it is much necessary input to fertilizer and textile factories. Coal also contributes to generate of thermal power, cement manufacture, and brick production by substituting diesel oil. Ethiopia has a lot of coal deposits. The most promising coal resource areas are found at Yayu, Debre Birhan, Delbi Moye, Chilga, Mush Valley and Wuchale (Ahmed, 2008).

The Yayu Woreda alone has more than 220 million tons of coal potential. In addition, it is believed that there would be 32 million tons of coal potential in Achebo area. Among them, an average of 70 tons are mined annually and supplied to AYKA Addis Textile and Investment Group PLC annually (Kifle, 2019). Ethiopia imports more than 750,000 tons of coal annually; from this more than three-fourths goes to cement businesses, which heavily depend on carbon intensive fuels (Samson, 2017).

2.7.3 Coal combusted products

Coal combustion products include fly ash, bottom ash, boiler slag, or flue gas desulfurization. The term coal ash is used interchangeably for different types of ash. Coal ash is a combination of fly ash and bottom ash. Fly ash is the fine ash produced in a coal-fired power station, which is collected using electrostatic precipitators. Bottom ash is the coarse ash that falls to the bottom of a furnace (Heidrich et al., 2013).

Fly ash is the residual remains after the combustion of coal and is made up of very fine particles of Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), Iron Oxide (Fe_2O_3) and Calcium Oxide (CaO). Fly ash with little or no cementing value has the ability to react with calcium hydroxide in the presence of water, and produce highly cementitious water insoluble products called pozzolanic reactivity. Based on chemical composition, ASTM 618 classified fly ash into two classes: class F and class C. The main difference between these classes is the amount of calcium, silica, alumina and iron content in the ash.

Class F: it is produced from burning of older anthracite and bituminous coal. This fly ash has pozzolanic properties, and contains less than 10% lime (CaO). The glassy silica and alumina in Class F fly ash have pozzolanic properties, therefore they need a cementing agent like cement, quicklime, or hydrated lime mixed with water to react and generate cementitious compounds. A geo-polymer can also be made by mixing a chemical activator like sodium silicate (water glass) with a Class F ash.

Class C: it is produced from the burning of younger lignite or sub-bituminous coal. In addition to its pozzolanic properties, class C fly ash has also some self-cementing properties. Class C fly ash hardens and becomes stronger over time when exposed to water. In most cases, Class C fly ash contains more than 20% lime (CaO). Unlike Class F, self-cementing Class C fly ash doesn't require an activator.

2.8 Soil Reinforcement

Soil reinforcement is a mechanical means of improving soils using fibrous materials. The fibrous materials can be geo-synthetics or fibers of a natural or synthetic origin. Fiber reinforcement has been applied in subgrade stabilization, embankment construction, and slope stabilization. Reinforcement is the technique of placing tensile elements in the soil to improve stability, strength, and control deformation. The fibers in the soil mass generate strains and tensile loads in the reinforcements. These tensile loads act to prevent soil movements and thus provide additional shear strength. The reinforcement acts as a tensile member coupled to the soil fill material by friction, adhesion, interlocking or confinement, and thus improves the stability and strength of the soil mass (Kumar et al., 2015). The primary purpose of reinforcing a soil mass is to improve its stability, to increase its shear and bearing capacity, to reduce settlement and lateral deformation of soils.

2.8.1 Classification of fiber-reinforced soil

Fiber reinforced soil can be classified into two groups based on their method of application: (i) Oriented distributed fiber reinforced soil (ODFS) and (ii) Randomly distributed fiber reinforced soil (RDFS).

i) Oriented (continuous) distributed fiber reinforced soil

Oriented distributed fiber reinforced soil (ODFS) is one of the reinforcement mechanisms where fibers can be introduced by planner systems in vertical, horizontal or both directions. The reinforcement material is put in layers and then the soil is compacted in a direction parallel to the shear plane (Gowthaman et al., 2018). It is the inclusion of planar sheets such as strips, fabrics, bars, grid etc into several layers of soil. It should be noted that the soil is first compacted to the required density, then the reinforcement material is placed and the sequence is repeated until the required thickness is achieved.

Oriented distributed fiber reinforced soil develops supplementary frictional strength along the fiber-reinforced planes whereas unreinforced zones provides survival by their own strength and there is a possibility to generate failure planes through weaker unreinforced zones. This type of reinforcement mechanism is similar to traditional geo-synthetic approaches in which materials were introduced to weaker planes of the soil as geo-grids, geo-cells, geo-mats or geo-textiles (Gowthaman et al., 2018).

ii) Randomly distributed fiber reinforced soil

Randomly distributed fiber reinforced soil (RDFS) is a well-known soil improvement technique in which fibers having a desired property and quantity are inserted randomly and compacted with soil. Compared to oriented distributed fiber reinforced soil, randomly distributed fiber reinforced soils has some advantages. It maintains the soil's strength isotropy and limits the formation of potential failure planes in which fibers make all the possible angles with any arbitrarily chosen fixed axis (Oderah, 2015). In randomly distributed fiber reinforced soils, fibers are distributed over the entire volume of the reinforced soil randomly by means of the mixing or blending process; and there should not be any discernible planes of weakness in reinforced soil. The discrete fibers are simply added and mixed randomly with soil in the same manner as cement, lime or other additives (Gowthaman et al., 2018). Conventional construction equipment can be used to mix the fibers within the soil mass and the soil mass

can be compacted without concern of damaging the reinforcement. The schematic diagrams of oriented and randomly distributed fiber reinforced soil are shown below in Figure 2.3.

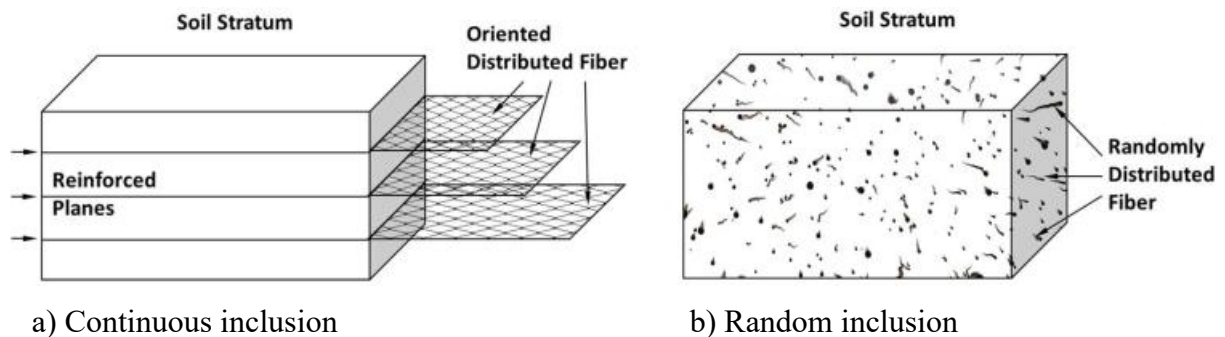


Figure 2.3 Fiber reinforcement mechanism of soil (Gowthaman et al., 2018)

2.9 Fibers

Fibers can be classified as natural fibers (coir, sisal, jute, bamboo, palm, kenaf, hemp, cane etc.) and synthetic fibers (polypropylene, polyethylene, polyester, glass fibers etc.). Natural fibers are fibers that are produced from plants (bamboo, jute, coir, hemp, sisal, etc.), animal parts (silk, hair, wool, etc.), minerals or geological processes which can be spun into thread or rope. Synthetic fibers are manmade or artificial fibers that are manufactured from chemical process (Mohammed, 2020). Due to their durability and tensile strength, synthetic fibers are preferred as reinforcing materials. However, the use of synthetic fibers as soil reinforcement can cause environmental problem such as environmental pollution, depletion of non-renewable resources and influx of heavy and dangerous substances to the geo-environment. Thus, geotechnical engineers are focused on modifying the existing weaker soil using ground improvement techniques by ensuring sustainability in land use (Ibrahim et al., 2010).

Natural fiber used as reinforcement can be suitable substitute for synthetic fiber because they have comparatively high strength, stiffness, and low density (Mizera et al., 2016). Due to this, soil reinforcement with natural fiber have gained great attention as one of the evolving sustainable soil strengthening techniques in geotechnical engineering by considering its unique advantages such as environmental friendliness, cost effectiveness, minimal energy consumption, light weight, resource abundance, and obviously the use of natural fibers reduces problems of waste disposal (Mizera et al., 2016).

2.10 Enset Plant

Enset (*Ensete ventricosum*) known as false banana is a large perennial monocarpic herb plant, similar in form to bananas of the genus *Musa*. *Ensete ventricosum* doesn't produce edible fruits and it's not categorized as common banana plants (Mizera et al., 2016). Enset is larger than banana plant which reach up to 10m in height (most of domesticated enset plants have heights of 4 - 6 m) and with the pseudostem more than 1m in diameter (Lemma et al., 2016). Enset is cultivated only in its native indigenous farming systems of southern and southwestern Ethiopia, with a great potential to provide year-round food production.

Enset are widely farmed for pseudostem base, underground corm, leaf sheaths and that gives a year-round dietary starch source, and typically harvested 4 - 7 years after planting (Tsegaye, 2002). It grows over a comparatively wide range of conditions, is drought-tolerant, and harvested at any time of the year, for several years. Enset is planted at elevations ranging from 1,100 to more than 3,000 meters above sea level, indicating the extent to which its natural distribution has been expanded artificially through domestication (Getu, 2012). Enset plant is main source of food for peoples in the southern region of Ethiopia mainly the Guarage, Sidama, Kambata, Wolaita, Hadiya and Dawro people (Maja, 2018). The enset plant provides fibers, medicines, animal fodder, roofing and packaging in addition to food source. A typical view of enset plant is shown in Figure 2.5.

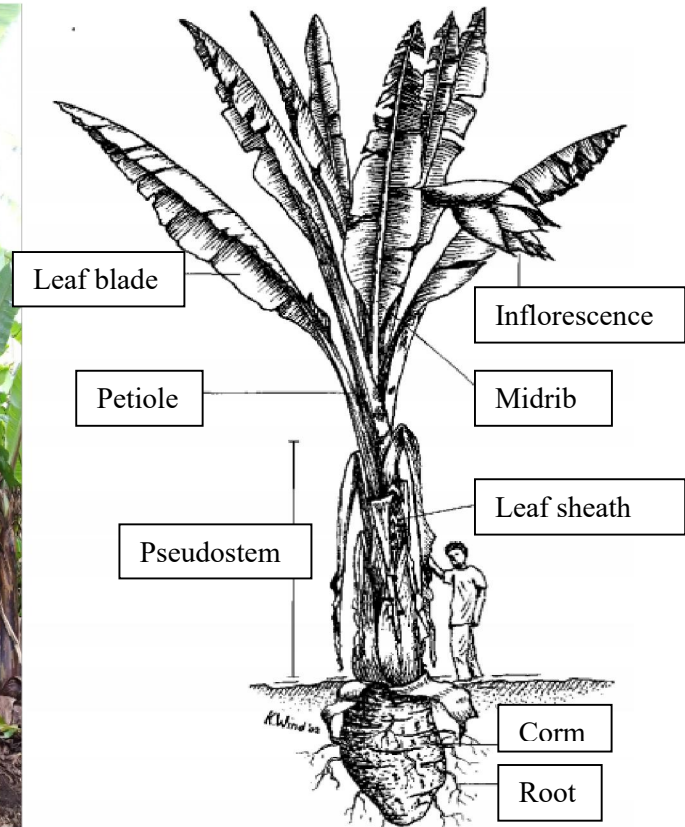
2.11 Enset Fiber

Enset fiber is among widely used natural fibers on Southern and southwestern area of Ethiopia. The fiber is extracted from the pseudostem and leaf parts of Enset plant. The extracted fibres are sun dried and used in rural areas to make sacks, bags, ropes, cordage, mats, sieves and tying materials for construction (in place of nails). The leaf blades of plant are used for serving cooked foods, for warping several materials like fermented enset, coffee, butter, and chat to prevent from drying (Teli & Terega, 2017).

Now a days this fiber has gain the attention of various researchers for applications in civil engineering works because it is locally available, cost effective, biodegradable hence it do not create disposal problem in environment and their inclusion significantly increases the engineering properties of soil (Maja, 2018).



a) Photographic view of enset plant



b) Elements of enset plant (Tsegaye, 2002)

Figure 2.4 Enset ventricosum plant

Enset fiber has a good structure, its tensile properties are comparable to most commercially available fibers, and its tensile strength is almost equal to that of abaca, cotton, banana and flax fibers. Due to its excellent engineering properties, this fiber has has unexploited potential in major sectors such as construction, marine, textile, automotive and renewable energy (Teli & Terega, 2017).

Microstructurally an enset fiber structure consists of cellulose, hemicellulose, lignin, ash and solvent extractives. However, cellulose is more predominant in enset fiber that gives higher mechanical strength (tensile and flexural strength) in addition of providing rigidity due to its crystalline nature (Teli & Terega, 2017). Hemicellulose acts as a cementing matrix between cellulose microfibrils and can be identified at the interface of cellulose and lignin. Lignin gives protection of layer which prevents the internal structure of fiber from degradation due to microorganism and chemical attack and assists with the water transportation (Gowthaman et al., 2018).



Figure 2.5 Photographic view of enset fiber

2.11.1 Physical and mechanical properties of enset fiber

The performance of reinforced soil depends on the mechanical properties of the reinforcement material. So it is important to know the physical and mechanical properties of the reinforcement material such as water absorption, diameter, density, specific gravity, tensile strength, and young's modulus (Mohammed, 2020). Enset fiber is a ligno-cellulosic fiber, obtained from the pseudo-stem of enset plant with comparatively good mechanical properties. It reaches relatively high specific strength and rigidity owing to their low density (Mizera et al., 2016). The physical and mechanical properties of enset fibers related to soil reinforcement from different authors are shown in Table 2.7.

Table 2.7 Physical and mechanical properties of enset fiber

Diameter (μm)	Density (g/cm^3)	Ultimate tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at break (%)	References
50 - 400	0.69	250 - 550	21 - 85	1.6 - 5.6	Mizera et al. (2016)
128	0.88	352	-	3.2	Teli & Terega (2017)
166	0.9	360.1	12.8	4	Balcha et al. (2021)

2.11.2 Chemical composition of enset fiber

The chemical composition of enset fibers have been reported by several researchers. Teli & Terega (2017) reported that enset fiber contains 64.46% cellulose, 22.47% hemicellulose, 6.88% lignin, 5.66% ash and 0.54% solvent extractives. The combined weight of the two major components that make up holocellulose (i.e. cellulose plus hemicellulose) was 87%,

which can also be used for various applications (i.e textile, automotive, paper, construction etc). Lemma et al. (2016) found that enset fiber contains 69.51% cellulose, 5.7% lignin and 4.62% ash. Esayas et al. (2018) indicated that enset fiber contains 62% cellulose, 19% hemicellulose, 5% lignin and 15.47% moisture content. The variation in chemical composition of enset fiber is due to different measurement method, source and age of fiber.

2.11.3 Extraction of enset fiber

The main reason for extraction of fiber from enset plant is due searching for food which is locally known as “kocho”. The fiber is a hair like structure, locally called “kacha” and is collected after scrapping of the leaf sheath and leaf bases around the pseudostem (Maja, 2018).

The Enset fiber was extracted from pseudostem part of the enset plant by using hand decortications (scrapping), the stem is made with several layers of sheathes of thickness 20-40mm range which is tightly overlapped. After dismantling and sorting as per fiber position across plant stem from outer to the core was performed. The pulpy tissue was scraped out, traditionally, by help of sharp-edged bamboo against flat wood along the fiber length. Such fibers are very long, often cut to 1-2m during extraction but it may extended to 6m or more depending upon the height of pseudostem, the extraction method and the intended end use. The fibers were then sun dried in the open air (Balcha et al., 2021).



a) dismantling enset sheathes

b) extraction of enset fiber

c) enset fiber

Figure 2.6 Enset fiber extraction process

2.11.4 Fiber treatment

All natural fibers are hydrophilic in nature, which results in a very poor interface between the fiber and the matrix (soil). Although fibers comprise many desirable engineering properties; however, degradation due to microorganism, moisture and alkali attack remains as a major challenge in geotechnical applications of fiber soil reinforcement technique. Biodegradation effect and moisture absorption are interconnected, and that provides favorable conditions for microorganisms to live and spread on fiber material. The presence of moisture on the particle interfaces acts as a lubricant layer that induce slipping and rupture effect which results in the reduction of friction and cohesion in fiber reinforced soil (Gowthaman et al., 2018).

The degradation heavily affects the durability of natural fiber in subsoil environment and depletes the reinforcing effect of fiber, is often considered as a challenge need be avoided. As to provide the long-term durability of fiber, treatments have been undertaken to alter characteristics of fibers. The treatments include physical treatment (beating, heating, coating), chemical treatment (alkalization, silane, acetylation, benzylation etc). Treatment increases surface adhesion properties of the fiber by removing impurities which increases tensile properties, elasticity, and dimensional stability (Getu, 2012).

Physical coating modify the surface of fibers by physically preventing the entry of moisture into the fiber, this technique improves the durability of natural fibers. Ramasubbarao (2014) conducted water absorption tests on uncoated and kerosene coated coir fibers and concluded that water absorption capacity of kerosene coated coir fiber reduced compared to that of uncoated coir fiber. Water absorption of coir fiber coated with kerosene and bitumen was conducted by Ramesh and Krishna (2011). According to authors, kerosene and bitumen coated coir fibers showed decreased water absorption. However, kerosene providing the highest reduction in moisture absorption compared to uncoated coir.

2.12 Previous Related Research Works

Kumar and Vikranth (2014) had evaluated the strength characteristics of black cotton soil treated with coconut coir fiber and fly ash. Unconfined compression strength (UCS) and California bearing ratio (CBR) were carried out using different percentages of fly ash at 5%, 10%, 15%, 20% and coconut coir at 0.25%, 0.5%, 0.75%, 1% to determine the variation of strength of the sub grade. From the test results it is concluded that the addition of 20% fly ash on black cotton soil, the CBR and UCS value are increased by 83% and 66% respectively compared to untreated soil. However, the addition of 20% of fly ash and 1% of coconut coir in combination to the soil increased the CBR and UCS value by 285% and 120% respectively which has better improvement than fly ash only.

Singh and Arif (2014) had presented the effect of inclusion of coconut coir fiber in silty sand soil mixed with coal ash. Unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted on the soil mixed with coal ash/coir fiber/both. The percentage of coal ash was taken as 20%, 30%, 40% and 50 % and coconut coir fiber varied as 0.25, 0.50, 0.75 and 1.0%. The coir was cut into pieces of length varying from 3cm to 5cm. A significant increase in UCS and CBR value were observed for addition of 20% of coal ash in the soil. The optimum percentage of soil-coal ash-coir fiber mix was taken as 79.75%, 20%, and 0.25% respectively by dry weight. They concluded that addition of coal ash-coconut coir fiber in to soil results significant increases in UCS and CBR.

Tiwari and Mahiyar (2014) had carried out experimental studies on black cotton soil stabilized with fly ash, coconut fiber and crushed glass at various percentages. Soil was replaced with 10%, 15%, 20%, 25% of fly ash, 0.25%, 0.5%, 0.75%, 1% of coconut fiber and 3%, 5%, 7% of crushed glass. Tests result indicates that reduction in swelling pressure, decrease in cohesion and increase in angle of friction as well increase in CBR values are observed due to addition of optimum combination to the soil. They concluded that addition of 20% fly ash, 1% coconut fiber and 5% crushed glass are taken as optimum combination for soil improvement.

Nurdin et al. (2016) evaluated clay soil stabilization with fly ash and palm oil fiber for landfill cover layer. Fiber content 0.5%, 1.0% and 2% by weight of soil mixed with 5%, 10% and 20% fly ash. The results showed that the addition of fly ash (10%) and palm oil fiber (1%) had enhanced the mechanical value of soils. The compressive strength of soils increased from

39.4kPa to 89.0kPa, decreased the value of soil hydraulic conductivity from 1.17×10^{-6} cm/s to 1.2×10^{-7} cm/s, increased in soil friction angle of 8.55° to 24° , and lowering the soil liquid limit of 33.48% to 24.5%, decreased of swelling potential of 8% to only 1.5% at the end of the wetting cycle, and reduced the crack intensity factor (CIF) from 1.96% to zero cracks. They concluded that soil-fly ash-fiber reinforcement can improve strength, resist of shrinkage and swelling potential, resist of crack intensity factor, and increases the resistance of the shear.

Paul and Sneha (2016) studied the effect of bamboo fiber on compaction and strength behavior of fly ash treated black cotton soil. The soil was replaced by fly ash contents of 15%, 20%, and 25% on dry weight basis. Further, optimum percentage (20%) of fly ash treated sample was tested with 0.25%, 0.50%, 0.75%, 1.0% and 1.25% bamboo fiber of length 25mm. Significant increase in UCS values, decrease in MDD and increase in OMC were observed for addition of bamboo fiber on fly ash treated soil. From their investigation, they concluded that addition of 20% of fly ash content and 1.0% of bamboo fiber was considered as optimum percentages for black cotton soil improvement.

Rout et al. (2017) presented the effect of fly ash and coir fiber on strength behavior of clayey sand soil. The soil was stabilized with 5%, 10%, 15%, and 20% of fly ash by dry weight of soil. Then, after determining the optimum percentage of fly ash (i.e. 10%), the soil-fly ash sample was reinforced with 3% and 5% coir fiber. The addition of fly ash and coir fiber increases MDD, UCS, and CBR values of the soil. They concluded that 10% fly ash and 5% coir fiber inclusion was taken as optimum percentage for maximum strength gain.

Table 2.8 Summary of related works

Authors	Type of fiber and additive	Fiber and additive (%)	Soil type	Author's findings
Kumar and Vikranth (2014)	Coconut coir & fly ash	(0.25-1.0) and (5-20)	Black cotton	CBR and UCS increased with the addition of fly ash and coir fiber. This increase was substantially at 20% of fly ash & 1% of coir fiber.
Singh and Arif (2014)	Coir & coal ash	(0.25-1.0) and (20-50)	Silty sand	Both CBR and UCS increased and addition of 20% coal ash and 0.25% coir fiber as optimum content.
Tiwari and Mahiyar (2014)	Coconut coir, Crushed glass & fly ash	(0.25-1.0), (3, 5 & 7) and (10-25)	Black cotton	CBR and soil friction angle increased; swelling pressure, permeability & cohesion decreased as well as MDD decreased. Optimum value was obtained at 20% of fly ash, 1% of coir fiber & 5% of crushed glass
Nuridin et al. (2016)	Palm oil fiber & fly ash	(0.5- 2.0) and (5-20)	Clay	UCS and friction angle increased; swelling pressure, permeability, liquid limit & crack intensity decreased and the peak value obtained at 10% of fly ash & 1% of palm oil fiber.
Paul and Sneha (2016)	Bamboo & fly ash	(0.25-1.0) and (15-25)	Black cotton	UCS increased and MDD decreased. 20% fly ash and 1% of bamboo fiber is taken as optimum improvement.
Rout et al. (2017)	Coir & fly ash	(3 & 5) and (5-20)	Clayey sand	Both CBR and UCS increased and MDD & OMC decreased and increased respectively. Maximum value obtained at 10% of fly ash & 5% of coir fiber.

From the reviewed literature, the following summary and conclusion was made and as follows. The previous investigations on soil improvement considered various factors that affect the strength characteristics of soils; such as type and amount of chemical additives and the fiber properties. The strength characteristics of soil increases until the optimum percentage of chemical additives and fibers, but beyond the optimum content any further addition of chemical additives and fiber reduces the strength behavior of soil composite. The optimum amount of chemical additives, optimum fiber content and length of fiber is different in various studies for different fiber and soil types.

The most widely used method to overcome the problem of expansive soil in Ethiopia is soil removal and replacement. Moreover, existing studies are mainly focused on chemical stabilization alone to improve the properties of expansive soils. Limited studies have been done on the combination of stabilization and fiber reinforcement. Particularly, the study on combined effect of fly ash and enset fiber on the strength properties of expansive soil is limited in literature. Therefore, it is necessary to conduct a systematic study regarding the effects of fly ash and enset fiber on strength properties of expansive soils.

CHAPTER THREE

DESCRIPTION OF STUDY AREA, MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The Tarcha-Chida project road is located in the Southern nation nationalities and peoples Regional State in between Dawro zone and Konta special woreda with its start at a distance of 82 km from Jimma town, just at the entrance of Chida town (422 km) from Addis Ababa. It traverses in the south direction to terminate at Tarcha town having total length of 58 Km. This road project is part of Chida-Sodo road upgrading project which named as Lot-3 Tarcha-Chida (St 58+000 to St 0+000). The project is passing through the villages and towns of Chida, Aba, Gorika, Wara, Lala and Tarcha. It has a latitude and longitude between 7°00'00" - 7°10'11"N and 37°10'24" - 36°59'58"E with an elevation between 1330 and 1670 meters.

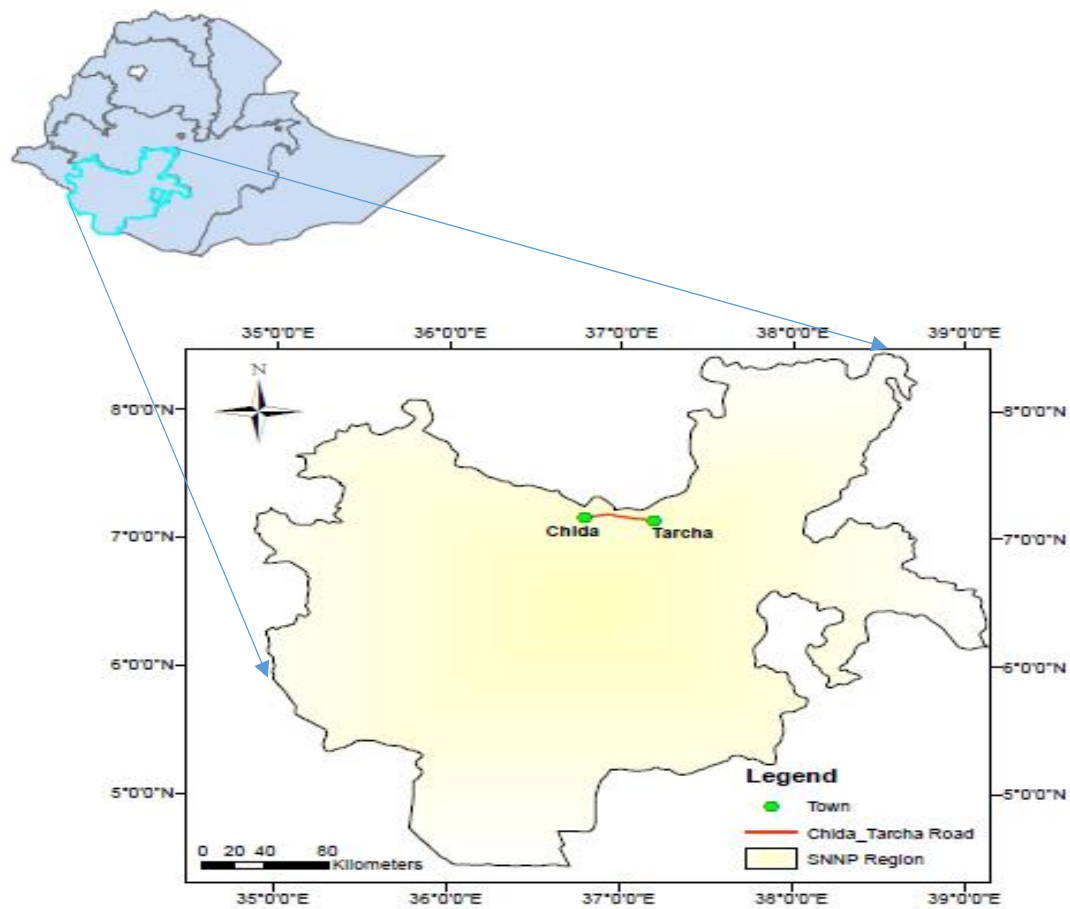


Figure 3.1 Study area location map

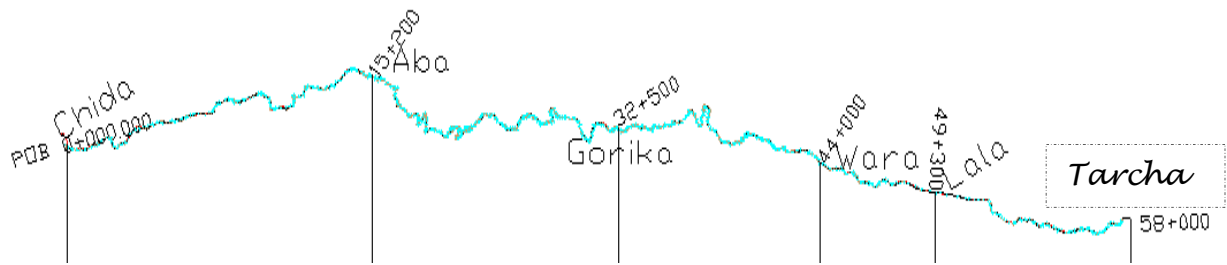


Figure 3.2 Road profile with its control points

3.1.2 Land Use and Cover

Most of the project corridor is covered with cereal crops such as wheat, peas, sorghum, maize, teff and beans. The area is a potential of enset, banana and moringa homestead plantations. The remaining land is covered with scattered trees of small leaves and shrubs. Mostly people are dependent on the farming and cattle breeding which is main livelihood for them.

3.1.3 Climate

Climate plays a great role in influencing moisture contents of sub-grade and sub-base soil. Parameters such as rainfall, temperature, relative humidity and evapotranspiration which are very important to evaluate the soaked condition of subgrade soil by infiltration water or increased ground water table.

3.1.3.1 Rainfall

The study area is characterized by wettest zone having mean annual rainfall of 21 years (1997 - 2017) is about 1033.1mm. Maximum monthly rainfall is recorded in April, May, August and September with the highest peak in August (140.6mm) and the minimum is recorded in December (19.5mm). The rainfall data obtained from Ethiopian National Metrological Agency (ENMA) between 1997 and 2017 are shown below in Table 3.1.

Table 3.1 Mean monthly rainfall (1997-2017)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RF (mm)	23.4	24.7	103.2	129.1	135.4	89	112.8	140.6	116.9	93.5	45	19.5

3.1.3.2 Temperature

According to Ethiopian Mapping Agency (EMA, 1981), Ethiopia is classified in to five climatic zones based on altitude and temperature.

Table 3.2 Climatic zone of Ethiopia based on altitude and temperature

No	Climate Zone	Altitude (a.m.s.l)	Temperature (°C)
1	Desert (Bereha)	Below 500	30-40
2	Tropical (Kolla)	500-1500	20-30
3	Sub Tropical (Weina Dega)	1500-2300	15-20
4	Temperate (Dega)	2300-3300	15-10
5	Alpine (Kur)	3300 & above	10 or less

The study area is with an altitude ranging from 1330 - 1670 meters a.m.s.l., has a minimum and maximum average monthly temperature of 14.8°C and 30.7°C respectively with mean monthly average temperature ranges from 20.8 °C to 23.2 °C. Based on the above classification, the study area has two climatic zones such as Tropical (Kolla) and Sub Tropical (Weina Dega). The temperature data obtained from Ethiopian National Metrological Agency (ENMA) between 2012 and 2017 are shown below in Table 3.3.

Table 3.3 Average monthly maximum and minimum temperature (2012-2017)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. Temp (°C)	29.5	30.7	30.2	26.8	28.4	27.3	26.5	26.9	27.5	28.1	28.3	28.7
Min. Temp (°C)	15.1	15.7	15.3	15	15.2	15	15.1	14.9	14.9	14.8	15	15
Mean. Temp (°C)	22.3	23.2	22.8	20.9	21.8	21.2	20.8	20.9	21.2	21.5	21.7	21.9

3.2 Materials

Three materials are used in this study. These are expansive soil, fly ash and enset fiber.

3.2.1 Expansive soil sample

The expansive soil sample was collected from Tarcha-Chida road section. Two representative sampling areas were selected based on their CBR value from different locations (at km 25+100 and km 25+900) to a depth of 1m below natural ground level. The sample then transported to materials testing laboratory planted in Gorka town, owned by Investstroyproekt LLC and Ethiopian Road Authority.

3.2.2 Coal fly ash

Waste fly ash was collected from AYKA Addis Textile factory which is located in Alemgena, Ethiopia.



a) Expansive soil



b) Test pit



c) Soil sample and fly ash



d) 20mm kerosene coated enset fiber

Figure 3.3 Materials used in present study

3.2.3 Enset fiber and its preparation

Enset fiber was collected from local area of Dawro zone, Disa woreda in southern part of Ethiopia. In order to protect the enset fiber from moisture effect and degradation, the fiber is coated by kerosene before mixing with soil. In this study kerosene is chosen from other treatment techniques because of its availability and suitability to coat many enset fibers with small amount of it. The amount of kerosene used was around 4 liters for all enset fiber coating.

The dried enset fibers were soaked in a container containing kerosene for 24 hours and then after 24 hours, the fiber was removed and air dried. To determine the optimum reinforcement regarding to fiber content and length, the coated enset fiber was cut into 15mm and 20mm length, and each length was prepared to 0.5%, 1%, 1.5% and 2% by weight of dry soil.

3.3 Methods

3.3.1 Sample preparation

After the collection of disturbed soil, moist sample was transported to the laboratory in plastic bags. Sample preparation was done in accordance with the method stated in AASHTO T87-86. Soil samples were air dried by spreading the material out in trays in the laboratory and leaving it open to the air. Then the soil and fly ash are mixed manually to get uniform mix ratio for each test accordingly to its proposed percentage. After optimum soil-fly ash mix was determined, kerosene coated enset fiber at varying percentage for both lengths was added and mixed manually for each test to determine soil-fly ash-fiber properties.

3.3.2 Experimental program

In this study, experimental program was divided in to four parts. In the first part, physical and engineering properties of soils from two stations (25+100 as TP-1 and 25+900 as TP-2) were characterized. In this part natural moisture content, specific gravity, Atterberg limit, grain size distribution, hydrometer analysis, free swell, free swell index and ratio, compaction characteristics (MDD and OMC), soaked CBR, CBR-swell and UCS tests were determined. In the second part, soil treatment with fly ash was conducted on TP-2 only, because the lower CBR and UCS values are obtained at this pit. Here, varying percentage of fly ash (10%, 15%, 20% and 25% by weight of dry soil) were used to evaluate their effect on Atterberg limit, specific gravity, free swell index and ratio, compaction (MDD and OMC), CBR and CBR-swell, and UCS tests. Then, the optimum mix ratio of soil-fly ash was determined. In the third part, compaction (MDD and OMC), CBR and CBR-swell, and UCS tests are conducted by mixing optimum soil-fly ash with kerosene coated enset fiber randomly at varying length and percentage of fiber to evaluate the soil-fly ash-fiber properties. In this part, the first series of test was related to the effect of fiber percentage (0.5%, 1.0%, 1.5% and 2.0% by weight of dry soil) on soil-fly ash-fiber properties while fiber length was constant. In the second series of test, the effect of fiber length (15 and 20mm) with constant fiber percentage was evaluated.

Lastly, the optimum amount soil-fly ash-fiber obtained for kerosene coated fiber was compared with uncoated fiber to evaluate the effect of coating the fiber on compaction (MDD and OMC), CBR and UCS value. All tests have been conducted in accordance with AASHTO or IS. The experimental programs of the present study are given in Table 3.4.

Table 3.4 Experimental program

Mix proportion of material used				Tests conducted						
Soil (%)	FA (%)	EF (%)	EF length (mm)	Grain size distribution	Atterberg limit	Specific gravity	Free swell tests	Modified proctor test	CBR	UCS
100	-	-	-	√	√	√	√	√	√	√
90	10	-	-	√	√	√	√	√	√	√
85	15	-	-	√	√	√	√	√	√	√
80	20	-	-	√	√	√	√	√	√	√
75	25	-	-	√	√	√	√	√	√	√
79.5	20	0.5	15 & 20	-	-	-	-	√	√	√
79	20	1.0	15 & 20	-	-	-	-	√	√	√
78.5	20	1.5	15 & 20	-	-	-	-	√	√	√
78	20	2.0	15 & 20	-	-	-	-	√	√	√
78.5	20	1.5*	20*	-	-	-	-	√	√	√

Note: * represent uncoated enset fiber; FA = Fly ash; EF = Enset fiber

3.3.3 Natural moisture content

Moisture content is defined as the ratio of mass of water to mass of solid particles. The test was conducted according to AASHTO T 265-12. For natural moisture content determination, the samples were kept in a plastic bag to prevent moisture loss during transportation from site to laboratory and the test was conducted immediately after the sample was taken from the site. The measured amount of wet soil and soil mixture was oven-dried at 105°C for 24 hours and the weight loss was measured.

3.3.4 Specific gravity

Specific gravity is the ratio of the mass of a given volume of solid matter at a stated temperature to the mass of the same volume of distilled water at a stated temperature. According to AASHTO T 100-14, there are two procedures for performing specific gravity of soil. These are Method-A, procedures for oven dried specimen and Method-B, procedure for

moist specimen. In this study the specific gravity of sample is determined using Method-A procedures.

3.3.5 Particle size distribution

The test was conducted in according to AASHTO T 88-13 standard. The distributions of particle sizes larger than No.200 (75 μ m) sieve is determined by sieve analysis while the distribution of particle size smaller than 75 μ m determined by hydrometer analysis. Dry sieving was only suitable for soils with negligible amounts of silt and clay but for cohesive soils wet sieving is the applicable method. To avoid the loss of fine particles, the soil sample was washed through the No.200 sieve. A hydrometer analysis was performed to measure the amount of silt and clay size particles. In this study both wet sieve analysis and hydrometer were conducted and a combined grain size distribution curve was plotted.

3.3.6 Atterberg limits

Atterberg limit tests are conducted on fine grained soils to determine the amount of water required to attain different behavioral states. The test includes the determination of the liquid limits, plastic limits and the plasticity index for the soil and soil-fly ash mixtures. The tests were conducted in accordance with AASHTO T 89-13 and T 90-14 standard. Atterberg limits were determined for air-dried samples passing No.40 (0.425mm) sieve.

Liquid limit (LL): The liquid limit is defined as the moisture content at the boundary between the liquid and plastic state. The soil or soil-fly ash sample was thoroughly mixed with water by alternately and repeatedly stirring, kneading, chopping with spatula and then placed in the Casagrande cup. The cup containing the sample was lifted and dropped at a rate of 2 drops/sec until the two sides of the sample come in contact at the bottom of the groove along a distance of about 13mm. The number of blows required to close the groove to this distance was recorded and its moisture content determined. The relationship between the water content and number of blow is plotted. The water content corresponding to the intersection of the line with the 25 blow abscissa is the liquid limit of the soil.

Plastic limit (PL): Plastic limit of soil is defined as the water content at which the soil changes from plastic state to semi-solid state. A portion of the natural soil or the soil-fly ash mixture used for the liquid limit test was taken for the determination of plastic limit. Then the soil or soil-fly ash sample was rolled in to diameter of 3mm thread until it begins to crumble.

Plastic index (PI): The plasticity index of the natural soil and the soil-fly ash sample is the difference between the liquid limits and their corresponding plastic limits.

3.3.7 Free swell test

Free swell test is the simplest test conducted to study the swelling property of the soil and soil-fly ash mixture. The method was suggested by Holtz and Gibbs, (1956) to measure the expansive potential of cohesive soils. This test was performed by slowly pouring 10ml of oven dry soil which has passed the No.40 (0.425mm) sieve in to 100 ml graduated cylinder filled with distilled water and letting the content for approximately 24 hours until all the soil completely settles on the bottom of graduated cylinder. Then the final volume of the soil or soil mixture was noted. The free swell value was calculated using Equation (2.1).

3.3.8 Free swell index

This test was conducted in accordance with IS: 2720 (Part 40) 1985 testing procedure. Two oven dried soil or soil-fly ash samples passing through 425 μ m sieve are taken and 10ml of each sample were placed separately in two 100ml graduated cylinder. One cylinder is filled with kerosene oil and the other with distilled water; then after 24 hours final volumes are noted. The free swell index value was determined using Equation (2.2).

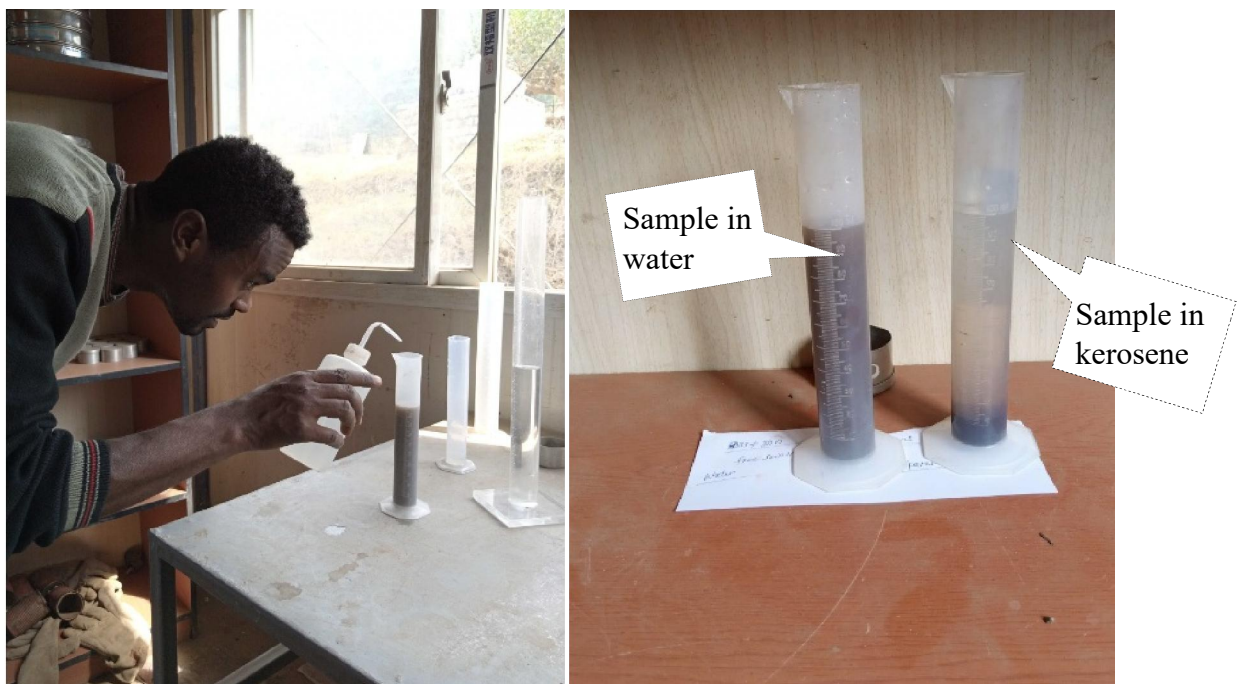


Figure 3.4 Photographic view of free swell and swell index test

3.3.9 Compaction test

Compaction is the densification of soil (pressing soil particles close to each other) by means of mechanical energy. Two types of compaction tests are: (1) standard proctor test, and (2) modified proctor test. In this study compaction was done by the modified proctor test according to AASHTO T 180-10. The soil passing No.4 (4.75mm) sieve was thoroughly mixed with measured quantity of water and then compacted in the mold in 5 approximately equal layers; each layer was given 56 uniformly distributed blows of 4.54kg rammer falling through a height of 457mm. Compaction was done in similar manner for soil treated with fly ash at its respective percentage (i.e. 10%, 15%, 20% and 25% by weight of dry soil). For reinforced sample, kerosene coated enset fiber was added to the soil-fly ash (optimum mix i.e. 80% soil and 20% fly ash) at four different percentages (i.e. 0.5%, 1%, 1.5% and 2% by weight of dry soil) for each 15mm and 20mm fiber length. Enset fibers were randomly distributed in soil-fly ash samples uniformly. The compaction curves are obtained by plotting the dry densities with reference to their water content for all tests. Then, their respective OMC and MDD were determined.

3.3.10 California bearing ratio (CBR) test

The California bearing ratio test is one of the most common strength tests used to evaluate subgrade quality of soils and base coarse materials in pavements. CBR test was performed according to AASHTO T 193-13 for the natural soil, soil-fly ash and soil-fly ash-fiber mixture based on their mix proportion. In this study CBR test samples were prepared by modified compaction effort (compacted in 5 layers and each layer subjected to 56 blows) for soil mixtures at their respective OMC and MDD obtained in the compaction test. The sample preparation for CBR test includes soil alone, soil with varying percentage of fly ash (10%, 15%, 20% and 25%), and soil with optimum fly ash (20%) and enset fiber of varying percentage and length (0.5%, 1%, 1.5% and 2% at 15mm and 20mm). The test was carried out for samples in water soaked condition. For soaked CBR test, the mold along with compacted sample was transferred to a tank containing water to soak for 4 days (96 hours). After 4 days of soaking, the samples were taken out from the soaking tank, poured the water off from the top and allowed to drain down ward for 15 minutes. Then the CBR mold along with soaked sample was brought to a loading frame for testing and load readings at penetrations of 0.64mm, 1.27mm, 1.91mm, 2.54mm, 3.81mm, 5.08mm, 6.35mm and 7.62mm are recorded.

Calculations

Bearing ratio: the bearing ratio is calculated by dividing the corrected stress values at 2.54mm and 5.08mm to the standard stresses of 6.9MPa and 10.3MPa respectively and multiplying by 100. But the bearing ratio reported for the soil is normally the one at 2.54 mm penetration. If the ratio at 5.08mm penetration is greater, redo the test. If the check test gives a similar result, use the bearing ratio at 5.08 mm penetration.

$$\text{CBR} = \frac{\text{stress}}{\text{standard stress}} * 100 \dots\dots\dots (3.1)$$



a) Soaked CBR sample with tripod in water tank



b) CBR test machine

Figure 3.5 Photographic view of soaked CBR test

3.3.11 CBR swell

The CBR swell of the soil or soil-fly ash-fiber was measured by placing the tripod with the dial indicator on the top marked point of the soaked CBR mold. The initial dial reading of the dial indicator on the soaked CBR mold was taken just after soaking the sample. At the end of 96 hours (4 days) the final dial reading of the dial indicator was taken and the swell percentage of the initial sample length were given by equation 3.2.

$$\text{CBR swell} = \frac{\text{change in length in mm during soaking}}{116.43 \text{ mm}} * 100\% \dots \dots \dots (3.2)$$

3.3.12 Unconfined compressive strength (UCS) test

UCS test is a special case of unconsolidated undrained triaxial test in which a cylindrical cohesive specimen without any lateral support is subjected to axial loading under strain controlled application. In this study the UCS were carried out according to AASHTO T 208-10. The sample preparation for UCS test includes soil alone, soil with varying percentage of fly ash (10%, 15%, 20% and 25%) and soil with optimum fly ash (20%), and enset fiber of varying percentage and length (0.5%, 1%, 1.5% and 2% at 15mm and 20mm). The test was carried out in cylindrical specimen with dimensions of 38mm diameter and 76mm in length. The sample was mixed with its respective optimum moisture content and compacted in a sample tube. Then the sample was removed from the sample tube and trimmed such that the ends are reasonably smooth and the length to diameter ratio is two. After that the sample was placed in a loading frame and an axial load was applied to the sample. The force applied to the sample and deformation was recorded automatically by the help of computer. Finally, stress versus strain graph was plotted and the water content of sample was determined.



a) Sample removal for UCS test



b) UCS test machine

Figure 3.6 Photographic view of UCS test

3.3.13 Water absorption test on Enset fiber

Water absorption test is used to determine the amount of water absorbed by enset fiber. Uncoated enset fiber and kerosene coated enset fiber were used to study the effect of kerosene on moisture absorption of fiber. In this test, enset fiber was dried with sun and immediately weighted which is taken as the dry initial weight of the fiber. Then the specimen was soaked in distilled water for 24 hours. After 24 hours the specimen was removed from water and placed on blotting cloth to remove excess water before weighing which is taken as final wet mass of the sample. For kerosene coated enset fiber, the dry enset fiber was immersed in kerosene for 24 hours, dried and initial mass was taken. Then coated dried enset fiber was immersed in water again for 24 hours and final wet mass of the sample was determined to see the effects of kerosene on the water absorption of fiber. The water absorption of the fiber was calculated as percent weight change.



Figure 3.7 Water absorption test on uncoated and kerosene coated enset fiber

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter presents the laboratory results and their discussions. The relevant physical and engineering properties of the soil are evaluated for natural and treated soil sample separately. Tests such as specific gravity, Atterberg limit, particle size analysis, free swell, free swell index, free swell ratio, compaction, soaked California bearing ratio (CBR) and unconfined compressive strength (UCS) test were conducted on soil and soil-fly ash samples. To evaluate strength characteristics of soil-fly ash-fiber samples; compaction, CBR and UCS tests were conducted.

4.1 Properties of Material Used for the Study

4.1.1 Natural soil

The results obtained from two test pits on natural soil are presented in Table 4.1. The soils are black in color with natural moisture content of 25.3% and 26.8% for TP-1 and TP-2 respectively. The specific gravity of soils in the study area is 2.62 and 2.60 for TP-1 and TP-2 respectively. From particle size distribution curve almost 80% of the soil is passing through No.200 (0.075mm) sieve having clay content 49.18% and 54.41%, silt fraction 31.27% and 27.25%, sand fraction 19.39% and 17.86%, and gravel fraction 0.16% and 0.48% for TP-1 and TP-2 respectively. From Atterberg limit results, liquid limits are 69.9% and 72.9%, plastic limits are 31.1% and 31.3%, and plasticity index are 38.8% and 41.6% for TP-1 and TP-2 respectively. The values indicate that the soil of the study area is highly plastic clay. Soil falls under A-7-6(34) and A-7-6(35) soil class based on AASHTO soil classification system, and CH (Inorganic clays of high plasticity) based on USCS soil classification system for TP-1 and TP-2 respectively. According to AASHTO classification system soils under this class are generally classified as a material of poor engineering property to be used as a subgrade material. Results that are related to swelling characteristics of the soil are also indicate that the soils are expansive clay with a free swell of 87.5% and 92.5%, free swell index of 78.6% and 83.3%, and free swell ratio of 1.79 and 1.83 for TP-1 and TP-2 respectively.

The soils have a maximum dry density of 1.58g/cm³ and 1.55g/cm³, optimum moisture content of 21.3% and 22.5%, soaked CBR value of 1.59% and 1.30%, and UCS value of 136.57kPa

and 126.66kPa for TP-1 and TP-2 respectively. Hence, the soil was found to be highly plastic expansive clay with low bearing capacity when it is soaked and high swelling potential, and this show that the soil fell below the standard recommendations especially for highway construction. Therefore, the soil need initial modification to improve its strength and engineering property. Details of the test results are shown in Appendices.

Table 4.1 Geotechnical properties of natural soils

Type of tests		Test Results	
		TP-1	TP-2
Natural moisture content, (%)		25.3	26.8
Depth of Sampling, (m)		1	1
Specific Gravity		2.62	2.60
Percentage passing No.200 sieve, (%)		80.45	81.66
Percent amount of particle size, (%)	Gravel (> 4.75mm)	0.16	0.48
	Sand (4.75-0.075mm)	19.39	17.86
	Silt (0.075-0.002mm)	31.27	27.25
	Clay (< 0.002mm)	49.18	54.41
Atterberg limits, (%)	Liquid Limit (LL)	69.9	72.9
	Plastic Limit (PL)	31.1	31.3
	Plasticity Index (PI)	38.8	41.6
Moisture-Density Relation	MDD, (g/cm ³)	1.58	1.55
	OMC, (%)	21.3	22.50
Soaked CBR, (%)		1.59	1.30
CBR Swell, (%)		8.45	10.69
Unconfined compression test	UCS, (kPa)	136.57	126.66
	Cu, (kPa)	68.29	63.33
Free swell, (%)		87.5	92.5
Free swell index, (%)		78.6	83.3
Free swell ratio		1.79	1.83
AASHTO Classification		A-7-6 (34)	A-7-6 (38)
USCS Classification		CH	CH
Color		Black	Black

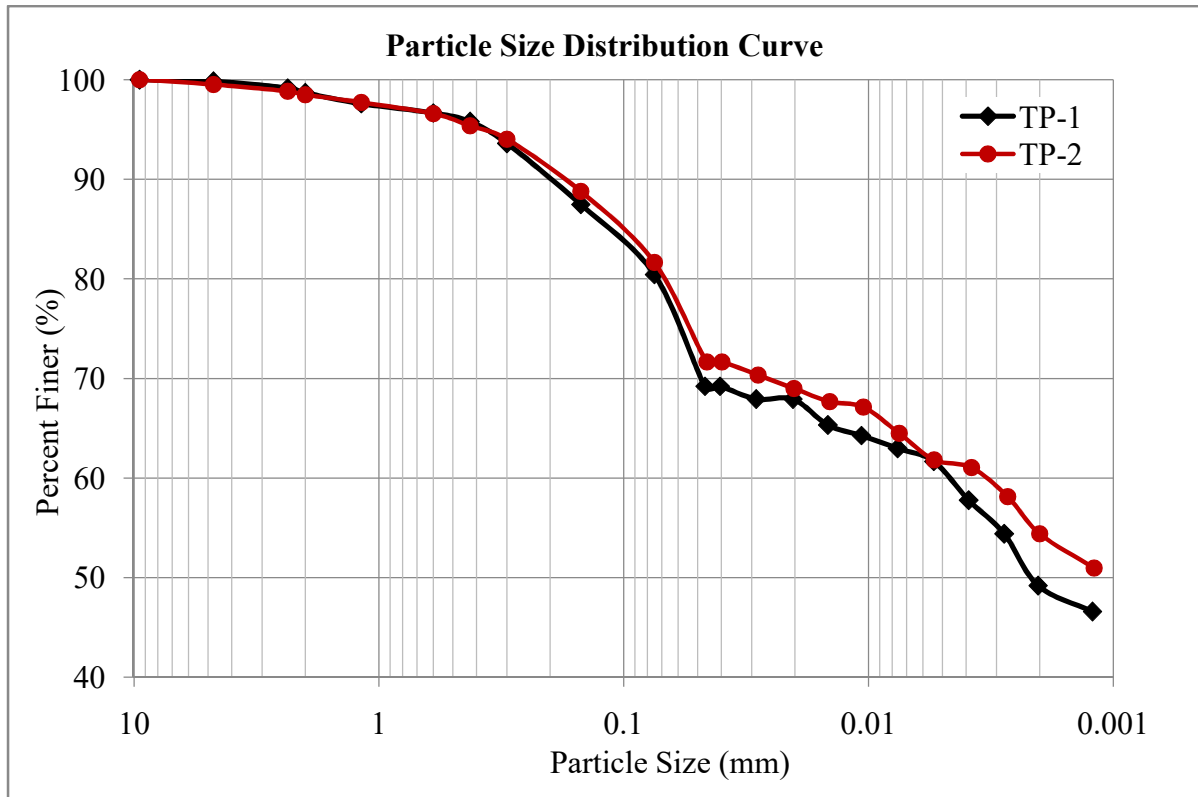


Figure 4.1 Particle size distribution curve for TP-1 and TP-2

4.1.2 Fly ash

The fly ash collected from AYKA Addis textile factory has pozzolanic property. The sum of percent composition of Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3) and Iron oxide (Fe_2O_3) is about 88% which indicates that the sample is categorized under class F fly ash (Kifle, 2019). Physical properties and particle size distribution of fly ash is shown in Table 4.2 and Figure 4.2 respectively. From particle size analysis, fly ash contains majority of sand and silt particles that results non-plastic property. Results from swelling test shows that fly ash has non-swelling character with free swell of 2.0%, free swell index of 1.49% and free swell ratio of 1.0.

Table 4.2 Physical properties of fly ash used in this study

Type of tests		Test Results
Natural moisture content, (%)		5.09
Specific Gravity		2.10
Percent amount of particle size, (%)	Gravel (> 4.75mm)	0.00
	Sand (4.75-0.075mm)	56.37
	Silt (0.075-0.002mm)	38.45
	Clay (< 0.002mm)	5.18
Atterberg limits, (%)	Liquid Limit (LL)	-
	Plastic Limit (PL)	NP
	Plasticity Index (PI)	-
Free swell, (%)		2
Free swell index, (%)		1.49
Free swell ratio		1.01

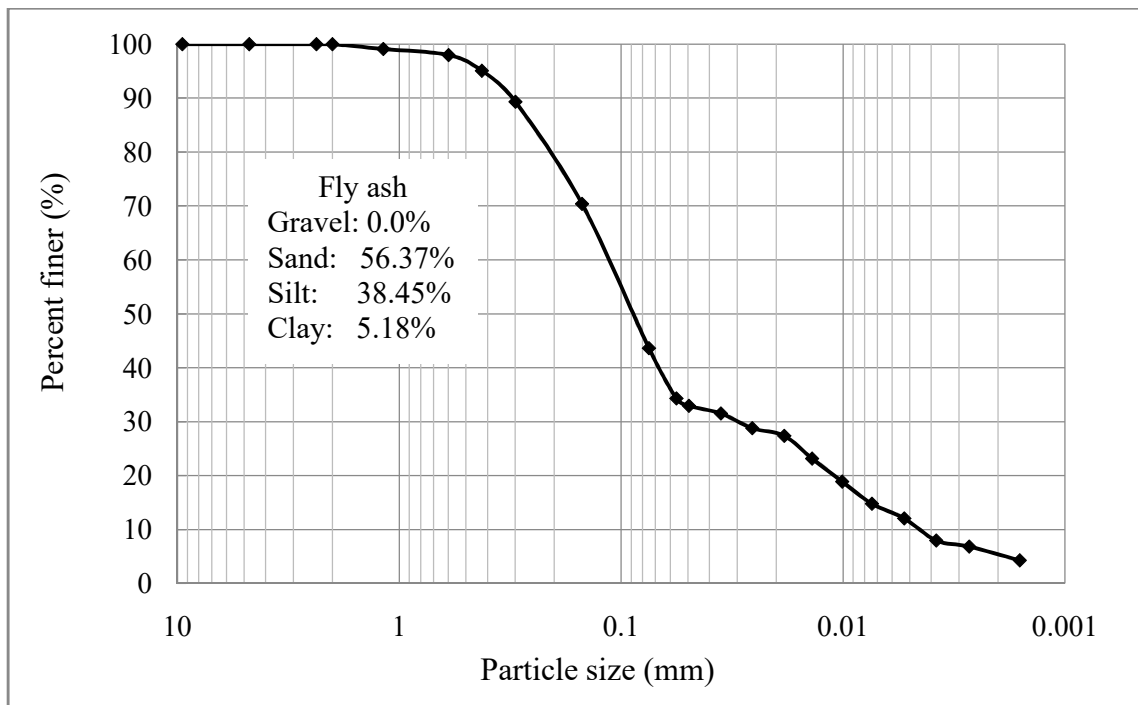


Figure 4.2 Particle size distribution curve for coal fly ash

4.1.3 Enset fiber

Enset fiber used in this study was white in color and has specific gravity of 1.06. The physical and mechanical property of enset fiber that was not conducted in this study was taken from literature. The reason behind this was lack of test equipments. From the literature, enset fiber has diameter about 0.16mm, tensile strength about 360Mpa and Young's modulus about 12.8Gpa (Balcha et al. 2021). The water absorption test conducted in this study shows that WAC of uncoated and kerosene coated enset fiber is 289.2% and 204.8% respectively. This shows that about 29% reduction occurred in water absorption by coating the enset fiber with kerosene.

4.2 Result and Discussion on Soil Treated with Fly Ash

For further study on properties of soil-fly ash, the TP-2 soil is used because it has less CBR and UCS value compared to TP-1.

4.2.1 Effect of fly ash on particle size analysis

From the particle size analysis of various combination for expansive soil with fly ash (FA), it is observed that the particles finer than 0.075mm are decreased due to increase in fly ash content. A summary of particle sizes are shown in Table 4.3 and their distribution curves are presented in Figure 4.3. From Table 4.3, it shows that the sand particles are increased and fine particles are decreased due to addition of 10% - 25% FA. From the particle size distribution curves of soil-fly ash, it is observed that the curves moves from right to left the percent of particle size finer than a specific size is reduced. This shows that, the particle size distributions of the treated soils are improved. For soil-fly ash mix, the curves are short because of only wet sieve analysis was done.

Table 4.3 Particle size distribution of expansive soil with various percentage of fly ash

Fly ash (%)	Particle size (%)		
	Gravel (>4.75mm)	Sand (4.75-0.075mm)	Fine (< 0.075mm)
0	0.48	17.86	81.66
10	0.0	21.67	78.33
15	0.0	27.75	72.25
20	0.24	31.98	67.77
25	0.16	36.33	63.51

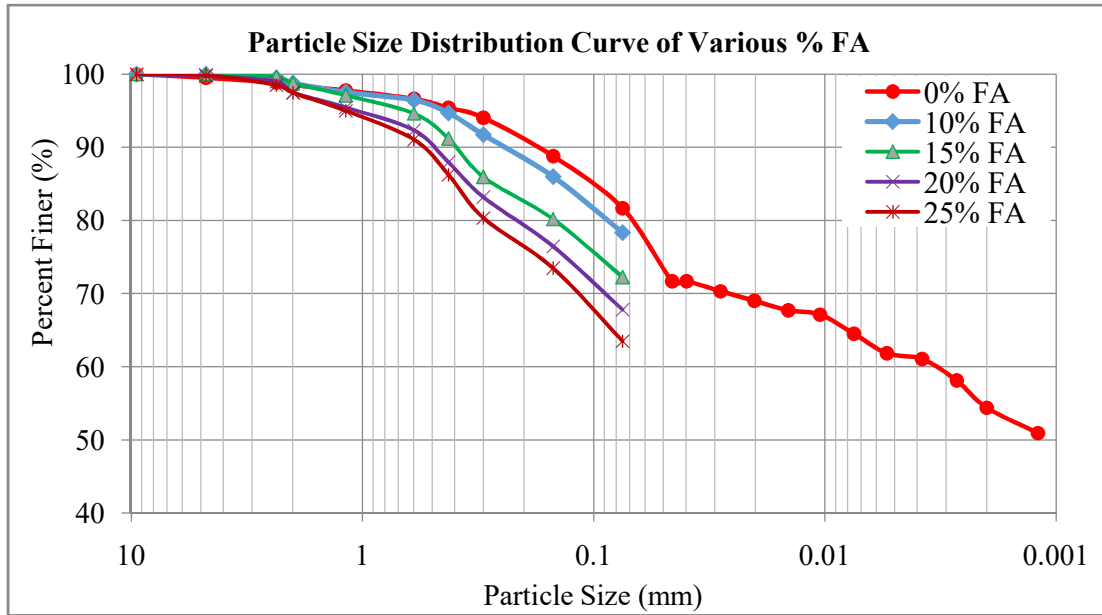


Figure 4.3 Particle size distribution curve of soil with various percentage of fly ash

4.2.2 Effect of fly ash on specific gravity

The effect of fly ash on the specific gravity of the soil is shown in Table 4.4 and Figure 4.4.

Table 4.4 Specific gravity of soil with various percentage of fly ash

Fly ash (%)	0	10	15	20	25
Specific gravity (Gs)	2.60	2.47	2.43	2.41	2.38
% decrease in Gs	0	5.2	6.5	7.6	8.5

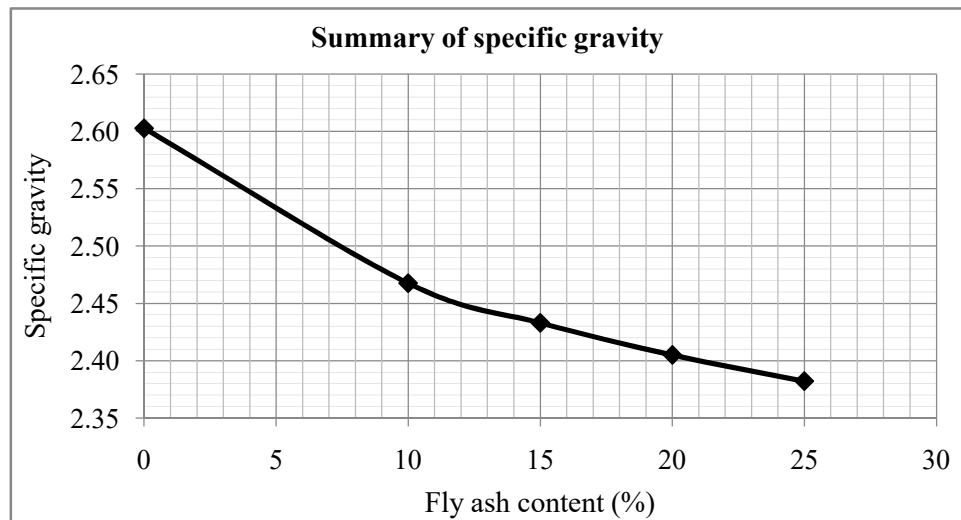


Figure 4.4 Variation of specific gravity of soil with fly ash content

Specific gravity of soil is decreased from 2.60 to 2.38 with increased fly ash content from 0% to 25%. For instance, the specific gravity of soil with 25% fly ash content is about 8.5% lower than that of soil alone. This decrease in specific gravity of soil-fly ash mix is due to the partial replacement of soil with the lower value of specific gravity of fly ash (i.e., 2.10). Details of the specific gravity test results are shown in Appendix B.

4.2.3 Effect of fly ash on Atterberg limit

The effect of fly ash on Atterberg limit of soil is summarized in Table 4.5 and shown in Figure 4.5. As shown in figure, liquid limit slightly decreased and plastic limit increased with the increment in fly ash content. However, the addition of fly ash decreased the plasticity index of soil. The higher reduction in plasticity index was obtained at 25% FA content which is 36.1% lower than that of natural soil.

Table 4.5 Summary of effect of fly ash on liquid and plastic limit

Fly ash (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	% decrease in PI
0	72.9	31.3	41.6	0.0
10	69	32.6	36.4	12.5
15	68.5	35.7	32.8	21.2
20	68	39.4	28.6	31.3
25	66	39.4	26.6	36.1

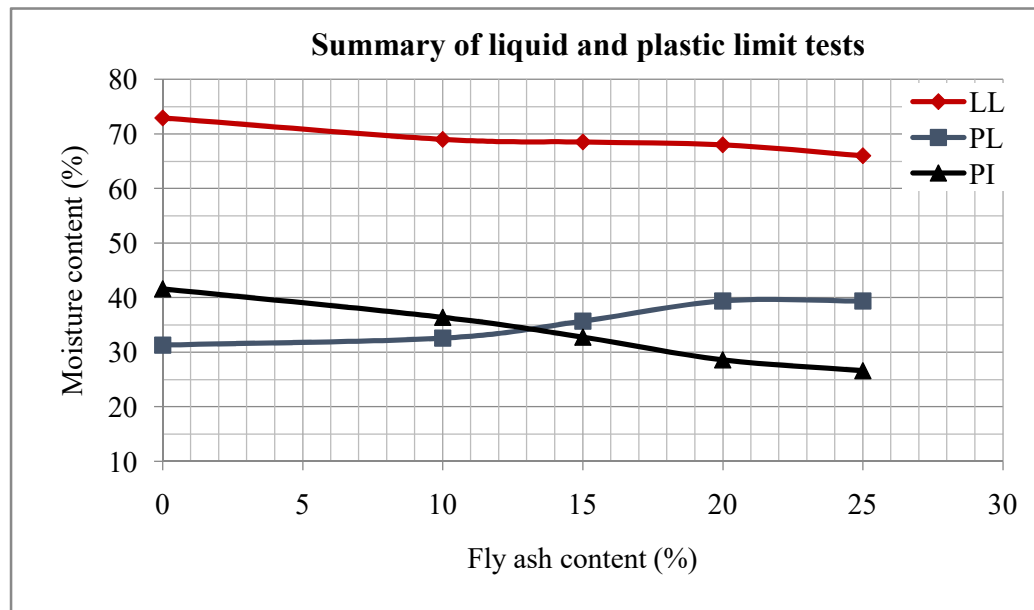


Figure 4.5 Variation of liquid and plastic limit of soil with fly ash content

The decrease in the plasticity index is due to the partial replacement of plastic soil particles with non-plastic fly ash materials, and may be due to reduction in clay fraction (which is responsible for plasticity of the soil). The change in plasticity is due to the cation exchange and flocculation of clay particles. Plasticity index is important in classifying fine-grained soils and is basic to the Casagrande plasticity chart. The higher the plasticity index, there will be the greater engineering problems associated with using the soil as an engineering material, such as road subgrade and foundation support for light building (Bowles, 1992). Details of the Atterberg limit test results are shown in Appendix D.

4.2.4 Effect of fly ash on soil classification

Summary of soil classification is presented in Table 4.6 and the plasticity chart for USCS classification is shown in Figure 4.6. Based on AASHTO classification system soil treated with 10% of fly ash is grouped under the category of A-7-6 with its group index of 32. However, soil treated with 15%, 20% and 25% of fly ash remains under group of A-7-5 with their group index of 26, 21 and 17 respectively. This is due to the fact that more 35% of the particles are passing No.200 (75 μ m) sieve, and they are classified as silt-clay materials. Based on USCS classification system soil treated with 10% fly ash is grouped as CH (Inorganic clays of high plasticity). But, soil mixed with 15%, 20% and 25% of fly ash fallen under group of MH (silty soil).

Table 4.6 Summary of effect of fly ash on soil classification

FA (%)	LL (%)	PI (%)	Gravel (%)	Sand (%)	Fine (%)	USCS	AASHTO
0	72.9	41.6	0.48	17.86	81.66	CH	A-7-6 (38)
10	69	36.4	0	21.67	78.33	CH	A-7-6 (32)
15	68.5	32.8	0	27.75	72.25	MH	A-7-5 (26)
20	68	28.6	0.24	31.98	67.75	MH	A-7-5 (21)
25	66	26.6	0.16	36.33	63.51	MH	A-7-5 (17)

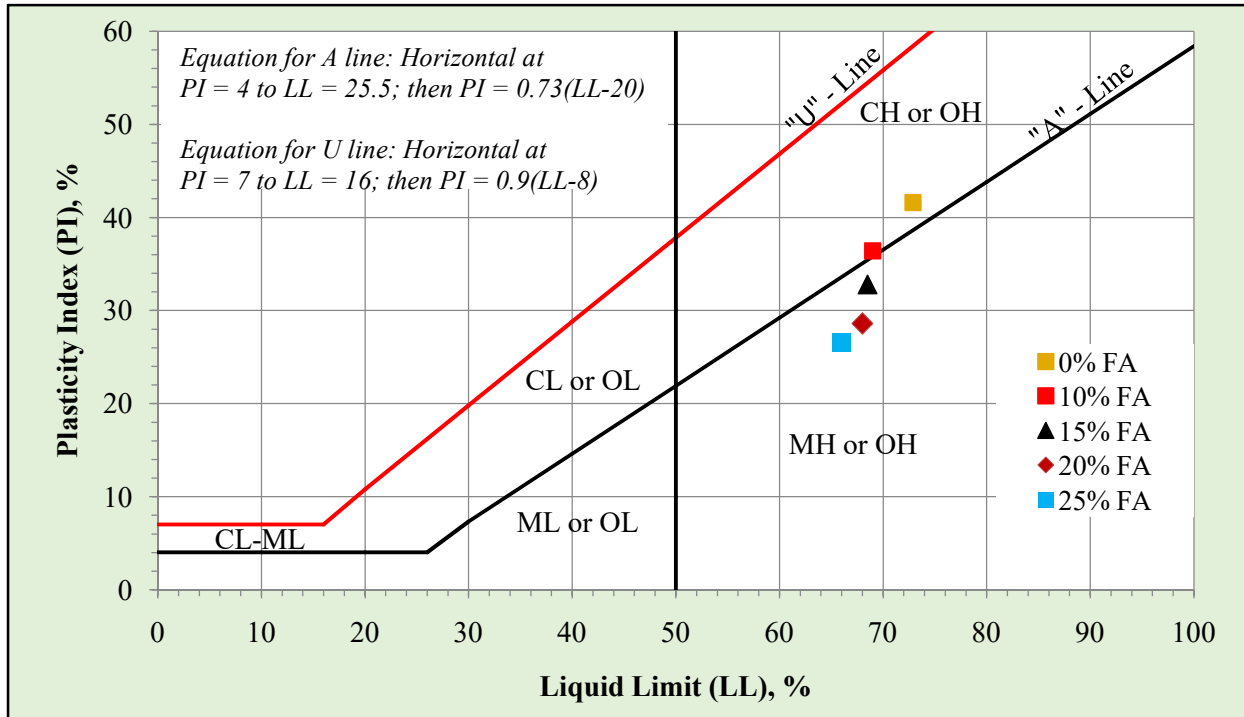


Figure 4.6 Plasticity chart of soil with various percentage of fly ash

From plasticity chart, all mix falls below A-line except mix of 10% FA which lies on A-line. This shows the addition of fly ash has effects on soil classification. In generally, soil classification changes from inorganic clays of high plasticity to inorganic silts due to addition of 10 - 25% fly ash content.

4.2.5 Effect of Fly ash on swelling characteristics

Swelling characteristic tests conducted in this study are free swell, free swell index and free swell ratio. This tests help to know the expansiveness of a soil-fly ash sample by measuring the volume after the sample was soaked and settled down in water or kerosene for 24 hrs. Details of the swelling characteristic test results are shown in Appendix E.

Table 4.7 Effect of fly ash on swelling characteristics of soil

Fly Ash (%)	Free swell (%)	Free swell index (%)	Free swell ratio
0	92.5	83.3	1.83
10	78.5	70.8	1.71
15	68.5	56.7	1.57
20	57.5	40.0	1.40
25	45.0	34.9	1.35

i) Free swell

The effect of fly ash on the free swell of expansive soil is shown in Figure 4.7. As shown in figure, the addition fly ash to expansive soil decreases the free swell. The decrease in free swell is directly proportional to the amount of fly ash. The highest decrease in free swell is obtained when the soil is treated with 25% fly ash which is 105.5% less than untreated soil.

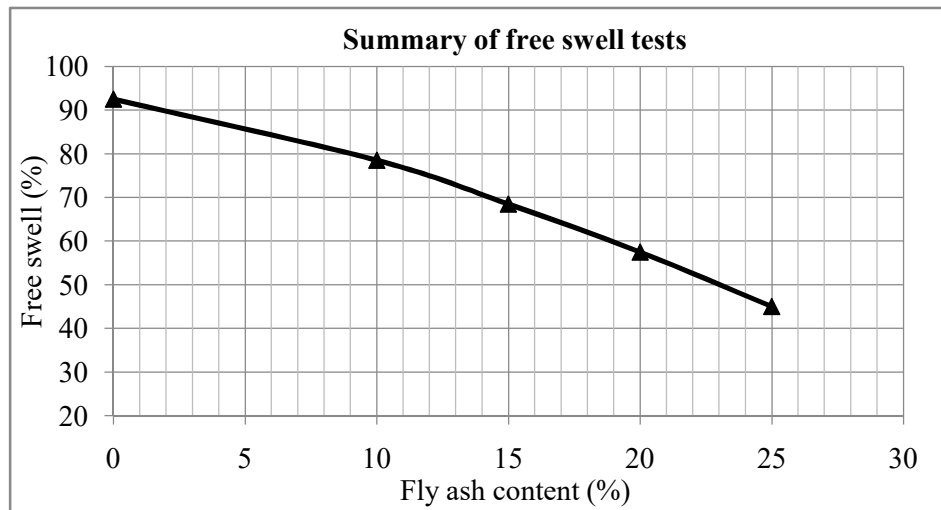


Figure 4.7 Variation of free swell for different percent of fly ash

ii) Free swell index

The effect of fly ash on the free swell index of expansive soil is shown in Figure 4.8.

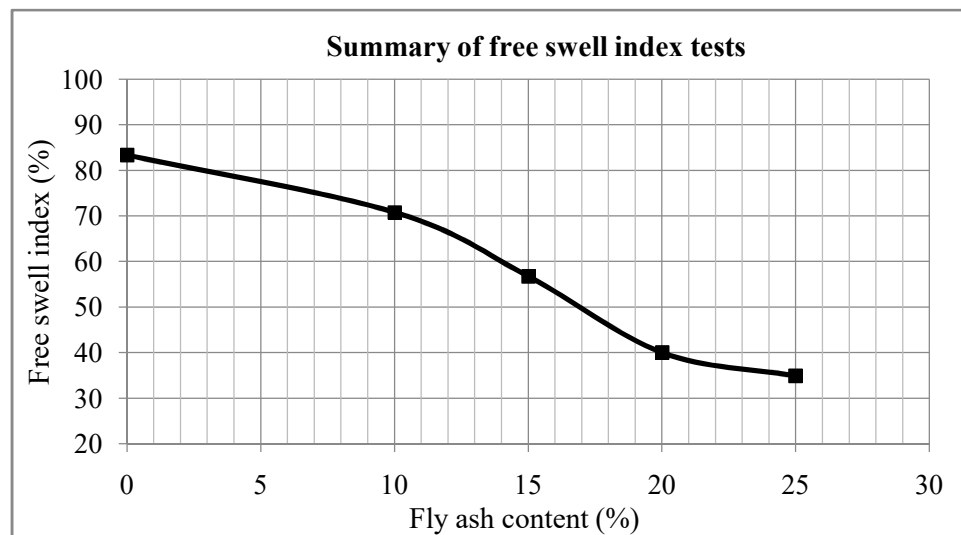


Figure 4.8 Variation of free swell index for different percent of fly ash

By referring to Figure 4.8 and Table 4.7, the free swell index value decreased from 83.3% to 34.9% with increased fly ash content from 0% to 25%. Based on swell classification for free swell index in Chapter two section 2.4.2. Table 2.2, the untreated soil has very high degree of expansion. However, free swell index value decreased up to 34.9% for 25% of fly ash and this makes the soil medium expansive.

iii) Free swell ratio

By referring to Figure 4.9 and Table 4.7, the free swell ratio value decreased from 1.83 to 1.35 with increased fly ash content from 0% to 25%. According to swell classification based on free swell ratio in Chapter two section 2.4.2. Table 2.3, the untreated soil is considered as moderate swelling soil. However, free swell ratio value decreased up to 1.35 for 25% of fly ash and this makes the soil low swelling.

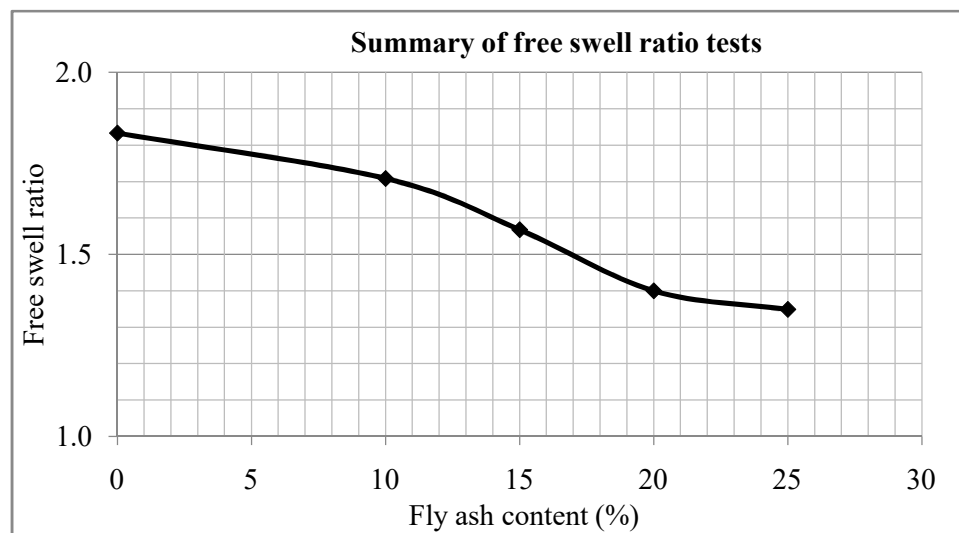


Figure 4.9 Effect of addition of fly ash on free swell ratio expansive soil

From the above three swelling characteristics (free swell, free swell index and free swell ratio) the decrease in swelling is mainly due to replacing some volume of expansive clay by non-swell fly ash material.

4.2.6 Effect of fly ash on compaction characteristics

As shown in Table 4.8 and Figure 4.10, maximum dry density decreases from 1.55g/cm^3 to 1.43g/cm^3 of soil samples with increased fly ash content from 0% to 25%. It shows the addition of 25% FA reduced the maximum dry density by 7.7% to that of untreated soil. Thus, the decrease in the maximum dry density is mainly due to the partial replacement of

comparatively heavy soils with the light weight fly ash and/or addition of low specific gravity fly ash in place of soil having comparatively high specific gravity. And also, the decrease is due to the flocculation and agglomeration of clay particles in the presence of sufficient water, resulting in an increase in voids and a corresponding decrease in dry density.

Table 4.8 Comparison of compaction test results of soil with different fly ash percentage

Fly ash (%)	MDD (g/cm ³)	OMC (%)	% decrease in MDD	% increase in OMC
0	1.55	22.5	0	0
10	1.52	22.8	1.9	1.3
15	1.48	23.5	4.5	4.4
20	1.46	24.3	5.8	8.0
25	1.43	26.3	7.7	16.9

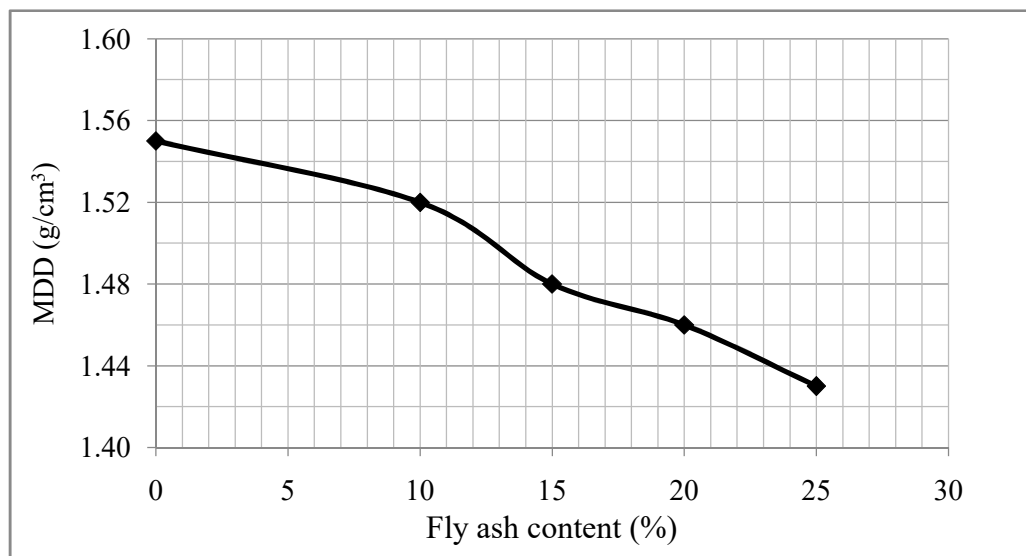


Figure 4.10 Effect of fly ash on MDD of expansive soil

As can be seen from Table 4.8 and Figure 4.11, the optimum moisture content of the soil samples increased from 22.5% to 26.3% with increases in fly ash content of 10% to 25%. It shows that the addition of 25% FA to soil increased the optimum moisture content by 16.9%. The reason for the increasing OMC may be attributable to the affinity of the soil-fly ash mixed samples for more water to complete the cation exchange reaction. Thus, the increase in OMC is may be due to more water absorption by fly ash. This implies that more water is needed in order to compact the soil with fly ash mixture.

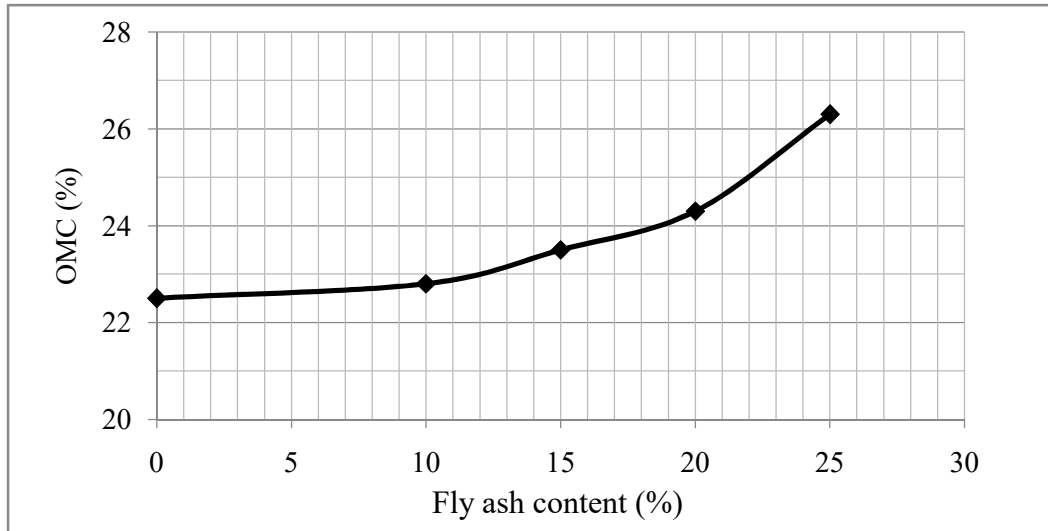


Figure 4.11 Effect of fly ash on OMC of expansive soil

From summary of compaction curve shown in Figure 4.12, with increasing fly ash content, compaction curves of treated soil shifted to the right with respect to untreated soil. This shows the addition of fly ash to soil decreased the maximum dry density and increased the optimum moisture content. Details of compaction test results are shown in Appendix F.

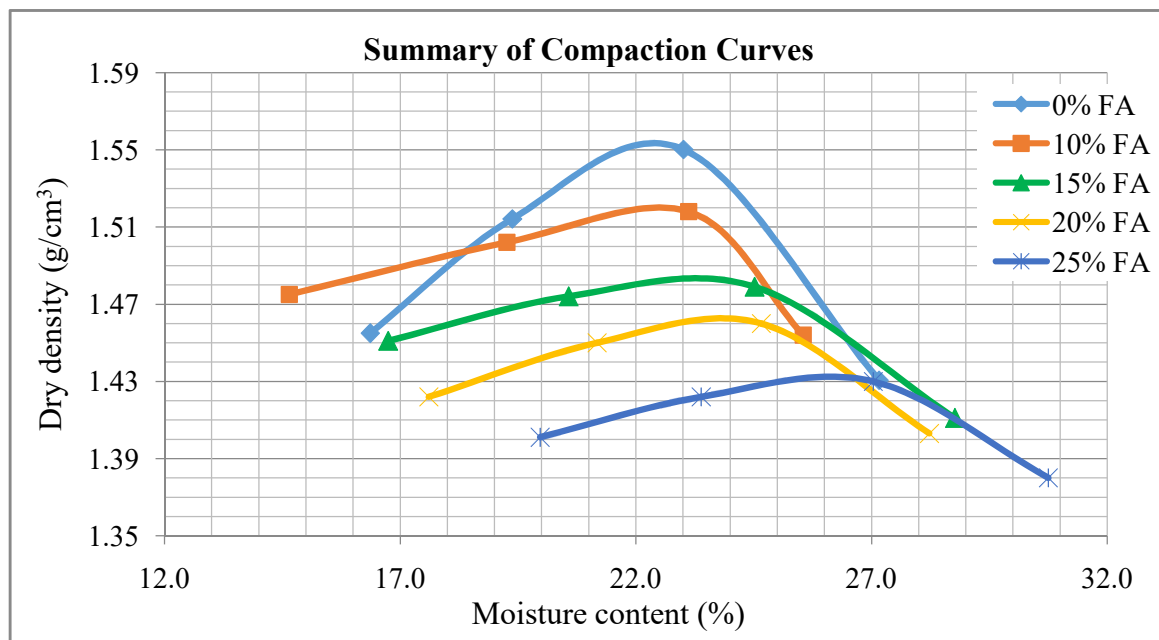


Figure 4.12 Summary of compaction curves for soil with various percentage of fly ash

4.2.7 Effect of fly ash on CBR and CBR-swell

i) CBR values

CBR is used to evaluate the performance of a soil for use of sub-grade, sub-base and base courses. The effect of fly ash on the CBR values of the soil mixture is shown in Table 4.9 and Figure 4.13. It is clear from the figure that CBR value of soil mixture increased with addition of fly ash content up to 20% and beyond this the value decreases. The increase in the CBR is because of gradual formation of cementitious compounds between fly ash and soil or may be due to the pozzolanic reactions of fly ash with soil. The decrease in the CBR after 20% fly ash is may be due to excess fly ash that occupies spaces within the sample and reduces bond in the soil.

Table 4.9 CBR test results of soil with different fly ash percentage

Fly ash (%)	CBR (%)	% increase in CBR
0	1.30	0.0
10	2.32	77.8
15	3.04	133.3
20	3.77	188.9
25	3.19	144.4

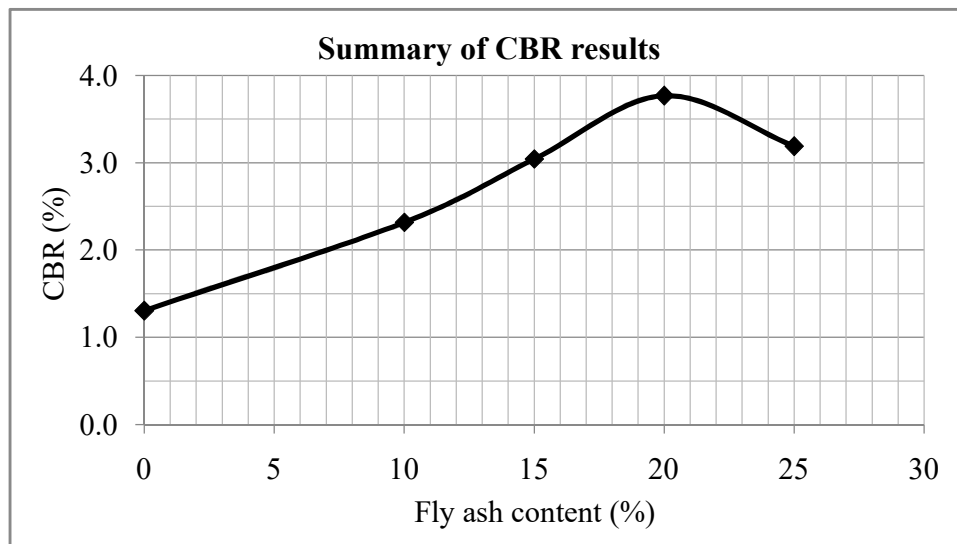


Figure 4.13 Variation of soaked CBR with different fly ash content

When treating the soil at 20% fly ash content the soil-fly ash sample gives a peak CBR value of 3.77% from a value of 1.30% for natural soil. The maximum and minimum CBR value of soil treated with fly ash is 2.9 times (188.9%) and 1.78 times (77.8%) higher than that of

untreated soil respectively. This shows that the load bearing capacity of the soil increased with fly ash treatment. Hence, the fly ash treated soil meet the minimum criteria as specified by Ethiopian Roads Authority pavement design manual (2002) specification for materials suitable for use as subgrade material of not less than 3% CBR determined at MDD and OMC. However, the minimum requirement of CBR specified for subgrade of Tarcha-Chida road project is 5% (from design specification), that the fly ash treated soil does not meet the criteria and further improvement is needed. It has been observed that the optimum amount of fly ash is 20% to obtain maximum CBR value and this amount of fly ash is used for further study with enset fiber. Details of CBR test results are shown in Appendix G.

ii) CBR-swell

The effect of fly ash on the CBR-swell values of the soil mixture is shown in Table 4.10 and Figure 4.14. It is clear from the figure that CBR-swell value of soil mixture decreases with addition of fly ash content.

Table 4.10 CBR swell results of soil with different fly ash percentage

Fly ash (%)	CBR swell (%)	% decrease in CBR swell
0	10.69	0.0
10	8.66	19.0
15	7.45	30.3
20	6.60	38.3
25	5.18	51.5

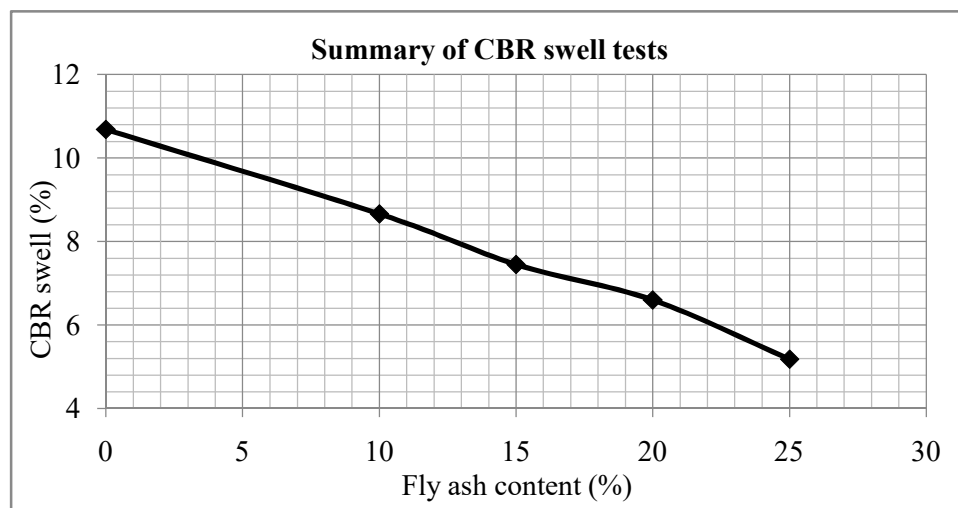


Figure 4.14 Effect of fly ash on CBR swell of expansive soil

Treating the soil at 25% fly ash content gives CBR-swell value of 5.18%. Thus, the CBR swell value of soil treated with fly ash is 51.5% lower than that of untreated soil and this shows the swelling potential of soil sample decrease with addition of fly ash.

4.2.8 Effect of fly ash on Unconfined Compressive Strength (UCS)

In this test a soil sample is subjected to axial load without a confining pressure. As it is shown in Table 4.11 and Figure 4.15, UCS value of soil mixture increases with addition of fly ash content up to 20% and beyond this limit the value decreases with the increase in fly ash content. The maximum value of UCS is 177.75kPa that observed at 20% fly ash content which is 1.4 times (40.3%) more than that of untreated soil. The lower value of UCS is 143.42kPa in case of 10% fly ash content which is 1.13times (13.2%) more than that of untreated soil.

Table 4.11 UCS test results of soil with different fly ash percentage

Fly Ash (%)	UCS (kPa)	Cu (kPa)	% increase in UCS value
0	126.66	63.33	0.0
10	143.42	71.71	13.2
15	153.58	76.79	21.3
20	177.75	88.88	40.3
25	167.39	83.70	32.2

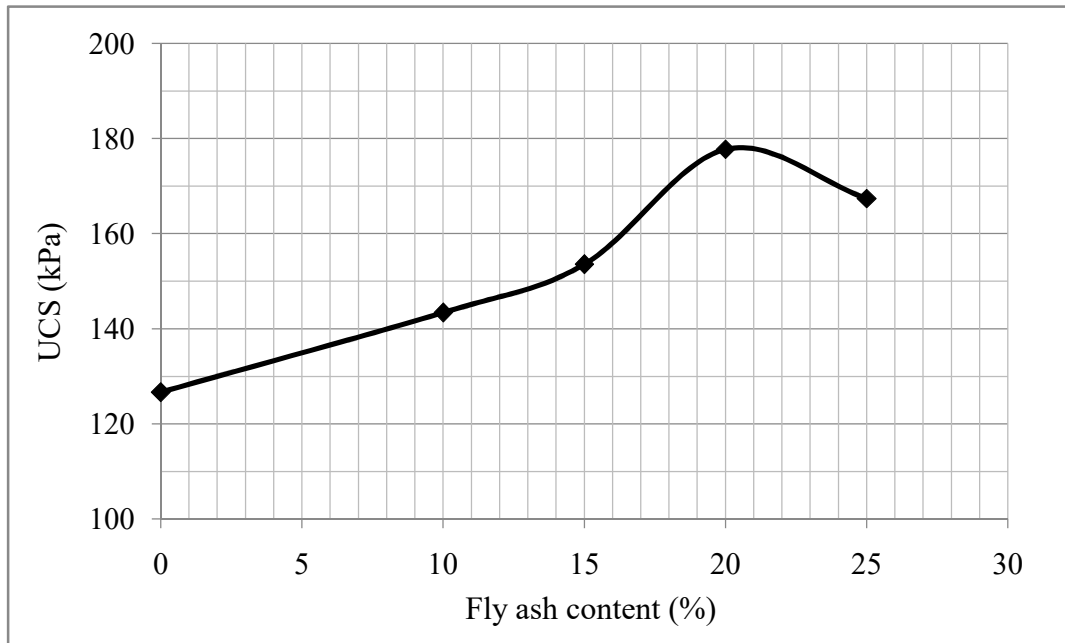


Figure 4.15 Variation of UCS for different percent of fly ash

The increase in UCS is due to the adhesion between the soil sample and the fly ash, which contribute to increasing resistance to axial applied force. But, further increment in fly ash content beyond the required, the strength of treated soil decreased. This is due to the fact that the addition of more cohesionless material to the clay soil reduces its natural cohesive force between the particles of clay soil. The stress-strain curves of UCS tests for various percentage fly ash are shown in Figure 4.16. Details of UCS test results are shown in Appendix H.

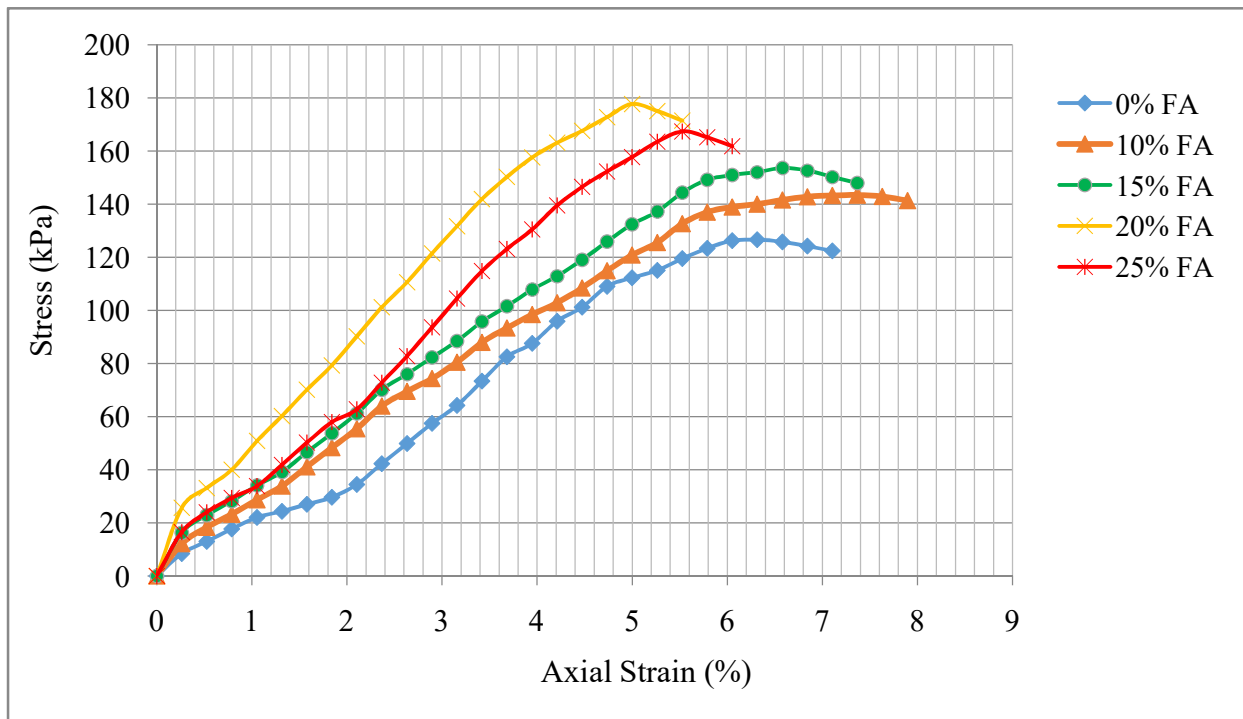


Figure 4.16 UCS stress-strain curve of soil with different percentage of fly ash

Soil is elasto-plastic materials and its elastic modulus is calculated from secant modulus. The secant modulus is preferable for non-elastic materials that can be determined at undrained shear strength (half of unconfined compression strength) with its respective strain. The values of the elastic modulus of the soil-fly ash were obtained from the gradient of stress-strain curves and they were 2.01, 2.66, 2.87, 4.29, and 3.12MPa for 0, 10, 15, 20, and 25% fly ash, respectively. In general, from the results of soil with different percentage of fly ash, the optimum fly ash content is found to be 20%. The optimum fly ash content is determined based on the strength characteristics of soil i.e. CBR and UCS.

4.2.9 Grand summary of test results for soil treated with fly ash

In here, summary of all test results performed on soil-fly ash are presented.

Table 4.12 Summary of all test results performed on soil with different percent of fly ash

Type of Tests		% of Fly ash Mixed with Expansive Soil				
		0	10	15	20	25
Percent amount of particle size, (%)	Gravel (> 4.75mm)	0.48	0	0	0.24	0.16
	Sand (4.75-0.075mm)	17.86	21.67	27.75	31.98	36.33
	Fine (< 0.075mm)	81.66	78.33	72.25	67.77	63.51
Specific Gravity		2.60	2.47	2.43	2.41	2.38
Atterberg Limits, (%)	Liquid Limit (LL)	72.9	69	68.5	68	66
	Plastic Limit (PL)	31.3	32.6	35.7	39.4	39.4
	Plasticity Index (PI)	41.6	36.4	32.8	28.6	26.6
Soil Classification	USCS	CH	CH	MH	MH	MH
	AASHTO	A-7-6	A-7-6	A-7-5	A-7-5	A-7-5
Swelling Characteristics	Free swell, (%)	92.5	78.5	68.5	57.5	45.0
	Free swell index, (%)	83.3	70.8	56.7	40.0	34.9
	Free swell ratio	1.83	1.71	1.57	1.40	1.35
Moisture-Density Relation	MDD, (g/cm ³)	1.55	1.52	1.48	1.46	1.43
	OMC, (%)	22.5	22.8	23.5	24.3	26.3
Soaked CBR, (%)		1.30	2.32	3.04	3.77	3.19
CBR Swell, (%)		10.69	8.66	7.45	6.6	5.18
Unconfined compression test	UCS, (kPa)	126.66	143.42	153.58	177.75	167.39
	Cu, (kPa)	63.33	71.71	76.79	88.88	83.70

4.3 Result and Discussion on Soil-Fly Ash Sample Reinforced with Enset Fiber

It is noted that optimum amount of fly ash based on CBR and UCS value was found to be 20%. This optimum amount of fly ash (20%) is used for further investigation on strength characteristics such as compaction, CBR and UCS of soil-fly ash with different percentage and length of enset fiber. In this portion, enset fiber was coated with kerosene to reduce moisture absorption of fiber.

4.3.1 Effect of enset fiber on Compaction characteristics of soil-fly ash sample

Combined compaction curves for different percentage of kerosene coated enset fiber at 15mm and 20mm length are shown in Figure 4.21 and 4.22 respectively. The comparisons of the results with respect to natural soil and optimum soil-fly ash sample are shown in Table 4.13.

Table 4.13 Comparison of compaction test results of soil-fly ash with different percentages and lengths of fiber

Fly ash (%)	Length of fiber (mm)	Fiber (%)	MDD (g/cm ³)	OMC (%)	% decrease in MDD compared to natural soil	% decrease in MDD compared to soil with 20% FA	% increase in OMC compared to natural soil	% increase in OMC compared to soil + 20% FA
0	0	0	1.55	22.5	0.0	-	0.0	-
20	0	0	1.46	24.3	5.8	0.0	8.0	0.0
20	15	0.5	1.44	27.0	7.2	1.5	20.0	11.1
20	15	1.0	1.41	28.4	8.9	3.3	26.2	16.9
20	15	1.5	1.39	29.8	10.1	4.5	32.4	22.6
20	15	2.0	1.37	31.5	11.7	6.3	40.0	29.6
20	0	0	1.46	24.3	5.8	0.0	8.0	0.0
20	20	0.5	1.43	27.4	7.9	2.2	21.8	12.8
20	20	1.0	1.41	29.3	9.0	3.4	30.2	20.6
20	20	1.5	1.38	31.2	10.9	5.4	38.7	28.4
20	20	2.0	1.36	32.6	12.2	6.8	44.9	34.2

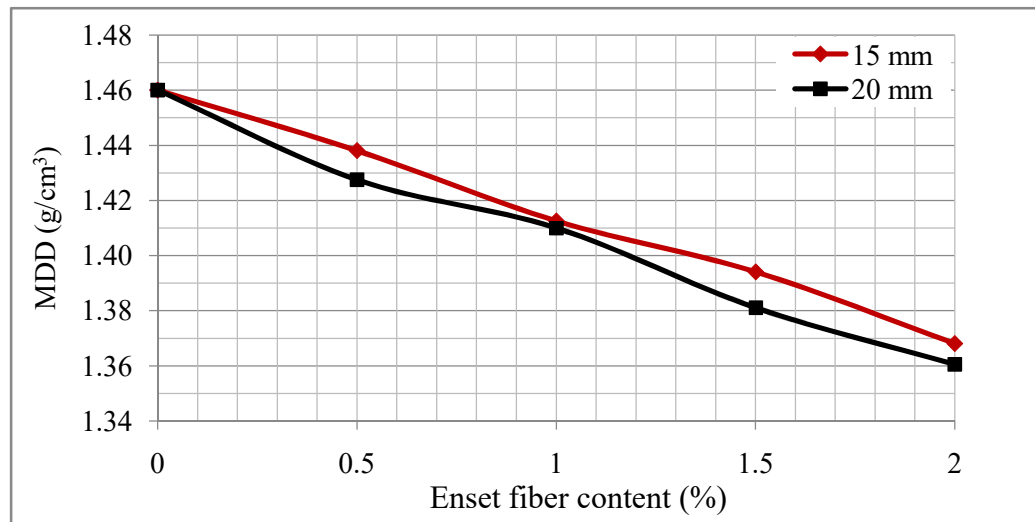


Figure 4.17 Effect of fiber percentage on MDD for 15mm and 20mm fiber length

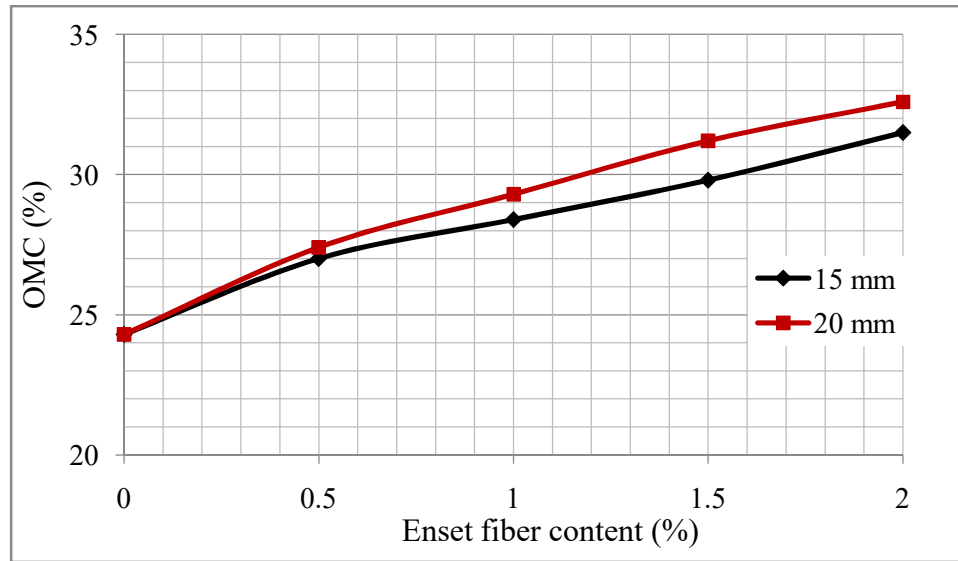


Figure 4.18 Effect of fiber percentage on OMC for 15mm and 20mm fiber length

Figure 4.17 above indicates that for the same length of fiber, when the percentage of fiber increases, MDD decreases. This is due to the addition of low density enset fiber in place of comparatively high density soil-fly ash sample. The higher and lower value of MDD is recorded at 0.5% and 2.0% of fiber content respectively for both lengths (15mm and 20mm). For example, the MDD decreases from 1.43 to 1.36g/cm³ as fiber percentage increases from 0.5 to 2.0% of 20mm fiber length respectively. The minimum value of MDD at 20mm fiber is about 12.2% and 6.8% less compared to natural soil and optimum soil-fly ash sample respectively. From Figure 4.18, it is clear that the OMC increases with an increase in fiber percentage for both lengths. This increase in OMC is directly proportional to the amount of fiber content. The increase in OMC value of soil-fly ash-fiber mix is due to the water absorption nature of the fibers. The maximum increase in OMC is recorded at 2.0% fiber of 20mm length which is 44.9% and 34.2% higher than that of natural soil and optimum soil-fly ash sample respectively.

The effect of fiber length on maximum dry density and optimum moisture content of soil-fly ash are shown in Figure 4.19 and Figure 4.20. As one can see from the figures, for each percentage of fiber MDD slightly decreases and OMC slightly increases with increase in fiber length. For example, at 2.0% of fiber content, MDD decreases from 1.37 to 1.36g/cm³ and OMC increases from 31.5 to 32.6% when fiber length increases from 15 to 20mm. This shows

increasing the enset fiber length results in more water absorption. However, for particular fiber percentage the variation in MDD and OMC is insignificant as length of enset fiber increases.

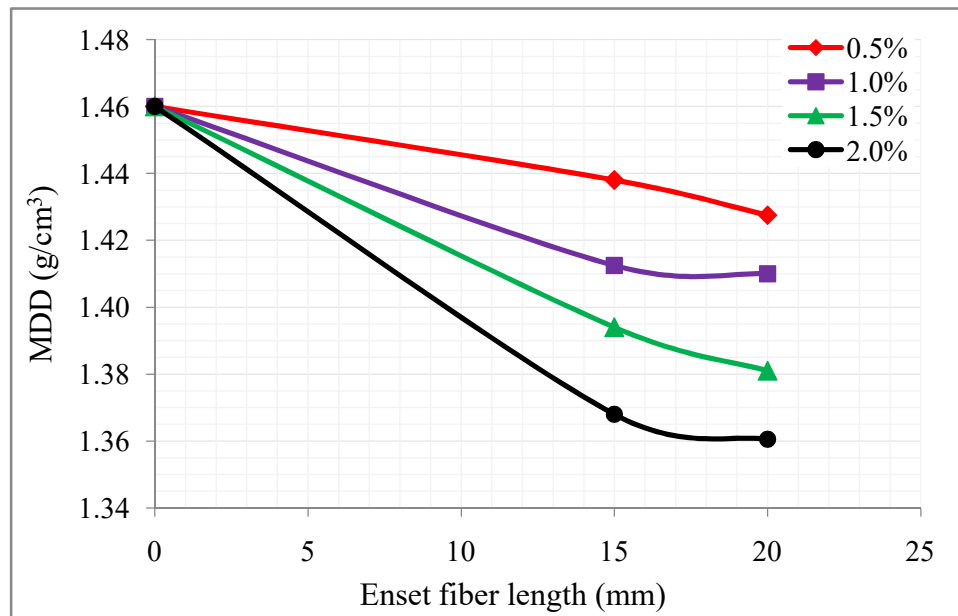


Figure 4.19 Effect of fiber length on MDD for each fiber percentage

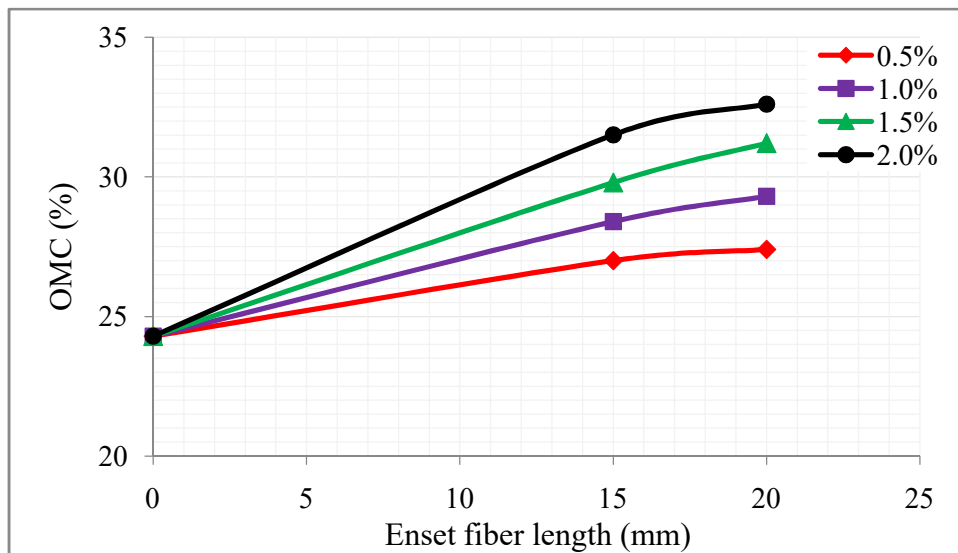


Figure 4.20 Effect of fiber length on OMC for each fiber percentage

Generally, the effect of addition of enset fiber on compaction characteristics of optimum soil-fly ash shows that the shapes of compaction curves are similar to that of natural soil and/or soil-fly ash. For all samples used in compaction, the dry density increases with increase in moisture content up to the point of optimum water content, and beyond increase in water

content decreases the dry density. Details of compaction test results on soil-fly ash-fiber are shown in Appendix F.

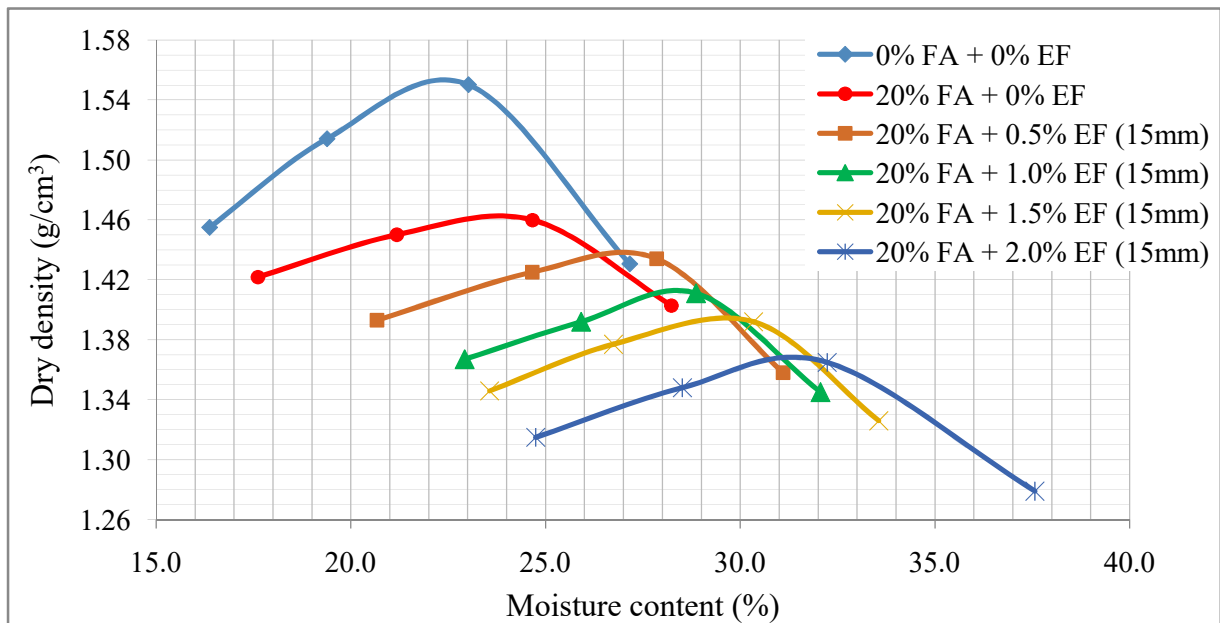


Figure 4.21 Combined compaction curves for different fiber percentage at 15mm fiber length

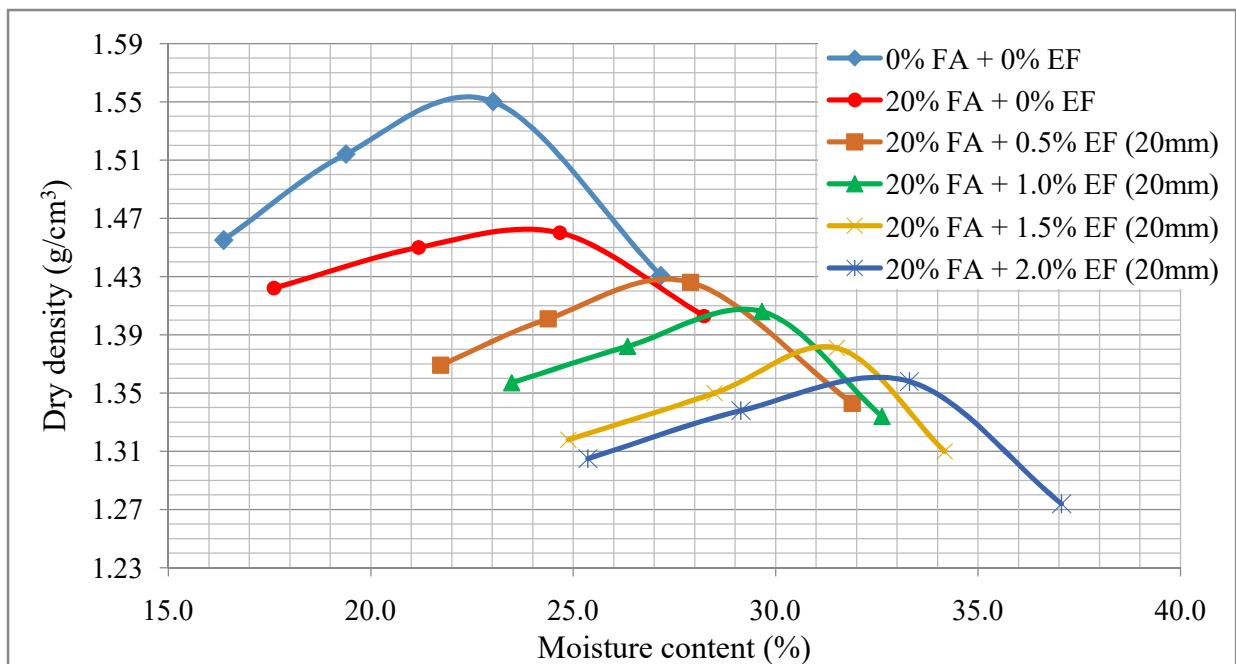


Figure 4.22 Combined compaction curves for different fiber percentage at 20mm fiber length

4.3.2 Effect of Enset fiber on CBR and CBR-swell of soil-fly ash sample

i) CBR value

The comparisons of the results with respect to natural soil and optimum soil-fly ash sample are shown in Table 4.14. The effect of fiber percentages and fiber lengths on CBR is presented in Figure 4.23 and 4.24.

Table 4.14 Comparison on CBR results of soil-fly ash with different percentages and lengths of fiber

Fly ash (%)	Length of fiber (mm)	Fiber (%)	CBR (%)	% increase in CBR compared to natural soil	% increase in CBR compared to soil + 20% FA
0	0	0	1.30	0.0	-
20	0	0	3.77	188.9	0.0
20	15	0.5	4.06	211.1	7.7
20	15	1.0	5.22	300.0	38.5
20	15	1.5	6.09	366.7	61.5
20	15	2.0	5.65	333.3	50.0
20	0	0	3.77	188.9	0.0
20	20	0.5	4.20	222.2	11.5
20	20	1.0	5.36	311.1	42.3
20	20	1.5	6.38	388.9	69.2
20	20	2.0	5.94	355.6	57.7

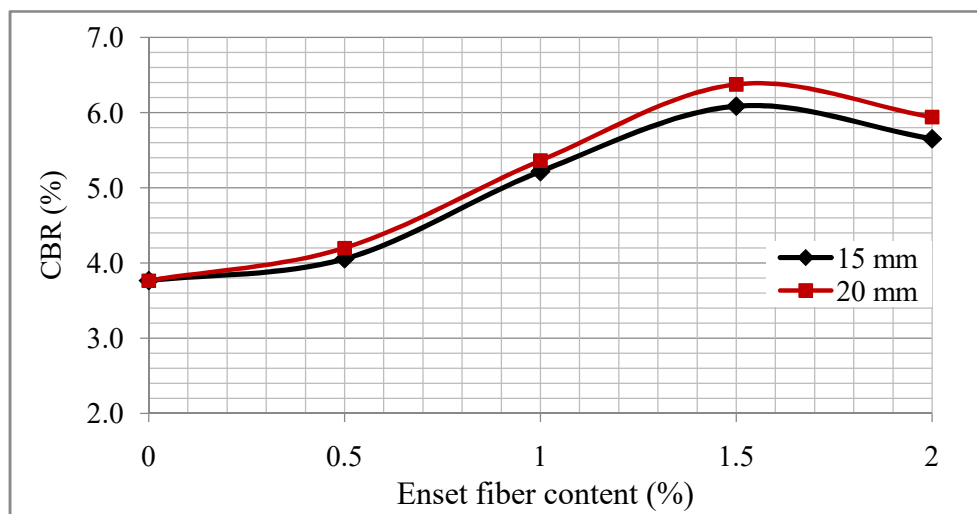


Figure 4.23 Effect of fiber percentage on CBR for 15mm and 20mm fiber length

As shown in Figure 4.23, it is clear that for both lengths (15mm and 20mm) the CBR value of soil-fly ash increased with increases in fiber content up to 1.5%, and beyond this further increase in fiber content decreases the CBR value. Results show that maximum increase in CBR value is 4.91 times (388.9%) higher than natural soil and/or 1.69 times (69.2%) higher than optimum soil-fly ash sample at fiber content of 1.5% for fiber length of 20mm. The minimum increase in CBR value is 3.12 times (211.1%) and 1.08 times (7.7%) high compared to natural soil and optimum soil-fly ash respectively at fiber content of 0.5% for 15mm fiber length. For example, the addition of enset fiber to optimum soil-fly ash sample increases the CBR value from 3.77% to 6.38% at 1.5% fiber content of 20mm length. This is because of the enset fibers that are randomly distributed into soil-fly ash sample improves its load deformation behavior by interacting with the soil and fly ash particles mechanically through surface friction and interlocking. The decrease in CBR value beyond the optimum percentage of enset fiber (for both 15mm and 20mm) is due to more amount fiber than required, which leads to poor bonding between the soil-fly ash and the fiber. Thus, the optimum fiber content corresponding to maximum improvement in CBR value is 1.5% of 20mm fiber length.

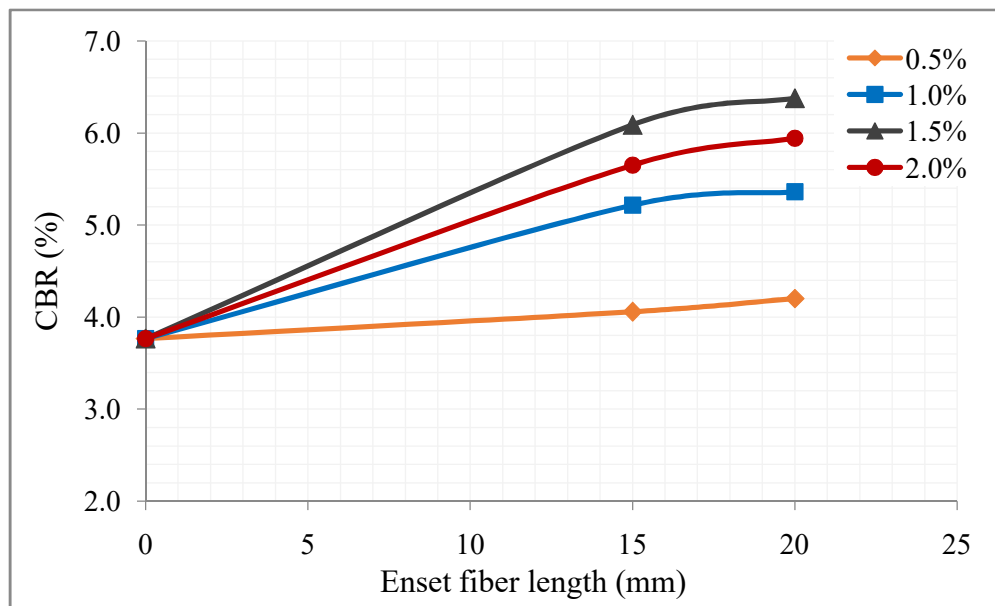


Figure 4.24 Effect of fiber length on CBR for each fiber percentage

As one can see from the Figure 4.24, for each percentage of fiber CBR value slightly increased as fiber length increase from 15 to 20mm. For example, at 1.5% of fiber content, CBR increases from 6.09% to 6.38% as fiber length increases from 15 to 20mm. This is due to the

fact that for shorter fibers the area in contact with soil is relatively less and therefore is less improvement. However, for particular fiber percentage the variation in CBR value is insignificant as length of enset fiber increases (from 15mm to 20mm). Details of CBR results on soil-fly ash-fiber are shown in Appendix G.

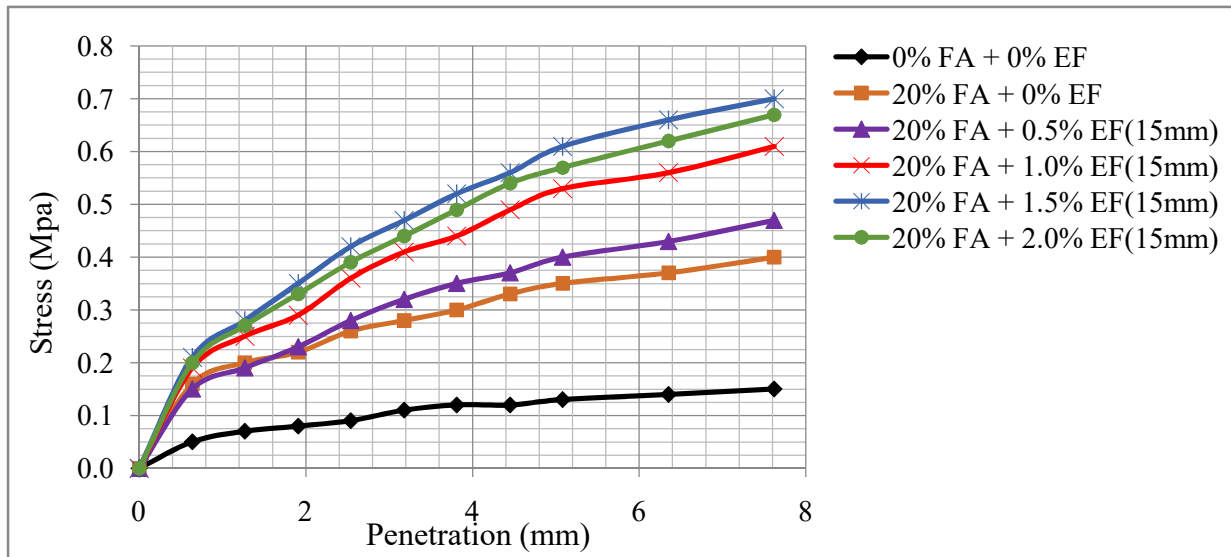


Figure 4.25 Combined CBR curves for different fiber percentage at 15mm fiber length

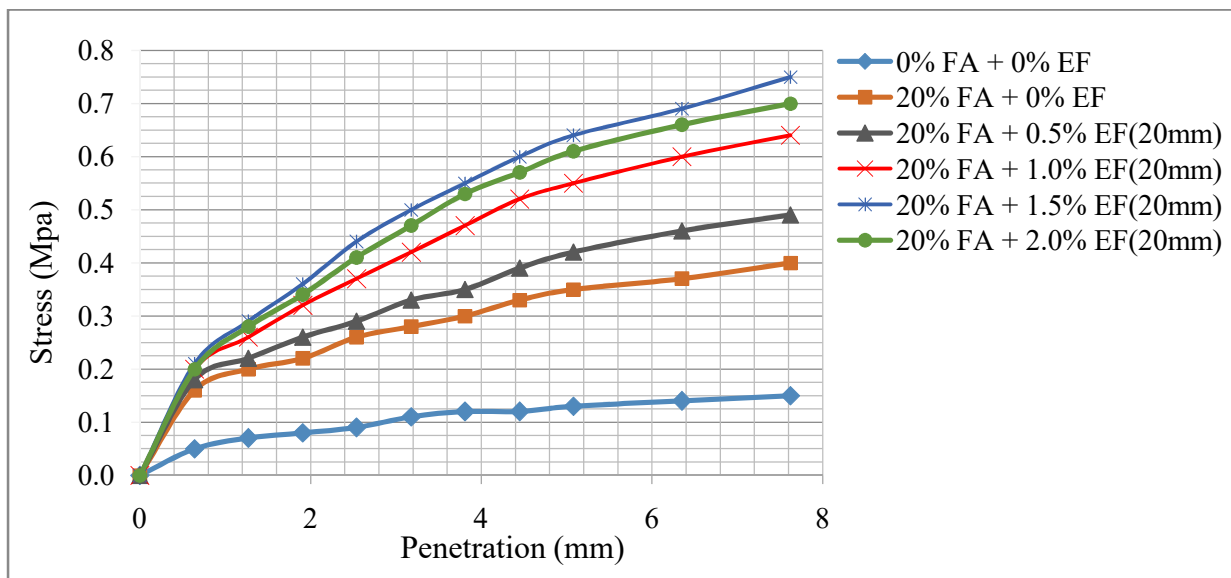


Figure 4.26 Combined CBR curves for different fiber percentage at 20mm fiber length

ii) CBR-swell

Table 4.15 CBR-swell results of soil-fly ash with different percentages and lengths of fiber

Fly ash (%)	Length of fiber (mm)	Fiber (%)	CBR swell (%)	% decrease in CBR swell compared to soil + 20% FA
20	0	0	6.60	0.0
20	15	0.5	6.17	6.5
20	15	1.0	5.05	23.4
20	15	1.5	3.49	47.1
20	15	2.0	3.75	43.1
20	0	0	6.60	0.0
20	20	0.5	6.28	4.8
20	20	1.0	4.89	25.9
20	20	1.5	3.32	49.6
20	20	2.0	4.05	38.7

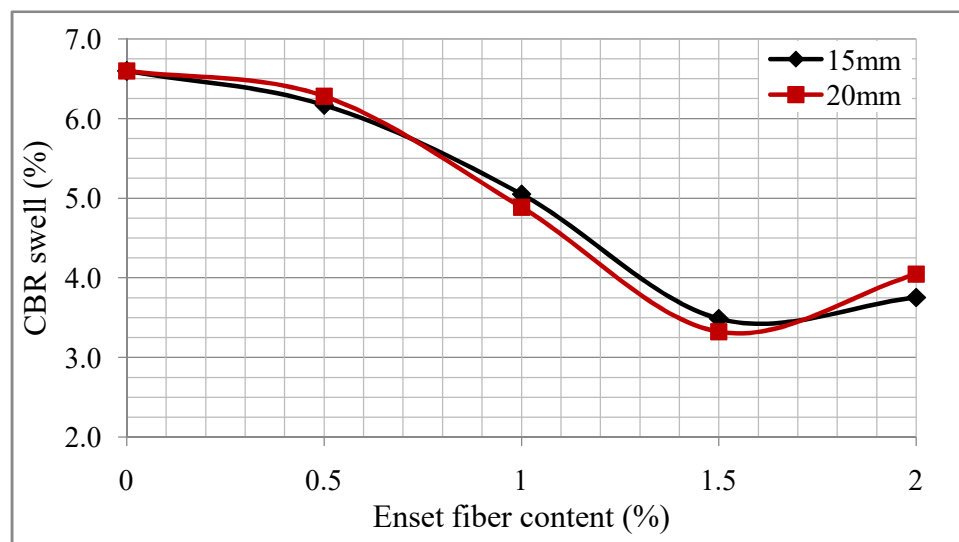


Figure 4.27 Effect of fiber percentage on CBR-swell for 15mm and 20mm fiber length

Figure 4.27 shows that for both lengths (15mm and 20mm) the CBR-swell value of soil-fly ash decreases with increase in fiber content up to 1.5%, then further increases in fiber content increases CBR-swell. Maximum reduction on CBR-swell value is recorded at 1.5% of 20mm fiber, which is 49.6% lower than that of optimum soil-fly ash. This reduction in CBR-swell is due to the bond or interlock of fiber with the soil-fly ash sample that may resist the expansion of the samples. Further increase in CBR-swell is due to weak soil-fiber interlock caused by high quantity of fiber in a sample than the required.

4.3.3 Effect of Enset fiber on UCS of soil-fly ash sample

The stress-strain curves from UCS tests conducted on optimum soil-fly ash with different percentage of enset fiber at 15mm and 20mm length is shown in Figure 4.30 and 4.31. The values of each length with various percentages are also tabulated in table below.

Table 4.16 Comparison on UCS results of soil-fly ash with different percentages and lengths of fiber

Fly ash (%)	Length of fiber (mm)	Fiber (%)	UCS (kPa)	Cu (kPa)	% increase in UCS compared to natural soil	% increase in UCS compared to soil + 20% FA
0	0	0	126.66	63.33	0.0	-
20	0	0	177.75	88.88	40.3	0.0
20	15	0.5	184.15	92.08	45.4	3.6
20	15	1.0	193.20	96.60	52.5	8.7
20	15	1.5	212.06	106.03	67.4	19.3
20	15	2.0	195.40	97.70	54.3	9.9
20	0	0	177.75	88.88	40.3	0.0
20	20	0.5	188.07	94.04	48.5	5.8
20	20	1.0	204.95	102.48	61.8	15.3
20	20	1.5	231.50	115.75	82.8	30.2
20	20	2.0	206.80	103.40	63.3	16.3

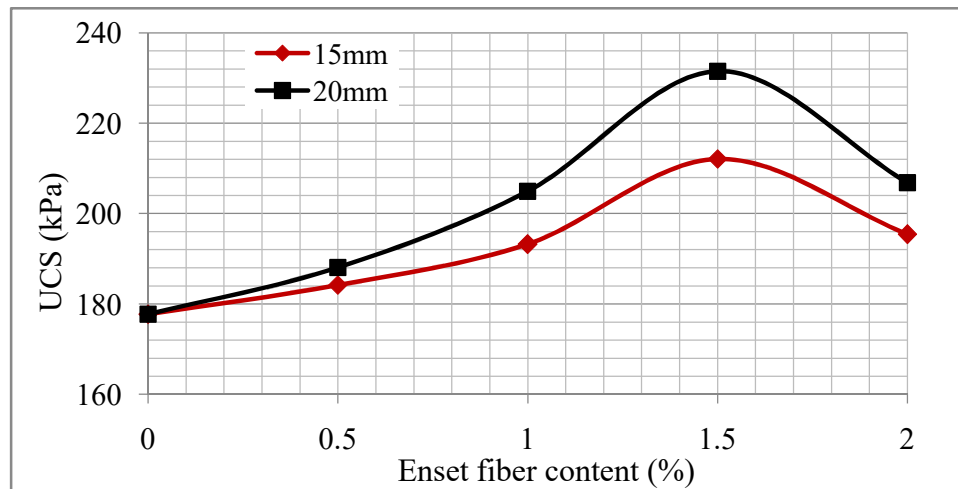


Figure 4.28 Effect of fiber percentage on UCS for 15mm and 20mm fiber length

From Figure 4.28, it is seen that increase in fiber content increases the UCS value up to 1.5%, but beyond 1.5% reinforcement the UCS value reduced. This trend is observed for both 15 and 20mm fiber lengths. For example, at 20mm fiber length the UCS value is 188.07kPa,

204.95kPa, 231.5kPa and 206.8kPa for 0.5%, 1.0%, 1.5% and 2.0% respectively. The maximum value of UCS observed at 1.5% fiber content of 20mm fiber length is 231.5kPa, which is 1.83 times (82.8%) and 1.3 times (30.2%) more than that of natural soil and optimum soil-fly ash sample respectively. The lowest value of UCS is recorded at 0.5% fiber content of 15mm length is 184.15kPa, which is 1.45 times (45.4%) and 1.04 times (3.6%) more than that of natural soil and optimum soil-fly ash sample respectively. The increase in fiber content consequently increases the friction between the discrete fiber and soil-fly ash particles, which contribute to increasing resistance to axial force applied. Beyond the required amount of fiber, UCS value of reinforced is sample reduced. This is due to the addition of more fiber leads to the domination of fiber-to-fiber interaction rather than soil-to-fiber interaction. Thus, the additions of 1.5% fibers at 20mm length contribute better improvement to UCS.

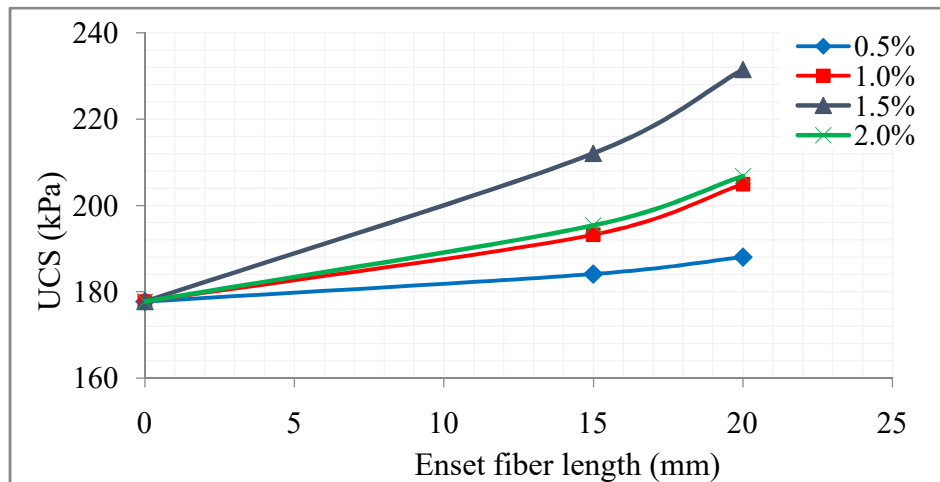


Figure 4.29 Effect of fiber length on UCS for each fiber percentage

The influence of fiber length on the UCS value is shown above in Figure 4.29. It is observed that for each fiber percentage, the UCS value increased as fiber length increase from 15 to 20mm. For example, at 1.5% of fiber the UCS value increased from 212.06kPa to 231.5kPa when fiber length increases from 15mm to 20mm respectively. This is due to the reason that when the fiber length increases, the total contact area between the fiber and the soil-fly ash increases that result in better strength. However, the optimum fiber length depends on fiber content.

From Figure 4.30 and 4.31 it is noted that the axial strain of reinforced sample increased with addition of fiber when it compared to natural soil and soil-fly ash sample. This shows the reinforced sample is more ductile in comparison to unreinforced sample. It also indicates that

the reinforced sample can resist higher loads at large deformations than unreinforced sample. Details of UCS results on soil-fly ash-fiber are shown in Appendix H.

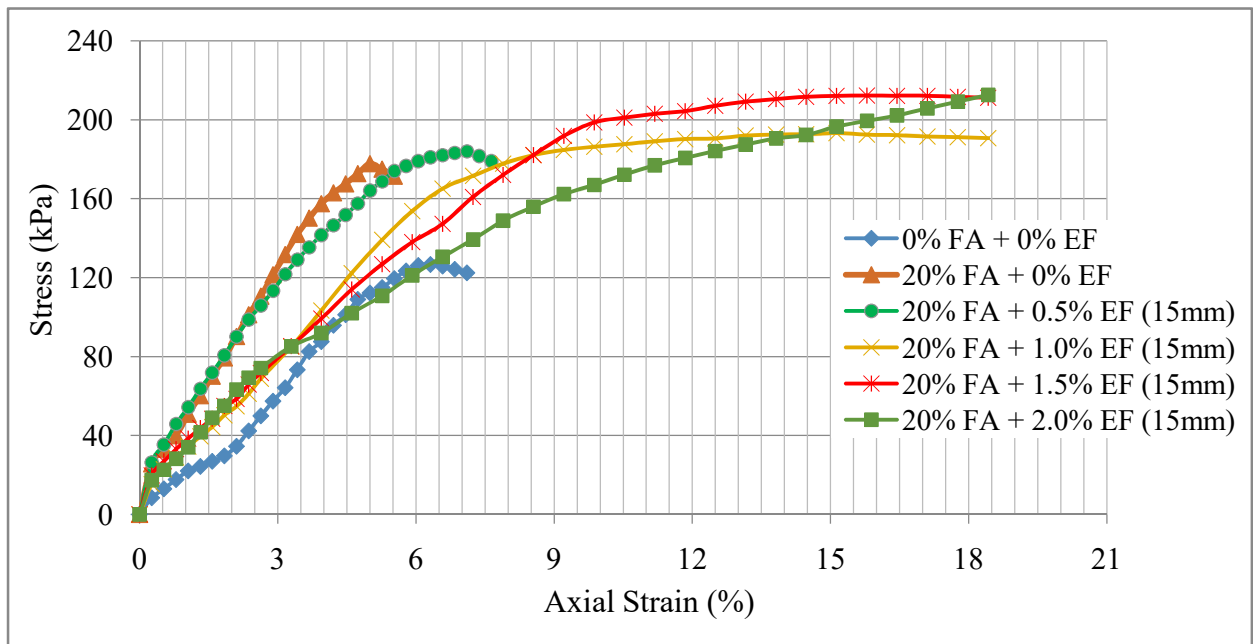


Figure 4.30 UCS stress-strain curves for different fiber percentage at 15mm fiber length

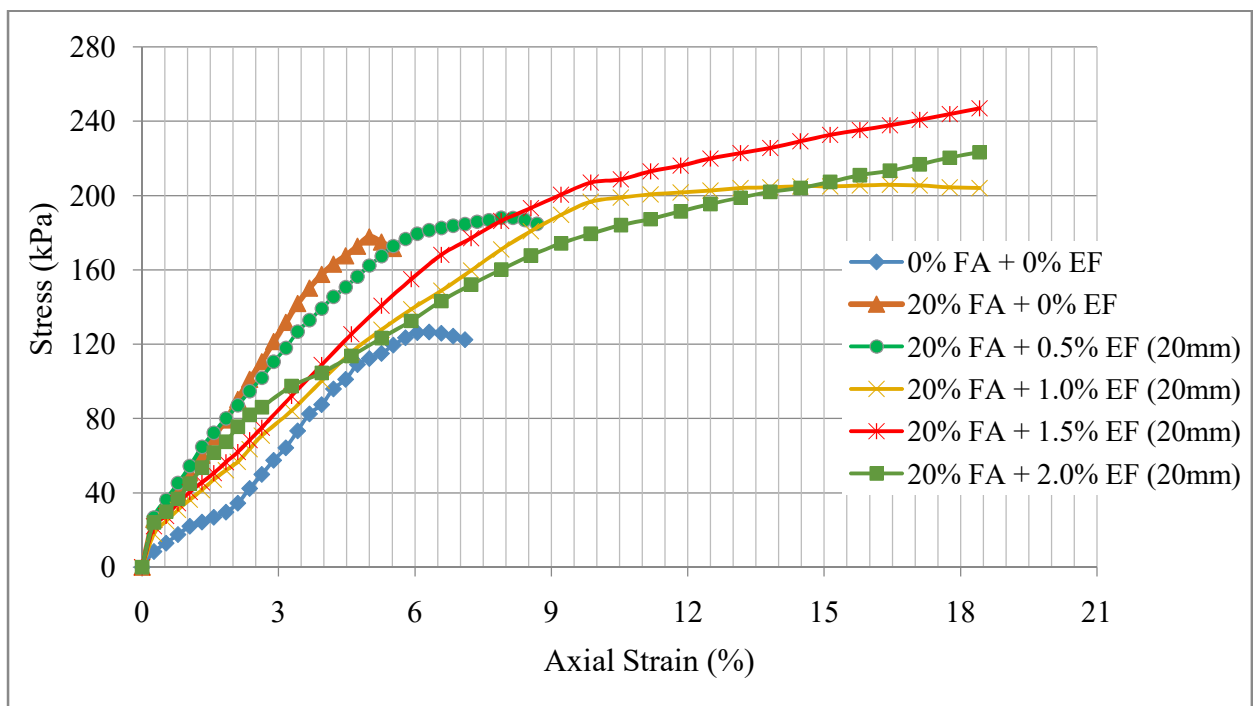


Figure 4.31 UCS stress-strain curves for different fiber percentage at 20mm fiber length

4.3.4 Grand summary of the results for optimum soil-fly ash reinforced with enset fiber

The table below shows the summary of all test results that is conducted to evaluate the strength characteristics of soil-fly ash-fiber reinforced samples. It was observed from both CBR and UCS test values; the optimum fiber content was taken as 1.5% at 20mm fiber length. Therefore, 1.5% of kerosene coated enset fiber at 20mm length was considered for a better reinforcement of optimum soil-fly ash sample.

Table 4.17 Summary of all the results performed on soil-fly ash with different percentages of fiber at 15mm and 20mm lengths

Length of fiber (mm)	Fiber (%)	Type of tests on soil-fly ash-enset fiber					
		MDD (g/cm ³)	OMC (%)	CBR (%)	CBR swell (%)	UCS (kPa)	Cu (kPa)
0	0	1.46	24.3	3.77	6.6	177.75	88.88
15	0.5	1.44	27.0	4.06	6.17	184.15	92.08
15	1.0	1.41	28.4	5.22	5.05	193.20	96.60
15	1.5	1.39	29.8	6.09	3.49	212.06	106.03
15	2.0	1.37	31.5	5.65	3.75	195.40	97.70
20	0.5	1.43	27.4	4.20	6.28	188.07	94.04
20	1.0	1.41	29.3	5.36	4.89	204.95	102.48
20	1.5	1.38	31.2	6.38	3.32	231.50	115.75
20	2.0	1.36	32.6	5.94	4.05	206.80	103.40

4.4 Comparison of Uncoated and Kerosene Coated Enset Fiber on Strength Property of Soil-Fly Ash

Comparisons on optimum proportion of sample (78.5% ES + 20% FA + 1.5% EF of 20mm length) were done for uncoated and kerosene coated fiber to determine the effect of coating on compaction, CBR and UCS.

Table 4.18 Results of Uncoated and Kerosene coated enset fiber with optimum proportion of its sample

Optimum proportion of materials	Type of Tests				
	MDD (g/cm ³)	OMC (%)	CBR (%)	CBR swell (%)	UCS (kPa)
78.5% ES + 20% FA + 1.5% EF (Uncoated fiber)	1.377	32.8	5.94	4.12	210.5
78.5% ES + 20% FA + 1.5% EF (Kerosene coated fiber)	1.381	31.2	6.38	3.32	231.5

The same samples were prepared for both cases but the only difference is that fiber is without and with kerosene coating.

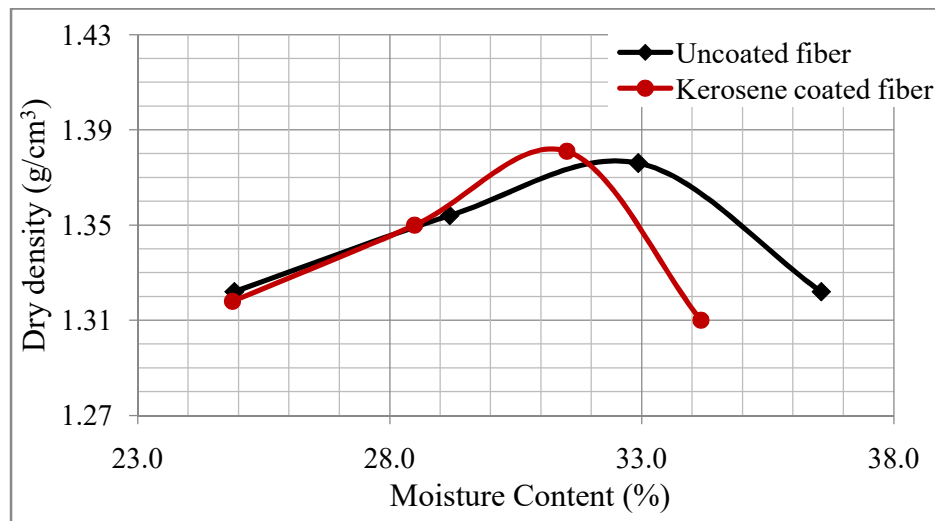


Figure 4.32 Effect of uncoated and kerosene coated fiber on compaction characteristics

From test results shown in Table 4.18 and Figure 4.32, it is seen that the variation in MDD of uncoated fiber and kerosene coated fiber is insignificant but MDD of uncoated fiber is little bit less than that of kerosene coated. The higher MDD for coated fiber is due to low water absorption of fiber and low moisture content. The OMC of uncoated fiber is about 5.13% higher than that of kerosene coated fiber. This is because of uncoated fiber absorb more water than kerosene coated fiber. This shows kerosene coating reduces moisture absorption of fiber.

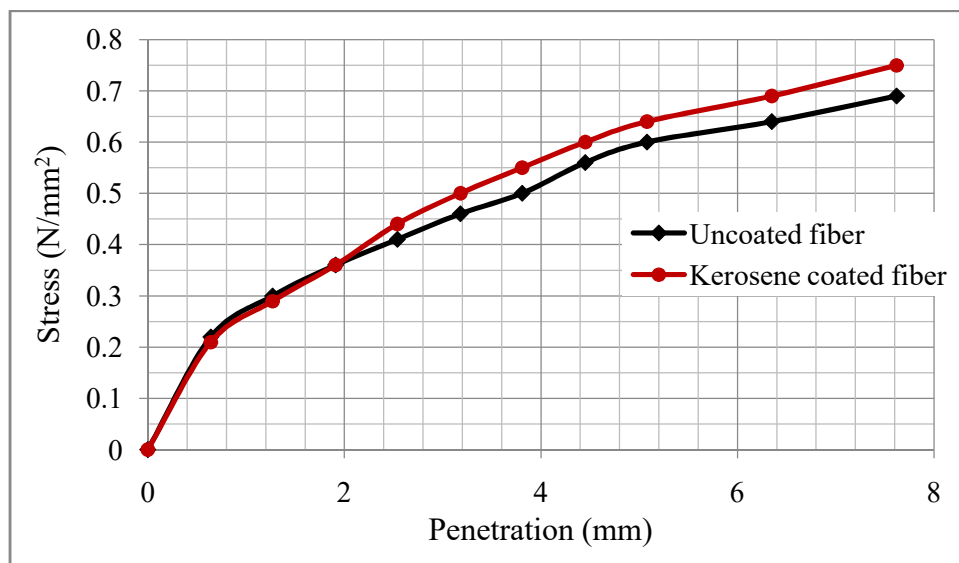


Figure 4.33 Effect of uncoated and kerosene coated fiber on CBR curve

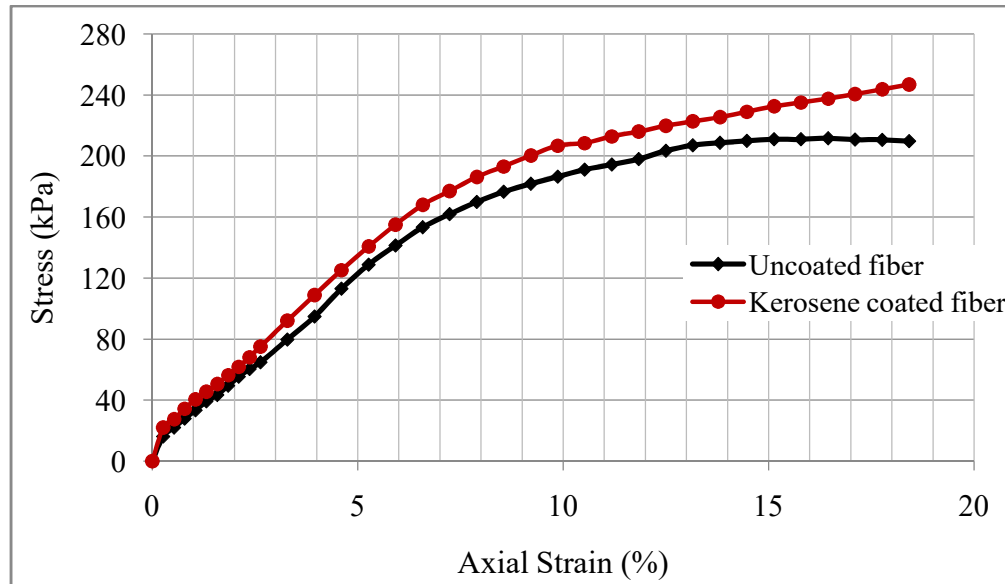


Figure 4.34 Effect of uncoated and kerosene coated fiber on UCS stress-strain curve

As shown above in Figure 4.33 and 4.34, both the CBR and UCS values of kerosene coated fiber are greater than uncoated fiber. The CBR value of kerosene coated fiber is about 7.4% more than that of uncoated fiber. Similarly, the UCS value of kerosene coated fiber is about 9.97% more than that of uncoated fiber. This indicates physical or surface treatment/coating of enset fiber with kerosene gives better result for reinforcement of soil-fly ash samples than uncoated fiber. In general, optimum soil-fly ash samples reinforced with kerosene coated fiber can have a better improvement on strength characteristics than uncoated fiber.

4.5 Cost Comparison of Subgrade Construction by Removal and Replacement versus Construction using Fly Ash and Enset Fiber

Cost of construction by removal and replacement and construction using fly ash and enset fiber is taken from the current price of the cost around the study area which included direct cost (i.e. material, labor and equipment) and indirect cost (overhead and profit). The cost comparison shown on Table 4.19 and Table 4.20 was made based on the following assumptions;

- ✓ Locations of selected material are the same for the study area.
- ✓ Material cost above the subgrade layer is the same in both cases, that the surfacing layer cost is not considered during the comparison, therefore, only the subgrade cost is analyzed for comparison.

- ✓ Similar road plan bottom width of 8m and 1km length road is used for the quantity tabulation. The expansive soil is removed to a depth of 0.8m after removing the top surface of soil 0.2m below the natural ground level.
- ✓ 20% of fly ash and 1.5% of enset fiber at 20mm length measured by weight of soil is used to improve the subgrade soil. Because in this study optimum CBR is obtained for 20% fly ash and 1.5% enset fiber at 20mm fiber length.
- ✓ During the application of the stabilizing agents, only the subgrade depth is scraped, stabilized and compacted.

Sample calculation

In 100% of sample, 20% fly ash and 1.5% enset fiber are needed to stabilize the expansive soil (i.e. 78.5%). To define it by weight, from 100kg of soil-fly ash-fiber materials we need 20kg of fly ash and 1.5kg of enset fiber as stabilizing agent and remaining 78.5kg were expansive soil.

Here, Unit weight of soil = Specific gravity of soil * Unit weight of water

Where, Specific gravity of soil = 2.60 and Unit weight of water = 1000 kg/m³

$$\text{Unit weight of soil} = 2.60 * 1000 \text{ kg/m}^3 = 2,600 \text{ kg/m}^3$$

$$1\text{m}^3 \text{ of soil} = 2,600 \text{ kg of soil}$$

So, 1kg of soil = 0.0003846 m³ of soil

Specific gravity of fly ash (FA) = 2.10 and Specific gravity of enset fiber = 1.06.

In the same manner to above calculation, Unit weight of fly ash = 2100 kg/m³

$$1\text{m}^3 \text{ of fly ash} = 2,100\text{kg of fly ash}$$

1kg of fly ash = 0.0004762 m³ of fly ash

$$\text{Unit weight of enset fiber} = 1060 \text{ kg/m}^3$$

1kg of enset fiber = 0.0009434 m³ of enset fiber

But for 78.5 kg of soil we need 20 kg of fly ash and 1.5 kg of enset fiber

$$\text{i.e. } 1 \text{ kg of soil} = 0.0003846 \text{ m}^3$$

$$78.5 \text{ kg of soil} = \underline{0.0302 \text{ m}^3} \text{ of soil}$$

1 kg of fly ash = 0.0004762 m^3 , then 20 kg of fly ash will be 0.0095 m^3

1 kg of enset fiber = 0.0009434 m^3 , then 1.5 kg of enset fiber will be 0.00142 m^3

So, 78.5 kg of soil = 0.0302 m^3 --- then, 20 kg of fly ash = 0.0095 m^3 and 1.5 kg of enset fiber = 0.00142 m^3 .

Therefore, 0.0302 m^3 of soil = 0.0095 m^3 of fly ash

1 m^3 of soil = 0.3146 m^3 of fly ash

0.0302 m^3 of soil = 0.00142 m^3 of enset fiber

1 m^3 of soil = 0.047 m^3 of enset fiber

Generally, it is to mean that; for 1 m^3 of expansive soil it was found 0.3146 m^3 of fly ash and 0.047 m^3 of enset fiber to be used as stabilizing agent.

Table 4.19 Cost of subgrade construction by removal of expansive soil and replace with borrow suitable soil

Description	Unit	Quantity	Unit price (birr)	Total price (birr/km)
Clearing and Grubbing (removing top 20cm soil)	m^2	8000	5.5	44,000
Undercut excavation of unsuitable soil to a depth of 80cm	m^3	6400	66.35	424,640
Removal of unsuitable material including all haul	m^3	7200	62.71	451,512
Selected material cut and borrow to fill including all haul	m^3	6400	279.3	1,787,520
Roadbed preparation and the compaction of material	m^3	6400	49.14	314,496
Total cost (birr)				3,022,168

Table 4.20 Cost of subgrade construction by stabilization of existing soil using 20% fly ash and 1.5% enset fiber at 20mm fiber length

Description	Unit	Quantity	Unit price (birr)	Total price (birr/km)
Clearing and Grubbing (removing top 20cm soil)	m ²	8000	5.5	44,000
Excavation of unsuitable soil to a depth of 80cm	m ³	6400	66.35	424,640
Fly ash collection and transportation (only transport and labor cost)	m ³	2013.44	300	604,032
Enset fiber preparation including collection and kerosene coating	Kg	96000	12	1,152,000
Removal of excess unsuitable material including all haul	m ³	1376	62.71	86,288.96
Compaction (including mixing and placing)	m ³	4180.37	49.14	205,423.38
Total cost (birr)				2,516,384.34

Table 4.21 Summary of cost comparison of replacing versus stabilizing

No.	Description	Total cost (birr/km)	% saving
1	Subgrade construction by removal of expansive soil and replace with borrow selected soil	3,022,168	16.7%
2	Subgrade construction by stabilizing the expansive soil with fly ash and enset fiber	2,516,384.34	
3	Difference (birr)	505,783.66	

From Table 4.21 above, it can be seen that the cost for stabilizing the expansive soil with fly ash and enset fiber (2,516,384.34 birr/km) is found to be lower than that of replacing the expansive soil with borrow selected material (3,022,168 birr/km). The cost comparison shows that there is 16.7% saving of cost by using fly ash and enset fiber for improvement over cost of replacing.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The following conclusions are drawn based on results obtained and discussions made in this study:

- ✓ The liquid limit, plasticity index, free swell, free swell index and MDD values decreased while plastic limit and OMC values increased with increasing the percentage of fly ash.
- ✓ Based on CBR and UCS test results, the addition of fly ash content showed a significant increase in both CBR and UCS values. The optimum CBR and UCS values of 3.77% and 177.75kPa respectively are obtained at 20% fly ash content and beyond this percentage both values are decreased. This shows that 20% fly ash was taken as optimum percentage for soil-fly ash mix.
- ✓ The MDD and OMC of soil-fly ash-fiber mix decreased and increased respectively with increasing the percentage of enset fiber for both lengths.
- ✓ The CBR value of soil-fly ash mix was found increased with the addition of enset fiber content up to 1.5% and beyond this percentage there was a decrease in CBR value for both fiber lengths (15mm and 20mm). The optimum CBR value of 6.38% was obtained at 1.5% fiber content for 20mm length which is 4.91 times (388.9%) higher than natural soil and/or 1.69 times (69.2%) higher than optimum soil-fly ash sample.
- ✓ The UCS value of soil-fly ash mix increases with the increase in percentage for both lengths of enset fiber; and the highest strength is observed at 1.5% fiber content, beyond this percentage UCS value reduced. The optimum UCS value of 231.5kPa is obtained at 1.5% fiber content for 20mm length which is 1.83 times (82.8%) more than natural soil and/or 1.3 times (30.2%) more than optimum soil-fly ash sample.
- ✓ It is concluded that inclusion of 1.5% enset fiber at 20mm length into optimum soil-fly ash mix is an optimum percentage for improvement based on CBR and UCS value.

Hence, soil stabilization using fly ash and enset fiber is found to be an alternative improvement technique for expansive subgrade soil.

5.2 Recommendation

- ✓ In Ethiopia there are many types natural fibers and also large amount of coal reserves to utilize the byproduct fly ash, but their promising combined ability to improve the properties of weak soil have not well explored. So broad researches are recommended on the applicability of fly ash and enset fiber on different types of soil; and also the effects of enset fiber with other chemical additives such as lime and cement to improve properties of weak soil are recommended for future study.
- ✓ The durability of natural fibers under soil or road pavement and effect of kerosene on the environment should be studied.
- ✓ Cutting of enset fiber and mixing with soil was done manually in this study. So I recommend designing of machine capable of cutting fiber to a desired length and mixing it for bulk uses in the field.

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APPENDICES

Appendix A - Natural moisture content test result

Table A-1 Natural moisture content test result for TP-1

Trial No	1	2	3
Container No	5	40	A3
Mass of wet soil + container (gm)	319.5	322.3	316.8
Mass of dry soil + container (gm)	263.3	266.5	261.2
Mass of water (gm)	56.20	55.80	55.60
Mass of container (gm)	42.7	43.1	41.8
Mass of dry soil (gm)	220.6	223.4	219.4
Moisture content (%)	25.48	24.98	25.34
Average moisture content (%)	25.27		

Table A-2 Natural moisture content test result for TP-2

Trial No	1	2	3
Container No	19	A6	B1
Mass of wet soil + container (gm)	311.0	318.5	312.6
Mass of dry soil + container (gm)	254.8	258.9	256.1
Mass of water (gm)	56.20	59.60	56.50
Mass of container (gm)	43.2	42.5	41.7
Mass of dry soil (gm)	211.6	216.4	214.4
Moisture content (%)	26.56	27.54	26.35
Average moisture content (%)	26.82		

Table A-3 Natural moisture content test result for (Fly ash only)

Trial No	1	2	3
Container No	A2	A6	12
Mass of wet fly ash + container (gm)	254	282	262.5
Mass of dry fly ash + container (gm)	243.5	270.6	251.8
Mass of water (gm)	10.50	11.40	10.70
Mass of container (gm)	41	41.5	42.5
Mass of dry fly ash (gm)	202.5	229.1	209.3
Moisture content (%)	5.19	4.98	5.11
Average moisture content (%)	5.09		

Appendix B - Specific gravity test result

Table B-1 Specific gravity test result for TP-1

1. Trial No.	1	2
2. Mass of Pycnometer + Soil	618.7	618.7
3. Mass of dry soil	200	200
4. Mass of Pycnometer with full of Water	1543.5	1545.1
5. Mass of Pycnometer + Soil + Water	1667.3	1668.5
6. Mass of equal volume of water as the soil solids, (3+4-5)	76.2	76.6
7. Specific Gravity at 24°C (3/6)	2.62	2.61
8. Conversion factor K	0.9991	0.9991
9. Specific gravity of soil at 20 °c	2.62	2.61
Average Specific Gravity	2.62	

Table B-2 Specific gravity test result for TP-2

1. Trial No.	1	2
2. Mass of Pycnometer + Soil	619.2	619.2
3. Mass of dry soil	200	200
4. Mass of Pycnometer with full of Water	1546.5	1546.5
5. Mass of Pycnometer + Soil + Water	1669.2	1670.3
6. Mass of equal volume of water as the soil solids, (3+4-5)	77.3	76.2
7. Specific Gravity at 25°C (3/6)	2.59	2.62
8. Conversion factor K	0.9988	0.9988
9. Specific gravity of soil at 20 °c	2.58	2.62
Average Specific Gravity	2.60	

Table B-3 Specific gravity test result for (Fly ash only)

1. Trial No.	1	2
2. Mass of Pycnometer + Fly ash	619	619
3. Mass of Fly ash	200	200
4. Mass of Pycnometer with full of Water	1546.2	1545.5
5. Mass of Pycnometer + Fly ash + Water	1651.7	1649.6
6. Mass of equal volume of water as the fly ash solids, (3+4-5)	94.5	95.9
7. Specific Gravity at 25°C (3/6)	2.12	2.09
8. Conversion factor K	0.9988	0.9988
9. Specific gravity of fly ash at 20 °c	2.11	2.08
Average Specific Gravity	2.10	

Specific gravity test result with varying percentage of fly ash

Table B-4 Specific gravity test result for (Soil + 10% fly ash)

1. Trial No.	1	2
2. Mass of Pycnometer + Sample	618.3	618.3
3. Mass of Sample	200	200
4. Mass of Pycnometer with full of Water	1545.9	1545.2
5. Mass of Pycnometer + Sample + Water	1665.1	1664.1
6. Mass of equal volume of water as the sample solids, (3+4-5)	80.8	81.1
7. Specific Gravity at 25°C (3/6)	2.48	2.47
8. Conversion factor K	0.9988	0.9988
9. Specific gravity of sample at 20 °c	2.47	2.46
Average Specific Gravity	2.47	

Table B-5 Specific gravity test result for (Soil + 20% fly ash)

1. Trial No.	1	2
2. Mass of Pycnometer + Sample	619.4	619.4
3. Mass of Sample	200	200
4. Mass of Pycnometer with full of Water	1547.1	1546.6
5. Mass of Pycnometer + Sample + Water	1664.2	1663.3
6. Mass of equal volume of water as the sample solids, (3+4-5)	82.9	83.3
7. Specific Gravity at 23°C (3/6)	2.41	2.40
8. Conversion factor K	0.9993	0.9993
9. Specific gravity of sample at 20 °c	2.41	2.40
Average Specific Gravity	2.41	

Table B-6 Specific gravity test result for (Soil + 25% fly ash)

1. Trial No.	1	2
2. Mass of Pycnometer + Sample	618.5	618.5
3. Mass of Sample	200	200
4. Mass of Pycnometer with full of Water	1547.3	1546.8
5. Mass of Pycnometer + Sample + Water	1663.9	1662.4
6. Mass of equal volume of water as the sample solids, (3+4-5)	83.4	84.4
7. Specific Gravity at 23°C (3/6)	2.40	2.37
8. Conversion factor K	0.9993	0.9993
9. Specific gravity of sample at 20 °c	2.40	2.37
Average Specific Gravity	2.38	

Appendix C - Wet sieve and hydrometer analysis test result

Table C-1 Wet sieve analysis result for TP-1

Total mass of soil washed = 500gm					
Mass of dry soil after wash = 98.8gm					
Sieve No	Sieve size (mm)	Mass of retained soil (gm)	Percentage retained (%)	Cumulative percent retained (%)	Percent finer (%)
4	4.75	0.8	0.16	0.16	99.84
8	2.36	3.3	0.66	0.82	99.18
10	2.00	2.5	0.50	1.32	98.68
16	1.18	5.3	1.06	2.39	97.61
30	0.60	4.7	0.94	3.33	96.67
40	0.425	4.4	0.88	4.21	95.79
50	0.30	10.9	2.19	6.40	93.60
100	0.15	30.5	6.12	12.51	87.49
200	0.075	35.1	7.04	19.55	80.45
	Pan	401.2	80.45	100.00	0.00
		498.7			

Table C-2 Hydrometer analysis test result for TP-1

Specific gravity of soil = 2.62				Mass of dry soil = 50g					
Type of hydrometer = 151H				Temp = 21.5-24°C					
Elapsed Time (min)	Actual Hydrometer Reading		Composite Correction	Corrected Hydrometer Reading	Effective Depth L (cm)	Coefficient K	Grain Size (mm)	% Passing	
	Temp (°C)							% Finer	% Finer Combined
0.75	1.0285	22.0	0.0019	1.0266	8.75	0.013656	0.0466	86.04	69.22
1	1.0285	22.0	0.0019	1.0266	8.75	0.013656	0.0404	86.04	69.22
2	1.0280	22.0	0.0019	1.0261	8.90	0.013656	0.0288	84.42	67.92
4	1.0280	22.0	0.0019	1.0261	8.90	0.013656	0.0204	84.42	67.92
8	1.0270	22.0	0.0019	1.0251	9.20	0.013656	0.0146	81.19	65.31
15	1.0265	22.5	0.0018	1.0247	9.30	0.013576	0.0107	79.89	64.27
30	1.0260	22.5	0.0018	1.0242	9.40	0.013576	0.0076	78.28	62.97
60	1.0255	22.5	0.0018	1.0237	9.55	0.013576	0.0054	76.66	61.67
120	1.0240	23.0	0.0018	1.0222	10.00	0.013496	0.0039	71.81	57.77
240	1.0225	24.0	0.0016	1.0209	10.50	0.013336	0.0028	67.60	54.39
480	1.0205	23.0	0.0016	1.0189	10.85	0.013496	0.0020	61.13	49.18
1440	1.0195	21.5	0.0016	1.0179	11.15	0.013825	0.0012	57.90	46.58

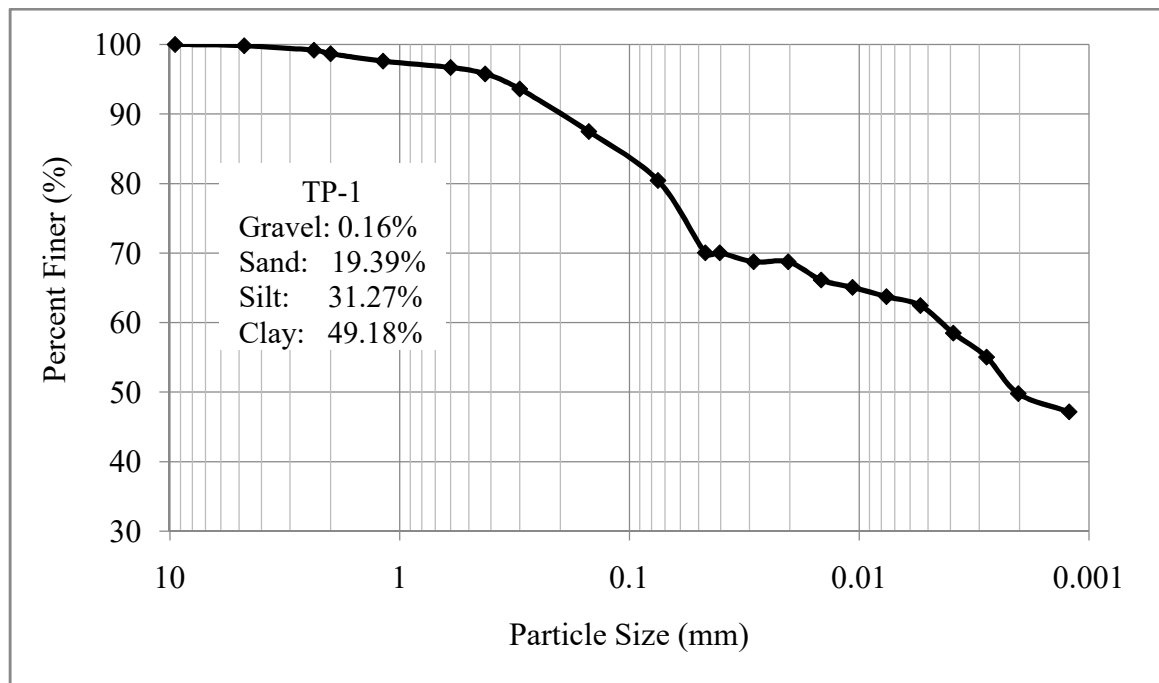


Figure C-1 Combined particle size distribution curve for TP-1

Table C-3 Wet sieve analysis result for TP-2

Total mass of soil washed = 500gm					
Mass of dry soil after wash = 91.6gm					
Sieve No	Sieve size (mm)	Mass of retained soil (gm)	Percentage retained (%)	Cumulative percent retained (%)	Percent finer (%)
4	4.75	2.4	0.48	0.48	99.52
8	2.36	3.4	0.68	1.16	98.84
10	2.00	1.7	0.34	1.50	98.50
16	1.18	3.8	0.76	2.26	97.74
30	0.60	5.7	1.14	3.40	96.60
40	0.425	6.0	1.20	4.61	95.39
50	0.30	6.8	1.36	5.97	94.03
100	0.15	26.2	5.25	11.21	88.79
200	0.075	35.6	7.13	18.34	81.66
	Pan	407.8	81.66	100.00	0.00
	Total	499.4			

Table C-4 Hydrometer analysis test result for TP-2

Specific gravity of soil = 2.60				Mass of dry soil = 50g					
Type of hydrometer = 151H				Temp = 21.5-24°C					
Elapsed Time (min)	Actual Hydrometer			Corrected Hydrometer Reading	Effective Depth L (cm)	Coefficient K	Grain Size (mm)	% Passing	
	Temp (°C)	Composite Correction	% Finer					% Combined	
0.75	1.0290	22.0	0.0020	1.0270	8.60	0.01353	0.0458	87.75	71.66
1	1.0290	22.0	0.0020	1.0270	8.60	0.01353	0.0397	87.75	71.66
2	1.0285	22.0	0.0020	1.0265	8.75	0.01353	0.0283	86.12	70.33
4	1.0280	22.0	0.0020	1.0260	8.90	0.01353	0.0202	84.50	69.00
8	1.0275	22.0	0.0020	1.0255	9.05	0.01353	0.0144	82.88	67.68
15	1.0270	22.5	0.0017	1.0253	9.20	0.01345	0.0105	82.22	67.14
30	1.0260	22.5	0.0017	1.0243	9.40	0.01345	0.0075	78.98	64.49
60	1.0250	22.5	0.0017	1.0233	9.70	0.01345	0.0054	75.72	61.84
120	1.0245	23.0	0.0015	1.0230	9.85	0.01337	0.0038	74.75	61.04
240	1.0235	24.0	0.0016	1.0219	10.10	0.01321	0.0027	71.18	58.12
480	1.0220	23.0	0.0015	1.0205	11.00	0.01337	0.0020	66.62	54.41
1440	1.0210	21.5	0.0018	1.0192	10.70	0.01361	0.0012	62.40	50.96

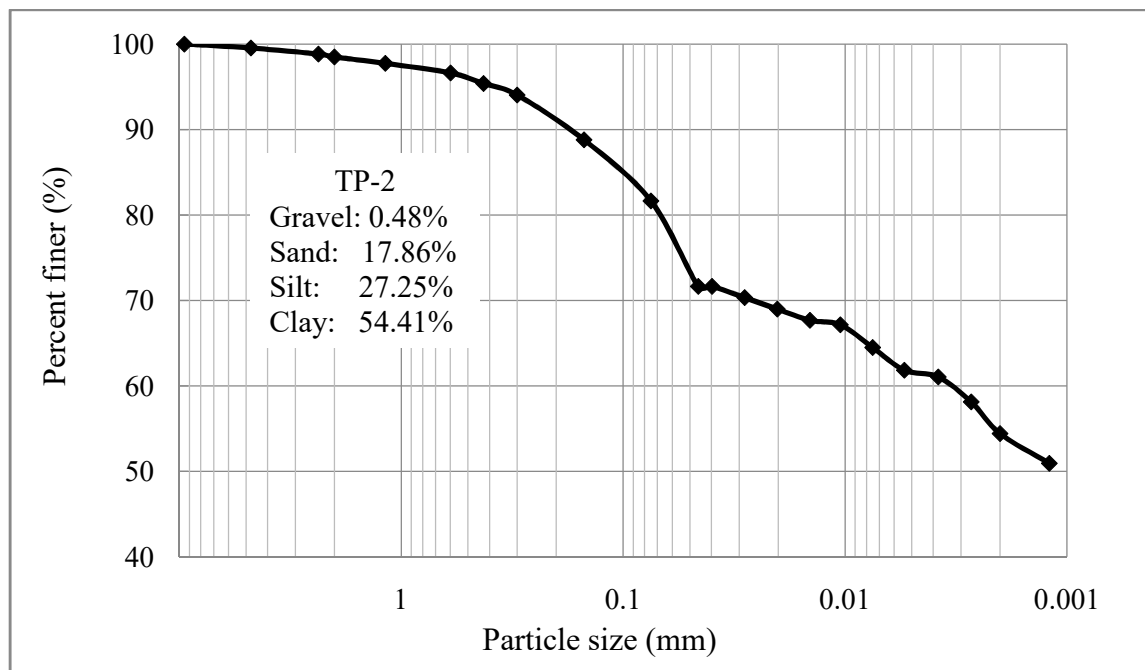


Figure C-2 Combined particle size distribution curve for TP-2

Table C-5 Dry sieve analysis result for Fly ash

Total mass of fly ash sieved = 500gm					
Sieve No	Sieve size (mm)	Mass of retained fly ash (gm)	Percentage retained (%)	Cumulative percent retained (%)	Percent finer (%)
4	4.75	0	0.00	0.00	100.00
8	2.36	0	0.00	0.00	100.00
10	2.00	0	0.00	0.00	100.00
16	1.18	4.3	0.86	0.86	99.14
30	0.60	5.7	1.14	2.00	98.00
40	0.425	14.6	2.92	4.93	95.07
50	0.30	28.7	5.75	10.67	89.33
100	0.15	94.7	18.96	29.64	70.36
200	0.075	133.5	26.73	56.37	43.63
	Pan	217.9	43.63	100.00	0.00
	Total	499.4			

Table C-6 Hydrometer analysis test result for Fly ash

Specific gravity of fly ash =2.1 Type of hydrometer = 151H				Mass of dry fly ash used = 50g Temp = 21.5-23°C					
Elapsed Time (min)	Actual Hydrometer Reading	Temp (°C)	Composite Correction	Corrected Hydrometer Reading	Effective Depth L (cm)	Coefficient K	Grain Size (mm)	% Passing	
								% Finer	% Finer Combined
0.75	1.026	22.0	0.0018	1.0242	9.40	0.01589	0.0563	78.65	34.31
1	1.025	22.0	0.0018	1.0232	9.70	0.01589	0.0495	75.40	32.90
2	1.024	22.0	0.0018	1.0222	10.00	0.01589	0.0355	72.15	31.48
4	1.022	22.0	0.0017	1.0203	10.50	0.01589	0.0257	65.98	28.78
8	1.021	22.0	0.0017	1.0193	10.70	0.01589	0.0184	62.72	27.37
15	1.018	22.5	0.0017	1.0163	11.50	0.01581	0.0138	52.97	23.11
30	1.015	22.5	0.0017	1.0133	12.30	0.01581	0.0101	43.22	18.86
60	1.012	22.5	0.0016	1.0104	13.10	0.01581	0.0074	33.80	14.75
120	1.010	23.0	0.0015	1.0085	13.70	0.01565	0.0053	27.62	12.05
240	1.007	23.0	0.0014	1.0056	14.40	0.01565	0.0038	18.20	7.94
480	1.006	23.0	0.0012	1.0048	14.70	0.01565	0.0027	15.60	6.81
1440	1.004	21.5	0.0010	1.0030	15.20	0.01594	0.0016	9.75	4.25

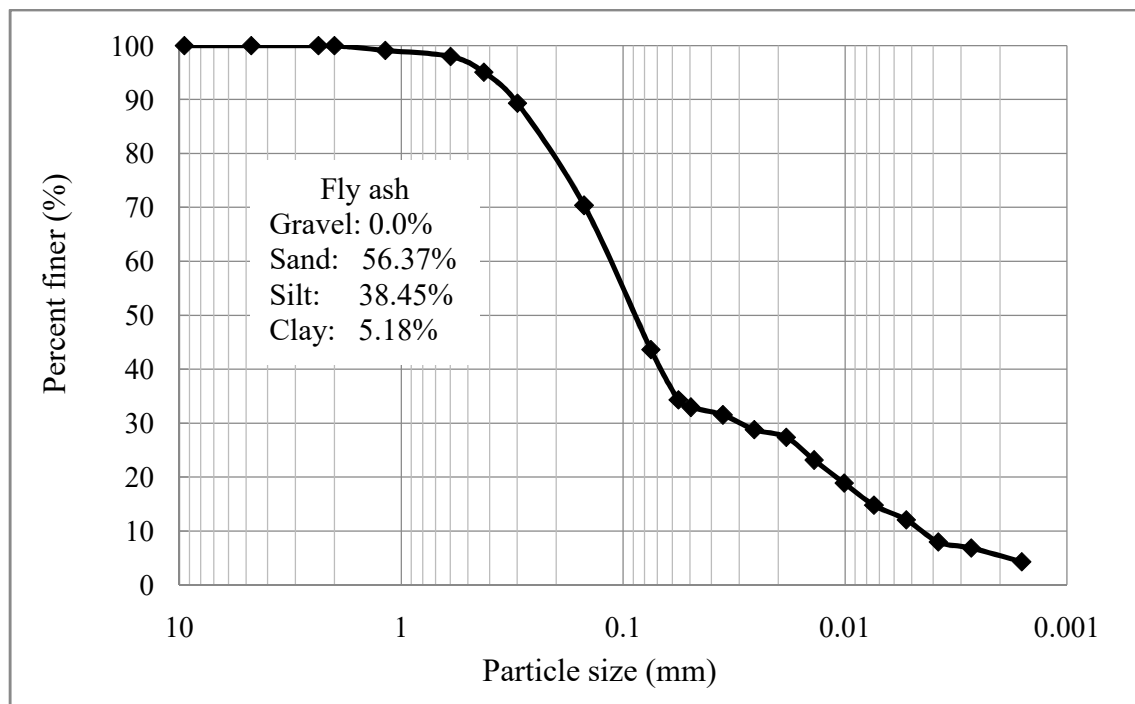


Figure C-3 Combined particle size distribution curve for Fly ash

Table C-7 Wet sieve analysis result for Soil + 10% FA

Total mass of soil-fly ash washed = 500gm					
Mass of dry soil-fly ash after wash = 109.2gm					
Sieve No	Sieve size (mm)	Mass of retained soil-fly ash (gm)	Percentage retained (%)	Cumulative percent retained (%)	Percent finer (%)
4	4.75	0	0.00	0.00	100.00
8	2.36	2.7	0.54	0.54	99.46
10	2.00	3.4	0.68	1.22	98.78
16	1.18	6.1	1.22	2.45	97.55
30	0.60	5.6	1.12	3.57	96.43
40	0.425	8.7	1.74	5.31	94.69
50	0.30	14.8	2.97	8.28	91.72
100	0.15	28.6	5.73	14.01	85.99
200	0.075	38.2	7.66	21.67	78.33
	Pan	390.8	78.33	100.00	0.00
	Total	498.9			

Appendix D - Liquid limit and plastic limit test results

Table D-1 Liquid limit and plastic limit for TP-1

	Liquid Limit			Plastic Limit	
Trial No	1	2	3	1	2
Container No	N1	N5	B4	D	L
Mass of wet soil + container (gm)	50.191	53.504	57.817	13.83	13.0
Mass of dry soil + container (gm)	36.958	39.035	44.083	13.197	12.401
Mass of water (gm)	13.23	14.47	13.73	0.63	0.60
Mass of container (gm)	17.785	18.399	24.713	11.165	10.47
Mass of dry soil (gm)	19.173	20.636	19.37	2.032	1.931
Moisture content (%)	69.02	70.12	70.90	31.15	31.02
No of Blows	32	24	19	-	-
Liquid Limit = 69.9%			Plastic Limit = 31.1%		
Plasticity index = 38.8%					

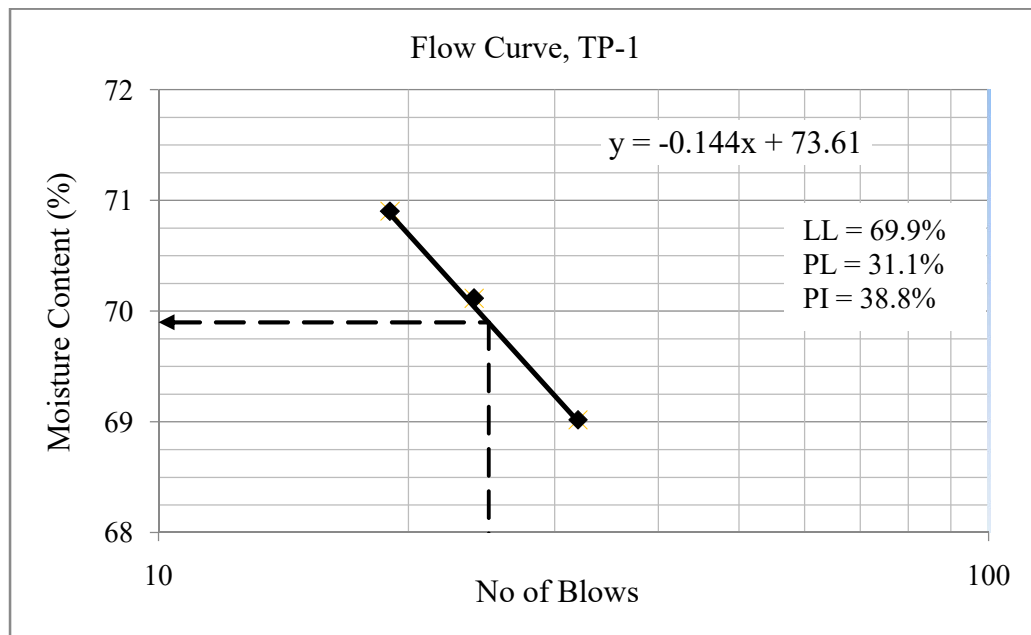


Figure D-1 Liquid limit determination for TP-1

Table D-2 Liquid limit and plastic limit for TP-2

	Liquid Limit			Plastic Limit	
Trial No	1	2	3	1	2
Container No	M7	N12	F10	C	L
Mass of wet soil + container (gm)	53.541	51.391	65.9	13.435	13.039
Mass of dry soil + container (gm)	40.009	38.205	50.535	12.847	12.426
Mass of water (gm)	13.532	13.186	15.365	0.588	0.613
Mass of container (gm)	20.228	19.988	31.302	10.966	10.474
Mass of dry soil (gm)	19.781	18.217	19.233	1.88	1.952
Moisture content (%)	68.41	72.38	79.89	31.26	31.40
No of Blows	34	28	15	-	-
Liquid Limit = 72.9%			Plastic Limit = 31.3%		
Plasticity index = 41.6%					

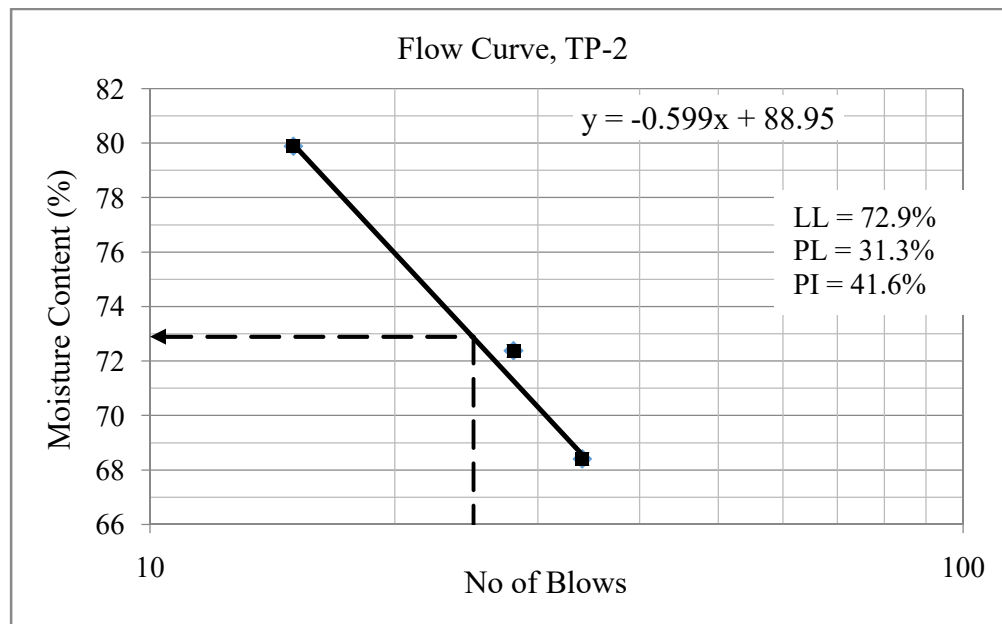


Figure D-2 Liquid limit determination for TP-2

Liquid limit and Plastic limit test results with varying percentage of fly ash

Table D-3 Liquid limit and plastic limit for (Soil + 10% fly ash)

	Liquid Limit			Plastic Limit	
Trial No	1	2	3	1	2
Container No	D30	M7	S	G	J
Mass of wet sample + container (gm)	62.569	54.212	54.073	13.703	13.131
Mass of dry sample + container (gm)	50.025	40.487	40.311	13.101	12.502
Mass of water (gm)	12.54	13.73	13.76	0.60	0.63
Mass of container (gm)	31.045	20.228	20.81	11.246	10.584
Mass of dry sample (gm)	18.98	20.259	19.501	1.855	1.918
Moisture content (%)	66.09	67.75	70.57	32.45	32.79
No of Blows	35	28	22	-	-
Liquid Limit = 69%			Plastic Limit = 32.6%		
Plasticity index = 36.4%					

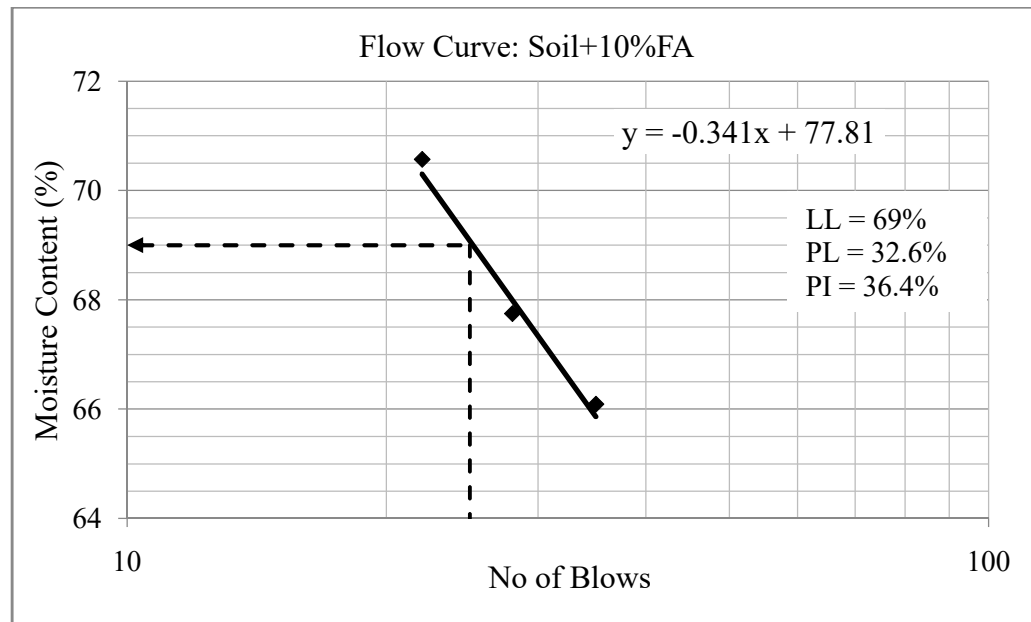


Figure D-3 Liquid limit determination for soil + 10% fly ash

Table D-4 Liquid limit and plastic limit for (Soil + 25% fly ash)

	Liquid Limit			Plastic Limit	
Trial No	1	2	3	1	2
Container No	F50	C10	E50	D	M
Mass of wet sample + container (gm)	63.225	61.676	61.62	12.616	13.369
Mass of dry sample + container (gm)	50.716	49.603	48.23	12.205	12.688
Mass of water (gm)	12.51	12.07	13.39	0.41	0.68
Mass of container (gm)	30.974	31.325	28.78	11.167	10.952
Mass of dry sample (gm)	19.742	18.278	19.45	1.038	1.736
Moisture content (%)	63.36	66.05	68.84	39.60	39.23
No of Blows	35	28	17	-	-
Liquid Limit = 66%			Plastic Limit = 39.4%		
Plasticity index = 26.6%					

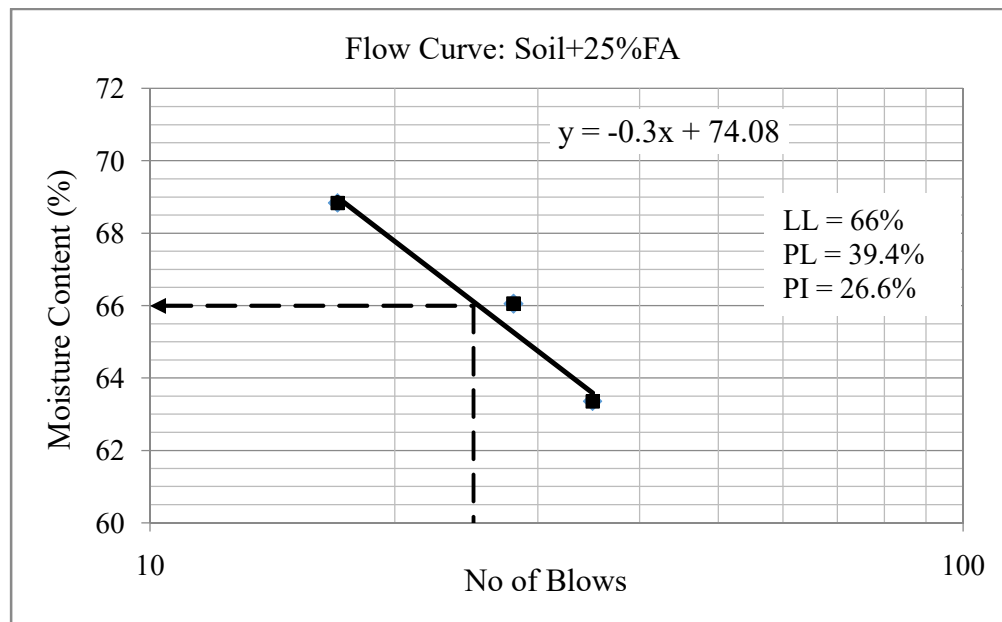


Figure D-4 Liquid limit determination for soil + 25% fly ash

Appendix E - Free swell, free swell index and free swell ratio test results

Table E-1 Free swell test result for TP-1

Initial volume of sample (ml)	Final volume of sample in water (ml)		Average final volume (ml)	Free swell (ml)
	Trial No.1	Trial No.2		
10	18.5	19	18.75	87.5

Table E-2 Free swell index test result for TP-1

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell index (%)
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.5	18.5	19	
	10.5		18.75	78.6

Table E-3 Free swell ratio test result for TP-1

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell ratio
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.5	18.5	19	
	10.5		18.75	1.79

Table E-4 Free swell test result for TP-2

Initial volume of sample (ml)	Final volume of sample in water (ml)		Average final volume (ml)	Free swell (ml)
	Trial No.1	Trial No.2		
10	19	19.5	19.25	92.5

Table E-5 Free swell index test result for TP-2

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell index (%)
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.5	19	19.5	
	10.5		19.25	83.3

Table E-6 Free swell ratio test result for TP-2

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell ratio
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.5	19	19.5	
	10.5		19.25	1.83

Table E-7 Free swell test result for (Fly ash only)

Initial volume of sample (ml)	Final volume of sample in water (ml)		Average final volume (ml)	Free swell (ml)
	Trial No.1	Trial No.2		
10	10.2	10.2	10.2	2.0

Table E-8 Free swell index test result for (Fly ash only)

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell index (%)
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10	10.1	10.2	10.2	1.49
	10.05		10.2	

Table E-9 Free swell ratio test result for (Fly ash only)

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell ratio
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10	10.1	10.2	10.2	1.01
	10.05		10.2	

Free swell, free swell index and free swell ratio results with varying percentage of fly ash

Table E-10 Free swell test result for (Soil + 10% fly ash)

Initial volume of sample (ml)	Final volume of sample in water (ml)		Average final volume (ml)	Free swell (ml)
	Trial No.1	Trial No.2		
10	17.7	18	17.85	78.5

Table E-11 Free swell index test result for (Soil + 10% fly ash)

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell index (%)
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.4	17.7	18	70.8
	10.45		17.85	

Table E-12 Free swell ratio test result for (Soil + 10% fly ash)

Final volume of sample in kerosene (ml)		Final volume of sample in water (ml)		Free swell ratio
Trial No.1	Trial No.2	Trial No.1	Trial No.2	
10.5	10.4	17.7	18	1.71
	10.45		17.85	

Appendix F - Compaction test results

Data's common for all Compaction tests	
No of Blows: 56	Weight of hammer (Kg) = 4.54
No of layers: 5	Volume of Mold (cm ³) = 2085

Table F-1 Compaction data sheet for TP-1

DENSITY	Trial No	1	2	3	4
	Mass of Mold (gm)	6190	6190	6190	6190
	Mass of wet soil + mold (gm)	9716	9968	10189	9946
	Mass of wet soil (gm)	3526.0	3778.0	3999.0	3756.0
	Volume of Mold (cm ³)	2085	2085	2085	2085
	Wet density of soil (g/cm ³)	1.69	1.81	1.92	1.80
MOISTURE	Container No	B-1	15	35	14
	Mass of wet soil + container (gm)	335.5	332.8	333.5	312.3
	Mass of dry soil + container (gm)	296.2	286.7	280.9	252.6
	Mass of water (gm)	39.30	46.10	52.60	59.70
	Mass of container (gm)	41.5	41.3	41.7	41.90
	Mass of dry soil (gm)	254.7	245.4	239.2	210.7
Moisture content (%)		15.43	18.79	21.99	28.33
Dry density of soil (g/cm ³)		1.465	1.525	1.572	1.404

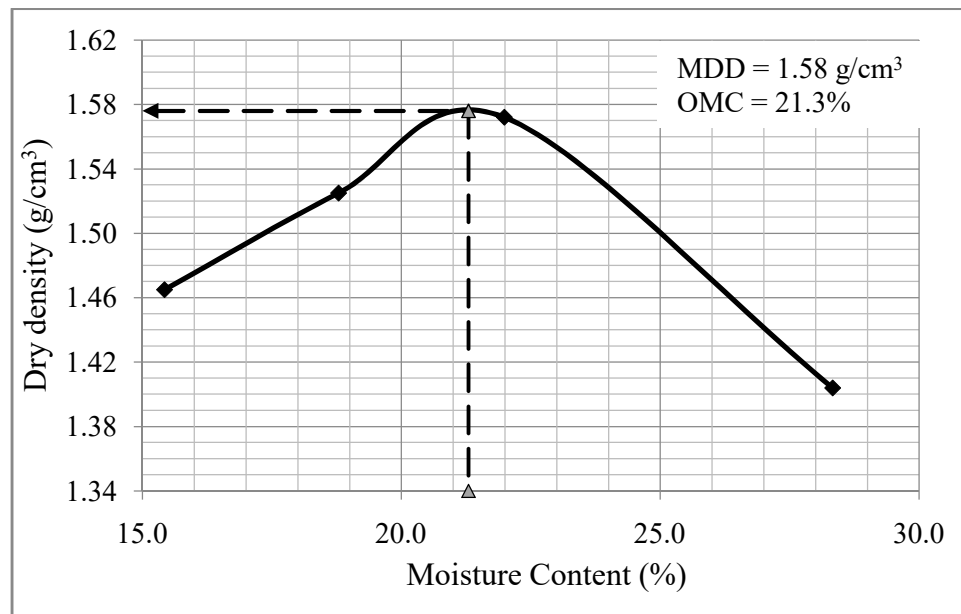


Figure F-1 Compaction curve for TP-1

Table F-2 Compaction data sheet for TP-2

DENSITY	Trial No	1	2	3	4
	Mass of Mold (gm)	6190	6190	6190	6190
	Mass of wet soil + mold (gm)	9720	9959	10166	9983
	Mass of wet soil (gm)	3530.0	3769.0	3976.0	3793.0
	Volume of Mold (cm ³)	2085	2085	2085	2085
	Wet density of soil (g/cm ³)	1.69	1.81	1.91	1.82
MOISTURE	Container No	A3	13	8	16
	Mass of wet soil + container (gm)	335	320.4	325.6	304.6
	Mass of dry soil + container (gm)	294.3	275.7	272.8	248.6
	Mass of water (gm)	40.70	44.70	52.80	56.00
	Mass of container (gm)	45.6	45.1	43.4	42.4
	Mass of dry soil (gm)	248.7	230.6	229.4	206.2
	Moisture content (%)	16.37	19.38	23.02	27.16
Dry density of soil (g/cm ³)		1.45	1.51	1.55	1.43

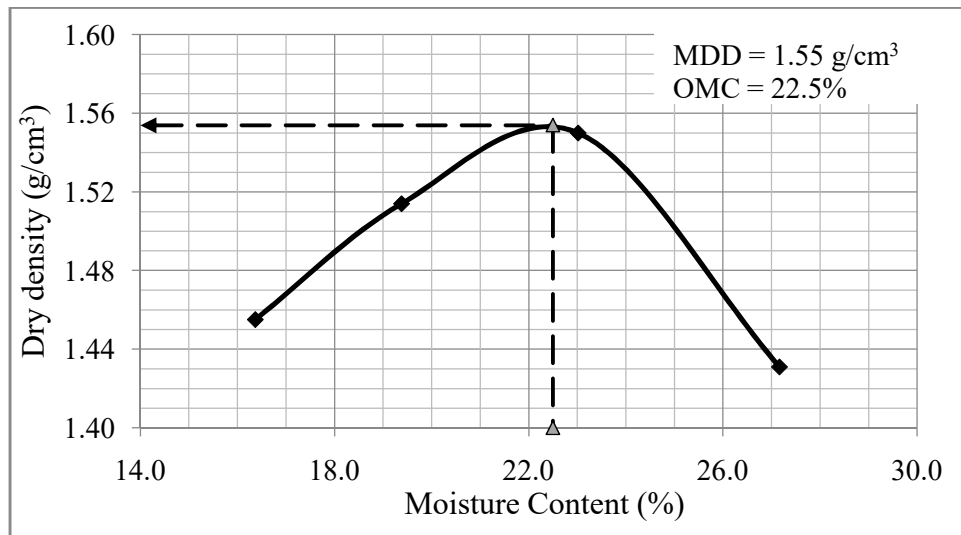


Figure F-2 Compaction curve for TP-2

Compaction test results with varying percentage of fly ash

Table F-3 Compaction data sheet for (Soil + 10% fly ash)

Trial No	1	2	3	4
Mass of Mold (gm)	6190	6190	6190	6190
Mass of wet soil-fly ash + mold (gm)	9716	9924	10086	9995
Mass of wet soil-fly ash (gm)	3526.0	3734.0	3896.0	3805.0
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash (g/cm ³)	1.69	1.79	1.87	1.82
Moisture content (%)	14.65	19.27	23.12	25.55
Dry density of soil-fly ash (g/cm ³)	1.475	1.502	1.518	1.454

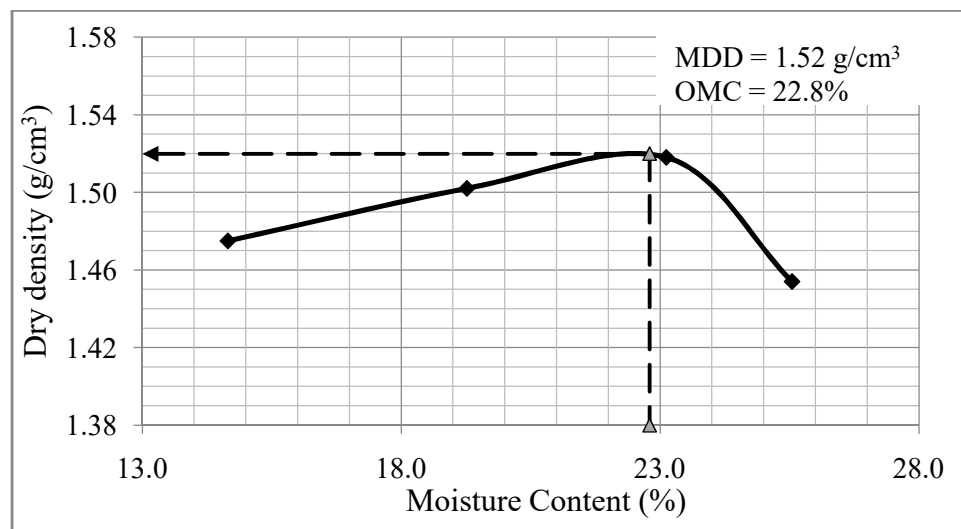


Figure F-3 Compaction curve for soil + 10% fly ash

Table F-4 Compaction data sheet for (Soil + 20% fly ash)

Trial No	1	2	3	4
Mass of Mold (gm)	6190	6190	6190	6190
Mass of wet soil-fly ash + mold (gm)	9677	9853	9985	9941
Mass of wet soil-fly ash (gm)	3487.0	3663.0	3795.0	3751.0
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash (g/cm ³)	1.67	1.76	1.82	1.80
Moisture content (%)	17.61	21.18	24.66	28.23
Dry density of soil-fly ash (g/cm ³)	1.422	1.450	1.460	1.403

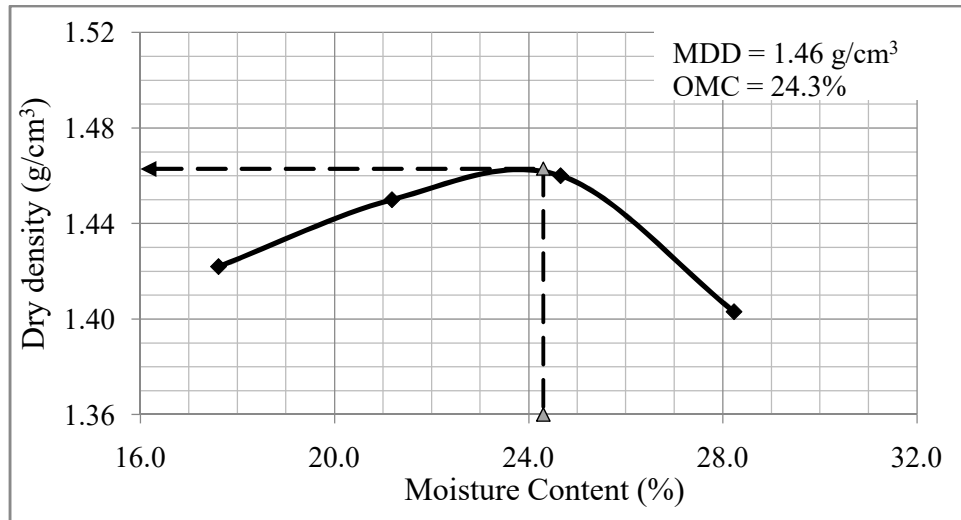


Figure F-4 Compaction curve for soil + 20% fly ash

Compaction test for soil treated with 20% fly ash & varying percentage of enset fiber

Table F-5 Compaction data sheet for (Soil + 20% FA + 0.5% EF, 15mm)

Trial No	1	2	3	4
Mass of Mold (gm)	6190	6190	6190	6190
Mass of wet soil-fly ash-fiber + mold (gm)	9695	9893	10012	9902
Mass of wet soil-fly ash-fiber (gm)	3505.0	3703.0	3822.0	3712.0
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash-fiber (g/cm ³)	1.68	1.78	1.83	1.78
Moisture content (%)	20.67	24.65	27.85	31.10
Dry density of soil-fly ash-fiber (g/cm ³)	1.393	1.425	1.434	1.358

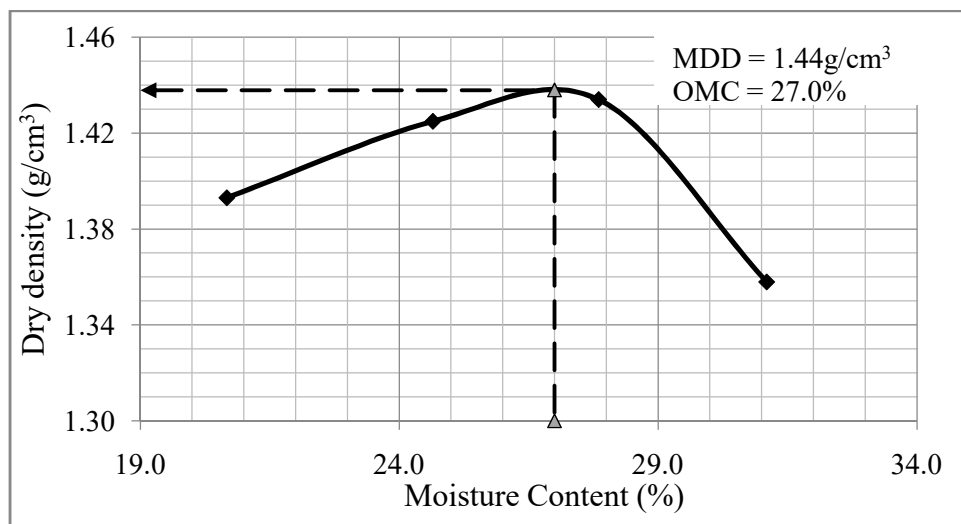


Figure F-5 Compaction curve for soil + 20% FA + 0.5% EF, 15mm length

Table F-6 Compaction data sheet for (Soil + 20% FA + 1.0% EF, 15mm)

Trial No	1	2	3	4
Mass of Mold (gm)	6190	6190	6190	6190
Mass of wet soil-fly ash-fiber + mold (gm)	9693	9845	9981	9894
Mass of wet soil-fly ash-fiber (gm)	3503	3655	3791	3704
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash-fiber (g/cm ³)	1.68	1.75	1.82	1.78
Moisture content (%)	22.92	25.91	28.86	32.06
Dry density of soil-fly ash-fiber (g/cm ³)	1.367	1.392	1.411	1.345

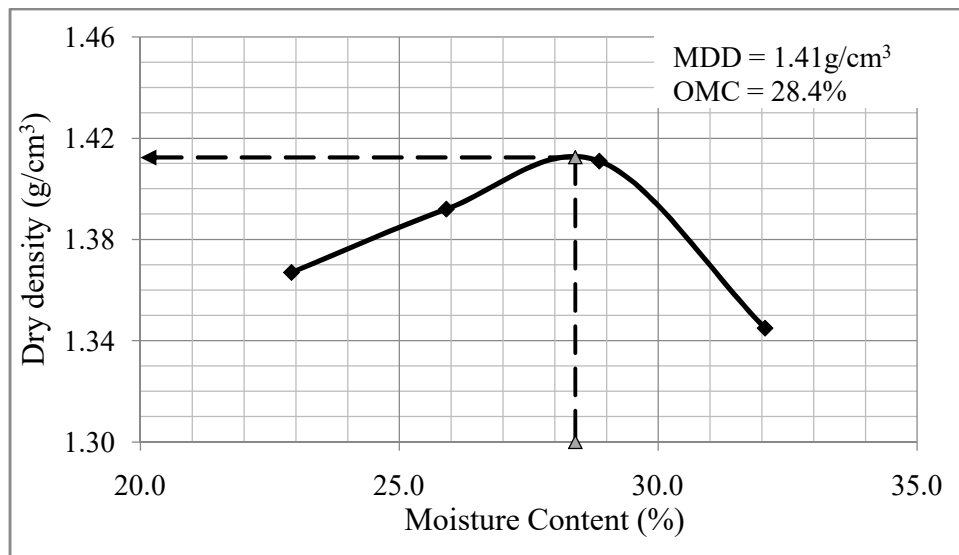


Figure F-6 Compaction curve for soil + 20% FA + 1.0% EF, 15mm length

Table F-7 Compaction data sheet for (Soil + 20% FA + 1.5% EF, 20mm kerosene coated fiber)

Trial No	1	2	3	4
Mass of Mold (gm)	6190	6190	6190	6190
Mass of wet soil-fly ash-fiber + mold (gm)	9621	9807	9978	9855
Mass of wet soil-fly ash-fiber (gm)	3431.0	3617.0	3788.0	3665.0
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash-fiber (g/cm ³)	1.65	1.73	1.82	1.76
Moisture content (%)	24.88	28.49	31.51	34.17
Dry density of soil-fly ash-fiber (g/cm ³)	1.318	1.350	1.381	1.310

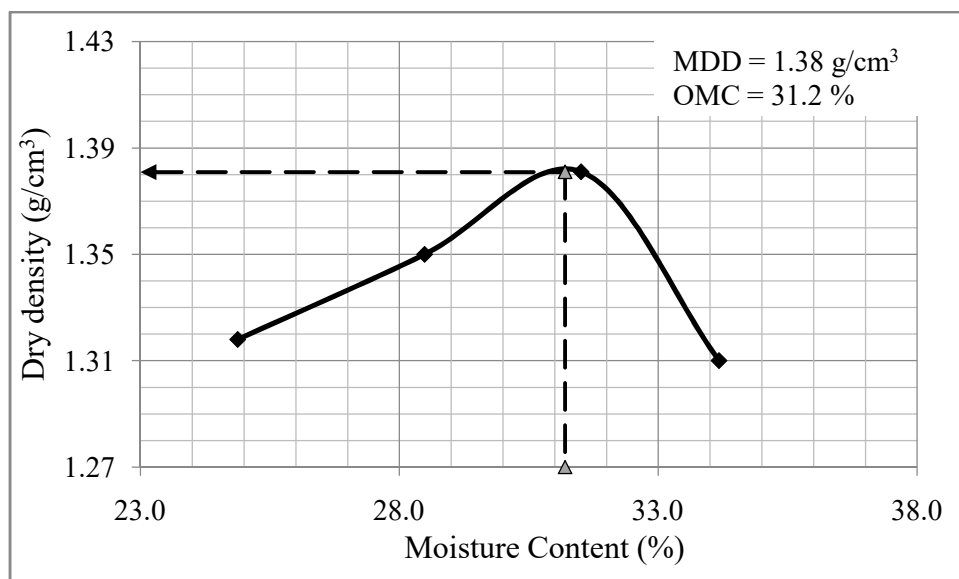


Figure F-7 Compaction curve for soil + 20% FA + 1.5% coated EF, 20mm length

Table F-8 Compaction data sheet for (Soil + 20% FA + 1.5% EF, 20mm uncoated fiber)

Trial No	1	2	3	4
Mass of Mold (gm)	6194	6194	6194	6194
Mass of wet soil-fly ash-fiber + mold (gm)	9637	9841	10008	9958
Mass of wet soil-fly ash-fiber (gm)	3443	3647	3814	3764
Volume of Mold (cm ³)	2085	2085	2085	2085
Wet density of soil-fly ash-fiber (g/cm ³)	1.65	1.75	1.83	1.81
Moisture content (%)	24.92	29.19	32.93	36.56
Dry density of soil-fly ash-fiber (g/cm ³)	1.322	1.354	1.376	1.322

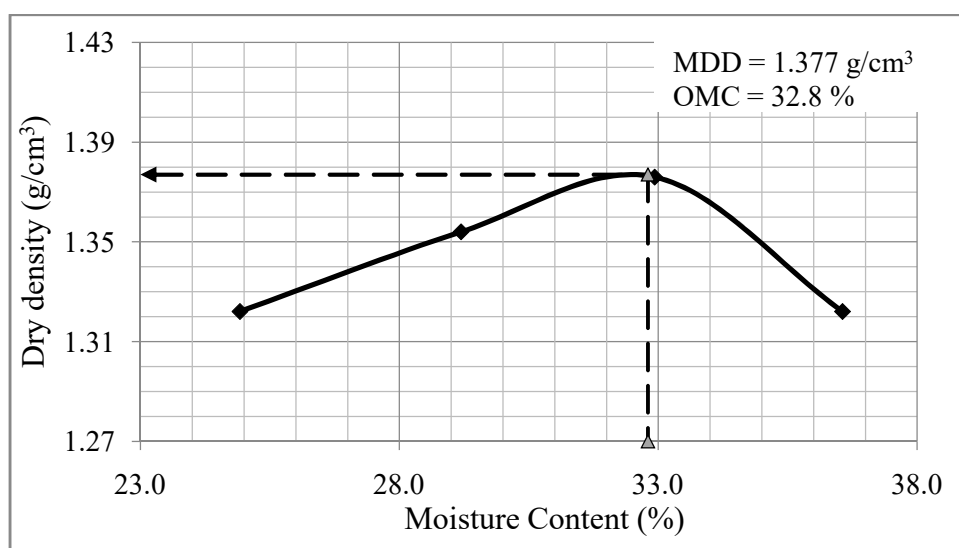


Figure F-8 Compaction curve for soil + 20% FA + 1.5% uncoated EF, 20mm length

Appendix G - California bearing ratio (one point soaked CBR) data sheet

Blow/Layer = 56/5	MDD (g/cm ³) = 1.53
Plunger area (mm ²) = 1935	OMC (%) = 24.8
Ring calib.factor (N/Div) = 22.651	CBR (%) = 1.59

Table G-1 CBR test result for TP-1

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	2.26
0		0	0	0		Final (mm)	12.1
0.64		4	90.6	0.05		Difference (mm)	9.84
1.27		6	135.9	0.07		Swell (%)	8.45
1.91		7	158.6	0.08			
2.54	6.9	9	203.9	0.11	1.59		
3.18		10	226.5	0.12			
3.81		11	249.2	0.13			
4.45		11	249.2	0.13			
5.08	10.3	12	271.8	0.14	1.36		
6.35		13	294.5	0.15			
7.62		14	317.1	0.16			

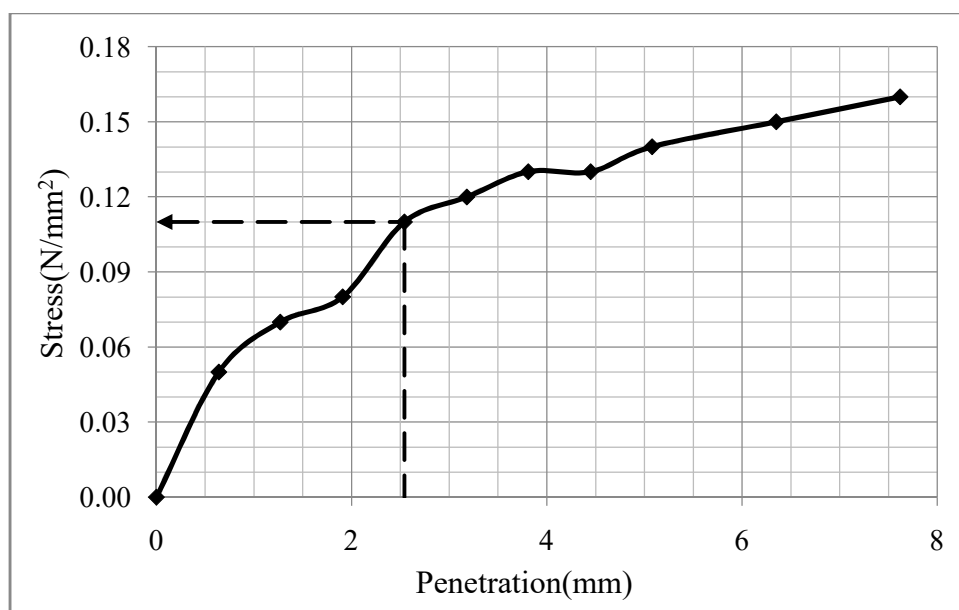


Figure G-1 CBR stress-penetration curve for TP-1

Blow/Layer = 56/5	MDD (g/cm ³) = 1.55
Plunger area (mm ²) = 1935	OMC (%) = 22.5
Ring calib.factor (N/Div) = 22.651	CBR (%) = 1.30

Table G-2 CBR test result for TP-2

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		5.8	
0.64		4	90.6	0.05		Final (mm)	18.24
1.27		6	135.9	0.07		Difference (mm)	12.44
1.91		7	158.6	0.08		Swell (%)	10.69
2.54	6.9	8	181.2	0.09	1.30		
3.18		9	203.9	0.11			
3.81		10	226.5	0.12			
4.45		10	226.5	0.12			
5.08	10.3	11	249.2	0.13	1.26		
6.35		12	271.8	0.14			
7.62		13	294.5	0.15			

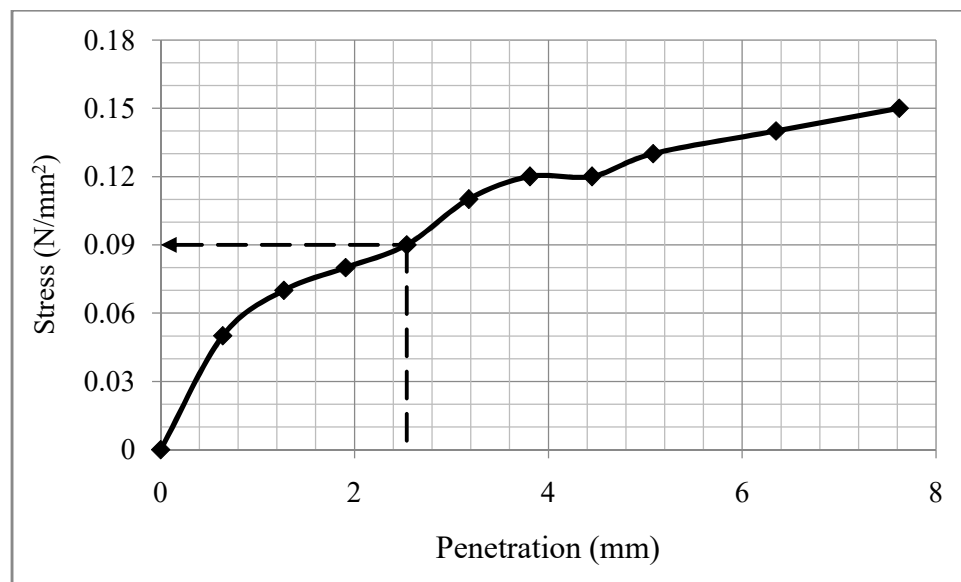


Figure G-2 CBR stress-penetration curve for TP-2

CBR test results with varying percentage of fly ash

Blow/Layer = 56/5	MDD (g/cm ³) = 1.52
Plunger area (mm ²) = 1935	OMC (%) = 22.5
Ring calib.factor (N/Div) = 22.651	CBR (%) = 2.32

Table G-3 CBR test result for (Soil + 10% fly ash)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	6.72
0		0	0	0		Final (mm)	16.8
0.64		7	158.6	0.08		Difference (mm)	10.08
1.27		10	226.5	0.12		Swell (%)	8.66
1.91		12	271.8	0.14			
2.54	6.9	14	317.1	0.16	2.32		
3.18		16	362.4	0.19			
3.81		17	385.1	0.20			
4.45		19	430.4	0.22			
5.08	10.3	20	453.0	0.23	2.23		
6.35		21	475.7	0.25			
7.62		23	521.0	0.27			

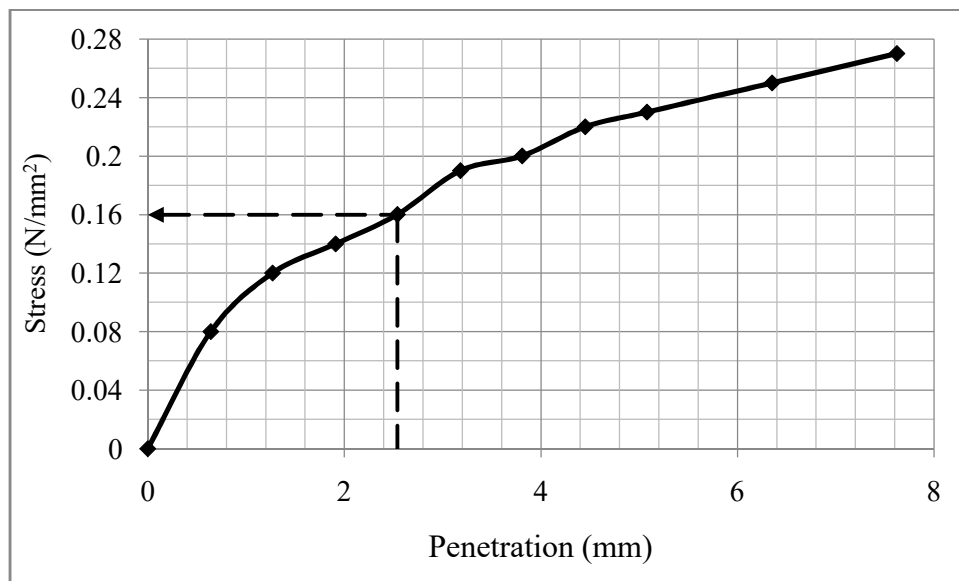


Figure G-3 CBR stress-penetration curve for soil + 10% fly ash

Blow/Layer = 56/5	MDD (g/cm ³) = 1.48
Plunger area (mm ²) = 1935	OMC (%) = 23.5
Ring calib.factor (N/Div) = 22.651	CBR (%) = 3.04

Table G-4 CBR test result for (Soil + 15% fly ash)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		8.05	
0.64		8	181.2	0.09		Final (mm)	16.72
1.27		12	271.8	0.14		Difference (mm)	8.67
1.91		15	339.8	0.18		Swell (%)	7.45
2.54	6.9	18	407.7	0.21	3.04		
3.18		20	453.0	0.23			
3.81		22	498.3	0.26			
4.45		24	543.6	0.28			
5.08	10.3	26	588.9	0.30	2.91		
6.35		27	611.6	0.32			
7.62		29	656.9	0.34			

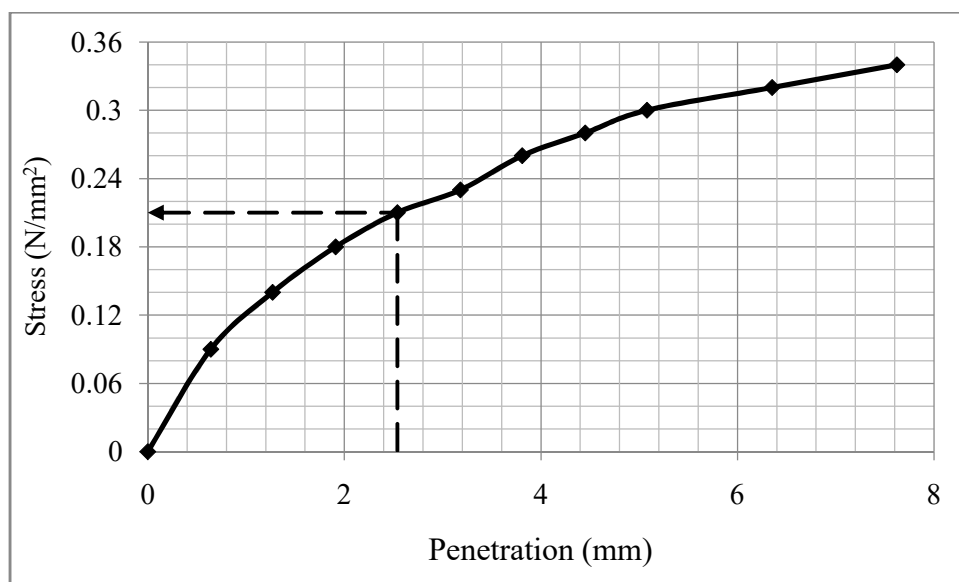


Figure G-4 CBR stress-penetration curve for soil + 15% fly ash

Blow/Layer = 56/5	MDD (g/cm ³) = 1.46
Plunger area (mm ²) = 1935	OMC (%) = 24.3
Ring calib.factor (N/Div) = 22.651	CBR (%) = 3.77

Table G-5 CBR test result for (Soil + 20% fly ash)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		8.44	
0.64		14	317.1	0.16		Final (mm)	16.12
1.27		17	385.1	0.20		Difference (mm)	7.68
1.91		19	430.4	0.22		Swell (%)	6.60
2.54	6.9	22	498.3	0.26	3.77		
3.18		24	543.6	0.28			
3.81		26	588.9	0.30			
4.45		28	634.2	0.33			
5.08	10.3	30	679.5	0.35	3.40		
6.35		32	724.8	0.37			
7.62		34	770.1	0.40			

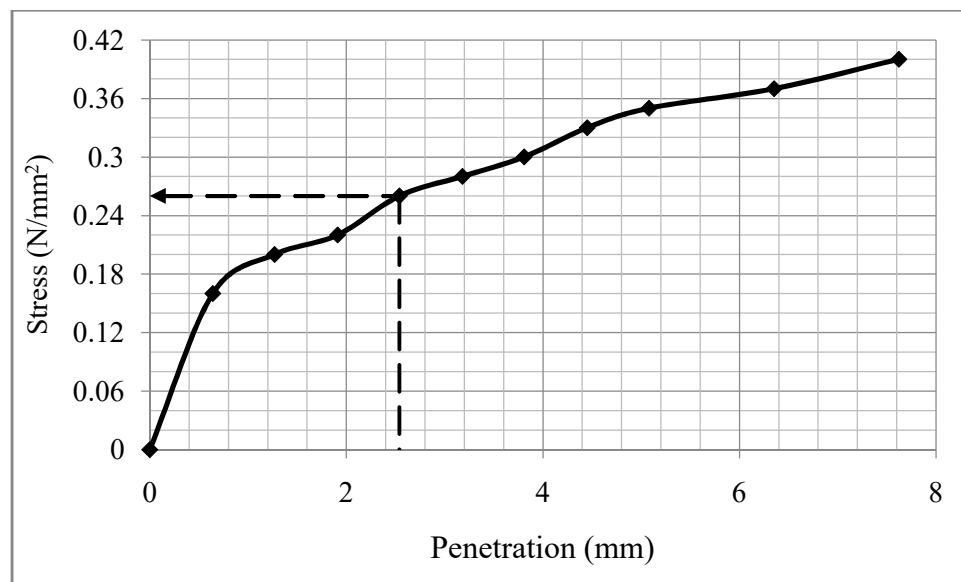


Figure G-5 CBR stress-penetration curve for soil + 20% fly ash

CBR test results for soil treated with 20% fly ash & varying percentage of enset fiber

Blow/Layer = 56/5	MDD (g/cm ³) = 1.44
Plunger area (mm ²) = 1935	OMC (%) = 27
Ring calib.factor (N/Div) = 22.651	CBR (%) = 4.06

Table G-6 CBR test result for (Soil + 20% FA + 0.5% EF, 15mm)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		4.32	
0.64		13	294.5	0.15		Final (mm)	11.5
1.27		16	362.4	0.19		Difference (mm)	7.18
1.91		20	453.0	0.23		Swell (%)	6.17
2.54	6.9	24	543.6	0.28	4.06		
3.18		27	611.6	0.32			
3.81		30	679.5	0.35			
4.45		32	724.8	0.37			
5.08	10.3	34	770.1	0.40	3.88		
6.35		37	838.1	0.43			
7.62		40	906.0	0.47			

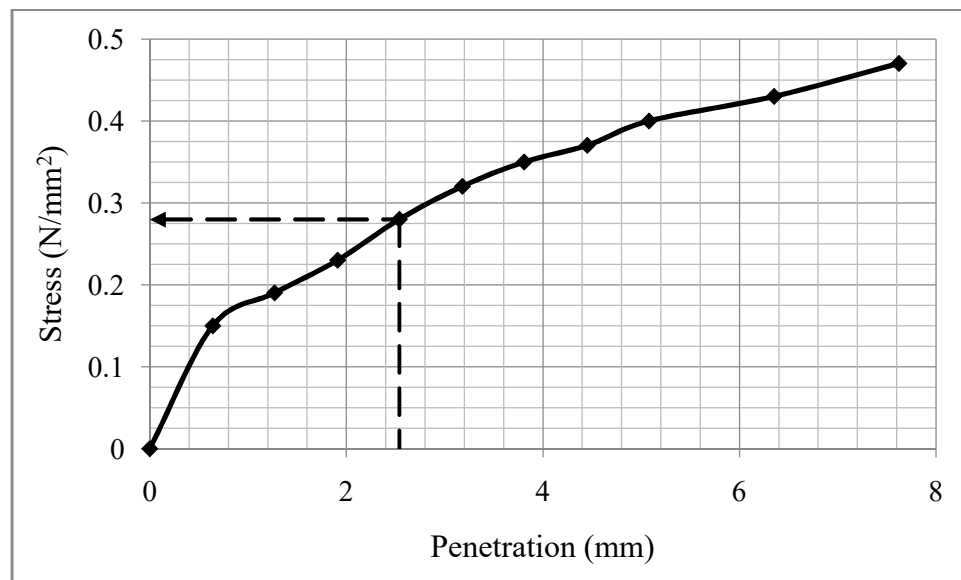


Figure G-6 CBR stress-penetration curve for soil + 20% FA + 0.5% EF, 15mm length

Blow/Layer = 56/5	MDD (g/cm ³) = 1.41
Plunger area (mm ²) = 1935	OMC (%) = 28.4
Ring calib.factor (N/Div) = 22.651	CBR (%) = 5.22

Table G-7 CBR test result for (Soil + 20% FA + 1.0% EF, 15mm)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		1.6	
0.64		16	362.4	0.19		7.48	
1.27		21	475.7	0.25		Difference (mm)	5.88
1.91		25	566.3	0.29		Swell (%)	5.05
2.54	6.9	31	702.2	0.36	5.22		
3.18		35	792.8	0.41			
3.81		38	860.7	0.44			
4.45		42	951.3	0.49			
5.08	10.3	45	1019.3	0.53	5.15		
6.35		48	1087.2	0.56			
7.62		52	1177.9	0.61			

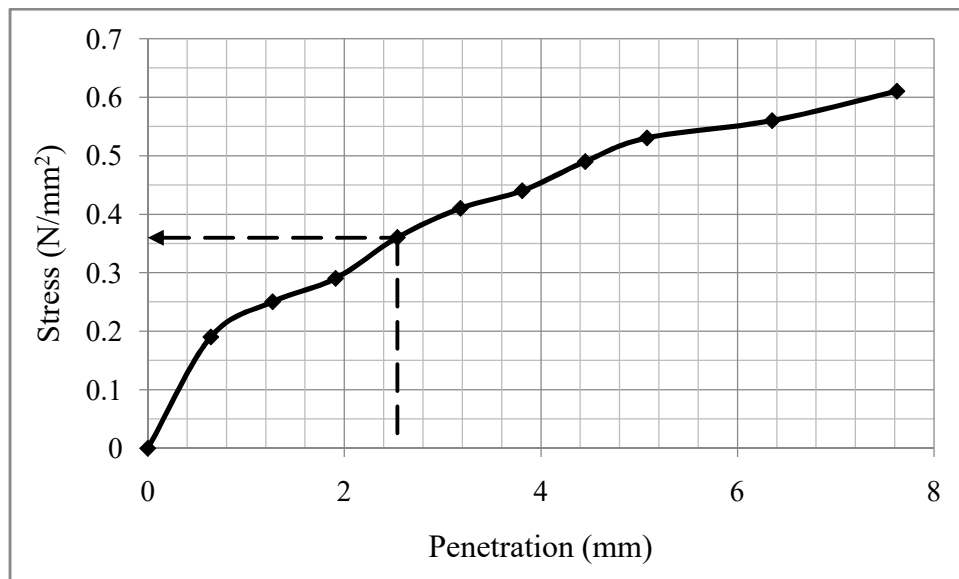


Figure G-7 CBR stress-penetration curve for soil + 20% FA + 1.0% EF, 15mm length

Blow/Layer = 56/5	MDD (g/cm ³) = 1.381
Plunger area (mm ²) = 1935	OMC (%) = 31.2
Ring calib.factor (N/Div) = 22.651	CBR (%) = 6.38

Table G-8 CBR test result for (Soil + 20% FA + 1.5% EF, 20mm kerosene coated fiber)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		9.46	
0.64		18	407.7	0.21		13.33	
1.27		25	566.3	0.29			
1.91		31	702.2	0.36			
2.54	6.9	38	860.7	0.44	6.38		
3.18		43	974.0	0.50			
3.81		47	1064.6	0.55			
4.45		51	1155.2	0.60			
5.08	10.3	55	1245.8	0.64	6.21		
6.35		59	1336.4	0.69			
7.62		64	1449.7	0.75			

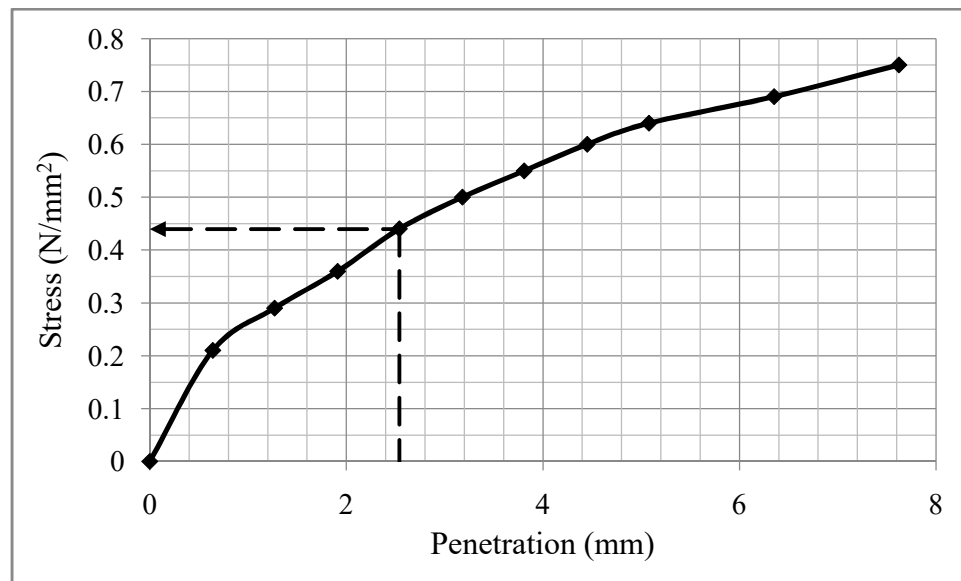


Figure G-8 CBR stress-penetration curve for soil + 20% FA + 1.5% coated EF, 20mm length

Blow/Layer = 56/5	MDD (g/cm ³) = 1.377
Plunger area (mm ²) = 1935	OMC (%) = 32.8
Ring calib.factor (N/Div) = 22.651	CBR (%) = 5.94

Table G- 9 CBR test result for (Soil + 20% FA + 1.5% EF, 20mm uncoated fiber)

CBR Data						Swell Data	
Penetration (mm)	Standard stress (N/mm ²)	Gauge Div	Load (N)	Stress (N/mm ²)	CBR (%)	Initial (mm)	
0		0	0	0		7.35	
0.64		19	430.4	0.22		Final (mm)	12.15
1.27		26	588.9	0.30		Difference (mm)	4.8
1.91		31	702.2	0.36		Swell (%)	4.12
2.54	6.9	35	792.8	0.41	5.94		
3.18		39	883.4	0.46			
3.81		43	974.0	0.50			
4.45		48	1087.2	0.56			
5.08	10.3	51	1155.2	0.60	5.83		
6.35		55	1245.8	0.64			
7.62		59	1336.4	0.69			

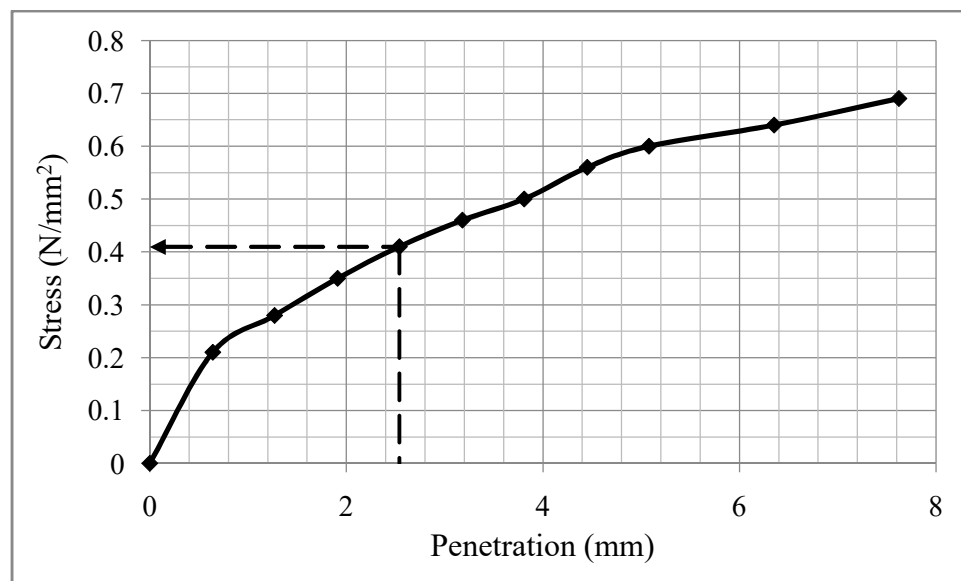


Figure G-9 CBR stress-penetration curve for soil + 20% FA + 1.5% uncoated EF, 20mm length

Appendix H - Unconfined compressive strength (UCS) test result

The following data shown in the table below are the same for all UCS tests conducted in this study.

Data those are common for all UCS test

Initial height of sample ΔH (cm)	7.6
Initial diameter of sample (cm)	3.8
Initial area (m^2)	0.00113
Initial volume (cm^3)	86.19
Rate of strain (mm/min)	1

Table H-1 UCS test result for TP-1

TP-1 (km 25+100)			Moisture content determination		
Weight (g) = 163.23			Wt of container (g)	18.21	
Volume (cm^3) = 86.19			Wt of container + wet soil (g)	109.63	
Bulk density (g/cm^3) = 1.89			Wt of container + dry soil (g)	91.58	
Moisture content (%) = 24.8			Wt of water (g)	18.05	
Dry density (g/cm^3) = 1.52			Wt of dry soil (g)	73.37	
			Moisture content (%)	24.60	
Sample Deformation ΔH (mm)	Strain $\epsilon = (\Delta H/H)$	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\epsilon)$ [m^2]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.00772	6.79
0.4	0.0053	0.526	0.001140	0.01295	11.36
0.6	0.0079	0.789	0.001143	0.01835	16.05
0.8	0.0105	1.053	0.001146	0.02338	20.40
1	0.0132	1.316	0.001149	0.02612	22.73
1.2	0.0158	1.579	0.001152	0.0292	25.34
1.4	0.0184	1.842	0.001155	0.03334	28.86
1.6	0.0211	2.105	0.001159	0.04251	36.69
1.8	0.0237	2.368	0.001162	0.05347	46.03
2	0.0263	2.632	0.001165	0.06312	54.19
2.2	0.0289	2.895	0.001168	0.07544	64.59
2.4	0.0316	3.158	0.001171	0.08664	73.98
2.6	0.0342	3.421	0.001174	0.09901	84.31
2.8	0.0368	3.684	0.001177	0.11136	94.57
3	0.0395	3.947	0.001181	0.12096	102.45
3.2	0.0421	4.211	0.001184	0.13188	111.39

3.4	0.0447	4.474	0.001187	0.1394	117.42
3.6	0.0474	4.737	0.001191	0.14858	124.80
3.8	0.0500	5.000	0.001194	0.15431	129.26
4	0.0526	5.263	0.001197	0.16008	133.72
4.2	0.0553	5.526	0.001200	0.16386	136.50
4.4	0.0579	5.789	0.001204	0.1644	136.57
4.6	0.0605	6.053	0.001207	0.16224	134.40
4.8	0.0632	6.316	0.001211	0.16022	132.35
5	0.0658	6.579	0.001214	0.15842	130.50

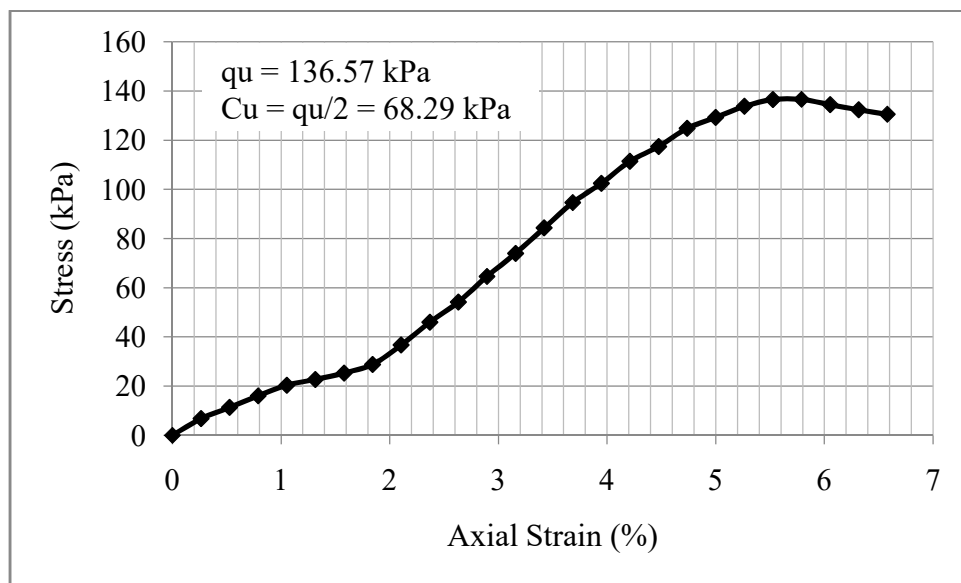


Figure H-1 UCS stress-strain curve for TP-1

Table H-2 UCS test result for TP-2

TP-2 (km 25+900)			Moisture content determination		
Weight (g) = 163.45			Wt of container (g)	17.58	
Volume (cm³) = 86.19			Wt of container + wet soil (g)	112.45	
Bulk density (g/cm³) = 1.9			Wt of container + dry soil (g)	95.21	
Moisture content (%) = 22.5			Wt of water (g)	17.24	
Dry density (g/cm³) = 1.55			Wt of dry soil (g)	77.63	
			Moisture content (%)	22.21	
Sample			Corrected Area		
Deformation	Strain	Axial	Ac =Ao/(1-ε)	Load	Stress
ΔH (mm)	ε = (ΔH/H)	Strain (%)	[m²]	[kN]	[kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.00961	8.45
0.4	0.0053	0.526	0.001140	0.01484	13.02
0.6	0.0079	0.789	0.001143	0.02024	17.71
0.8	0.0105	1.053	0.001146	0.02527	22.05
1	0.0132	1.316	0.001149	0.02801	24.37
1.2	0.0158	1.579	0.001152	0.03109	26.98
1.4	0.0184	1.842	0.001155	0.03423	29.63
1.6	0.0211	2.105	0.001159	0.04001	34.54
1.8	0.0237	2.368	0.001162	0.04922	42.37
2	0.0263	2.632	0.001165	0.05814	49.92
2.2	0.0289	2.895	0.001168	0.06715	57.50
2.4	0.0316	3.158	0.001171	0.07519	64.20
2.6	0.0342	3.421	0.001174	0.08616	73.37
2.8	0.0368	3.684	0.001177	0.09717	82.52
3	0.0395	3.947	0.001181	0.10342	87.59
3.2	0.0421	4.211	0.001184	0.11361	95.96
3.4	0.0447	4.474	0.001187	0.12013	101.19
3.6	0.0474	4.737	0.001191	0.12985	109.07
3.8	0.0500	5.000	0.001194	0.13404	112.28
4	0.0526	5.263	0.001197	0.13774	115.06
4.2	0.0553	5.526	0.001200	0.14352	119.55
4.4	0.0579	5.789	0.001204	0.1486	123.44
4.6	0.0605	6.053	0.001207	0.15242	126.26
4.8	0.0632	6.316	0.001211	0.15333	126.66
5	0.0658	6.579	0.001214	0.15278	125.85
5.2	0.0684	6.842	0.001217	0.15127	124.26
5.4	0.0711	7.105	0.001221	0.14951	122.46

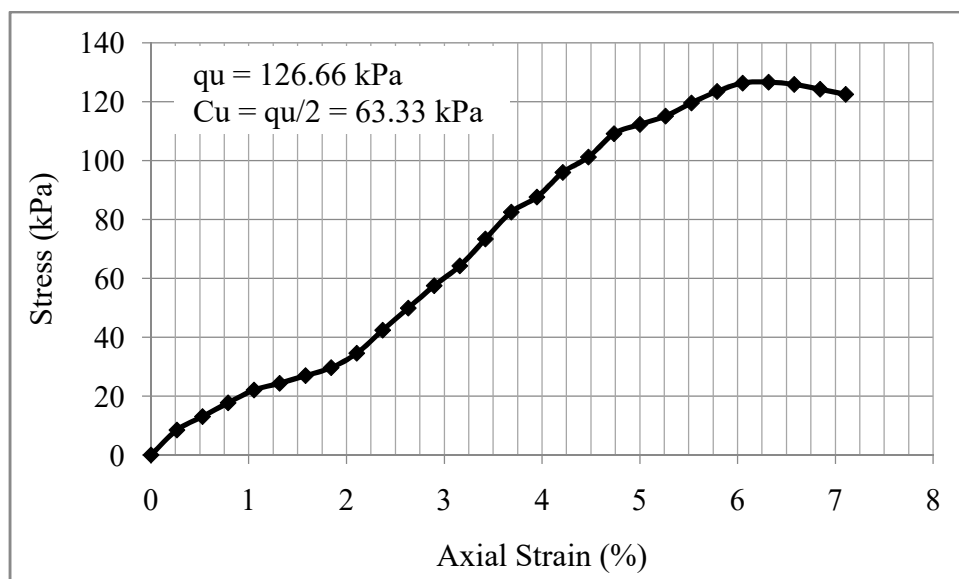


Figure H-2 UCS stress-strain curve for TP-2

UCS test results with varying percentage of fly ash

Table H-3 UCS test result for (Soil + 10% fly ash)

Weight (g) = 158.3			Moisture content (%) = 22.2		
Volume (cm ³) = 86.19			Dry density (g/cm ³) = 1.52		
Bulk density (g/cm ³) = 1.85					
Sample	Strain		Corrected Area		Stress
Deformation	Strain	Axial	Ac = Ao/(1-ε)	Load	
ΔH (mm)	ε = (ΔH/H)	Strain (%)	[m ²]	[kN]	[kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.01391	12.23
0.4	0.0053	0.526	0.001140	0.02097	18.39
0.6	0.0079	0.789	0.001143	0.02657	23.24
0.8	0.0105	1.053	0.001146	0.03289	28.70
1	0.0132	1.316	0.001149	0.03898	33.92
1.2	0.0158	1.579	0.001152	0.04735	41.09
1.4	0.0184	1.842	0.001155	0.05581	48.30
1.6	0.0211	2.105	0.001159	0.06431	55.51
1.8	0.0237	2.368	0.001162	0.07435	64.01
2	0.0263	2.632	0.001165	0.08099	69.53
2.2	0.0289	2.895	0.001168	0.08685	74.36
2.4	0.0316	3.158	0.001171	0.09431	80.53
2.6	0.0342	3.421	0.001174	0.10335	88.01

2.8	0.0368	3.684	0.001177	0.11002	93.44
3	0.0395	3.947	0.001181	0.11629	98.49
3.2	0.0421	4.211	0.001184	0.12182	102.89
3.4	0.0447	4.474	0.001187	0.12883	108.51
3.6	0.0474	4.737	0.001191	0.1369	114.99
3.8	0.0500	5.000	0.001194	0.14434	120.91
4	0.0526	5.263	0.001197	0.15033	125.58
4.2	0.0553	5.526	0.001200	0.15929	132.69
4.4	0.0579	5.789	0.001204	0.16496	137.03
4.6	0.0605	6.053	0.001207	0.16764	138.87
4.8	0.0632	6.316	0.001211	0.16944	139.97
5	0.0658	6.579	0.001214	0.17183	141.54
5.2	0.0684	6.842	0.001217	0.17381	142.77
5.4	0.0711	7.105	0.001221	0.17485	143.22
5.6	0.0737	7.368	0.001224	0.17559	143.42
5.8	0.0763	7.632	0.001228	0.17541	142.86
6	0.0789	7.895	0.001231	0.17401	141.32

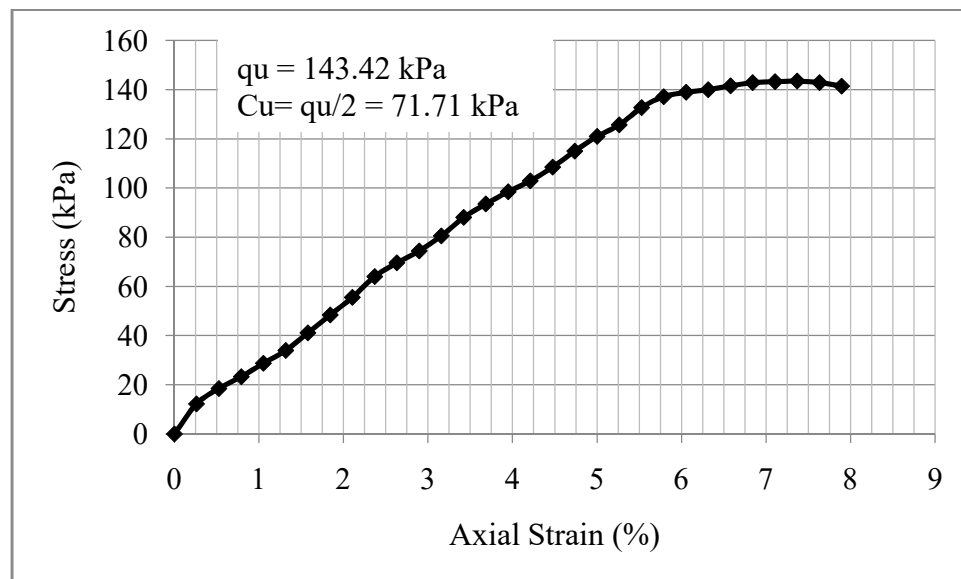


Figure H-3 UCS stress-strain curve for soil + 10% fly ash

Table H-4 UCS test result for (Soil + 20% fly ash)

Weight (g) = 157.4			Moisture content (%) = 24.3		
Volume (cm³) = 86.19			Dry density (g/cm³) = 1.47		
Bulk density (g/cm³) = 1.83					
Sample		Corrected Area			
Deformation	Strain	Axial	Ac = Ao/(1-ε)	Load	Stress
ΔH (mm)	ε = (ΔH/H)	Strain (%)	[m²]	[kN]	[kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.02923	25.71
0.4	0.0053	0.526	0.001140	0.03776	33.12
0.6	0.0079	0.789	0.001143	0.04572	40.00
0.8	0.0105	1.053	0.001146	0.05828	50.85
1	0.0132	1.316	0.001149	0.06927	60.27
1.2	0.0158	1.579	0.001152	0.08084	70.15
1.4	0.0184	1.842	0.001155	0.09163	79.31
1.6	0.0211	2.105	0.001159	0.10458	90.27
1.8	0.0237	2.368	0.001162	0.11753	101.18
2	0.0263	2.632	0.001165	0.12887	110.64
2.2	0.0289	2.895	0.001168	0.14182	121.43
2.4	0.0316	3.158	0.001171	0.15423	131.70
2.6	0.0342	3.421	0.001174	0.16664	141.91
2.8	0.0368	3.684	0.001177	0.1769	150.23
3	0.0395	3.947	0.001181	0.18607	157.59
3.2	0.0421	4.211	0.001184	0.19308	163.08
3.4	0.0447	4.474	0.001187	0.19897	167.59
3.6	0.0474	4.737	0.001191	0.20568	172.77
3.8	0.0500	5.000	0.001194	0.2122	177.75
4	0.0526	5.263	0.001197	0.2095	175.00
4.2	0.0553	5.526	0.001200	0.20588	171.50

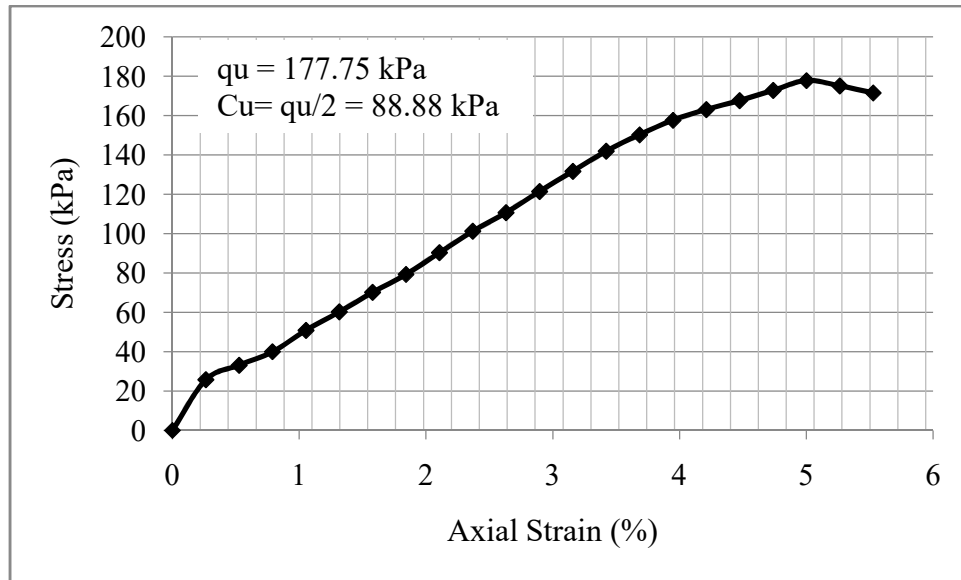


Figure H-4 UCS stress-strain curve for soil + 20% fly ash

Table H-5 UCS test result for (Soil + 25% fly ash)

Weight (g) = 154.6			Moisture content (%) = 26.2		
Volume (cm ³) = 86.19			Dry density (g/cm ³) = 1.43		
Bulk density (g/cm ³) = 1.81					
Sample Deformation ΔH (mm)	Strain $\epsilon = (\Delta H/H)$	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\epsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0.00
0.2	0.0026	0.263	0.001137	0.01878	16.52
0.4	0.0053	0.526	0.001140	0.02736	24.00
0.6	0.0079	0.789	0.001143	0.03361	29.40
0.8	0.0105	1.053	0.001146	0.03885	33.90
1	0.0132	1.316	0.001149	0.0481	41.85
1.2	0.0158	1.579	0.001152	0.05788	50.23
1.4	0.0184	1.842	0.001155	0.06695	57.95
1.6	0.0211	2.105	0.001159	0.07272	62.77
1.8	0.0237	2.368	0.001162	0.0846	72.83
2	0.0263	2.632	0.001165	0.09647	82.82
2.2	0.0289	2.895	0.001168	0.10942	93.69
2.4	0.0316	3.158	0.001171	0.12237	104.49
2.6	0.0342	3.421	0.001174	0.13478	114.78
2.8	0.0368	3.684	0.001177	0.14504	123.18
3	0.0395	3.947	0.001181	0.15413	130.54

3.2	0.0421	4.211	0.001184	0.16522	139.55
3.4	0.0447	4.474	0.001187	0.17396	146.53
3.6	0.0474	4.737	0.001191	0.18135	152.33
3.8	0.0500	5.000	0.001194	0.18834	157.76
4	0.0526	5.263	0.001197	0.19577	163.53
4.2	0.0553	5.526	0.001200	0.20094	167.39
4.4	0.0579	5.789	0.001204	0.19881	165.15
4.6	0.0605	6.053	0.001207	0.19532	161.80

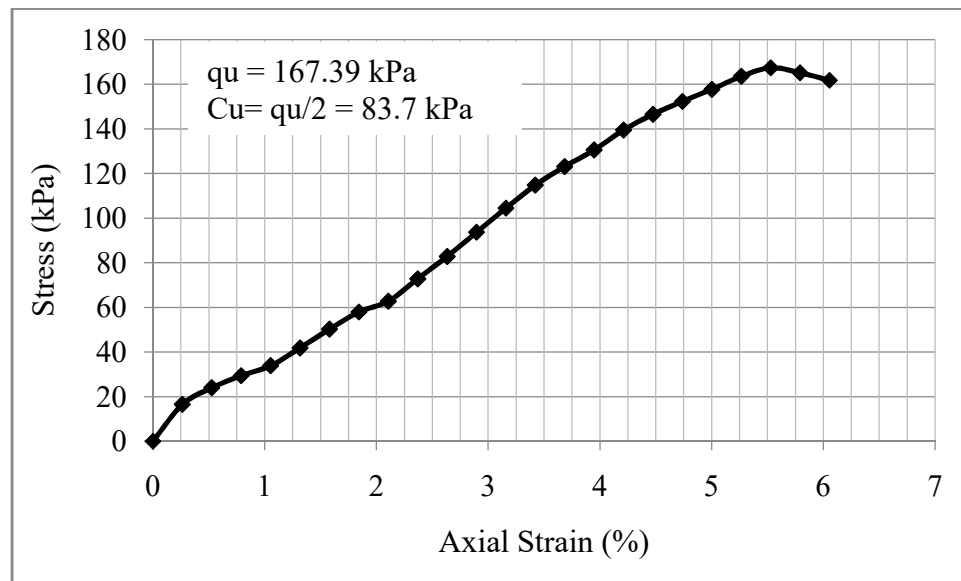


Figure H-5 UCS stress-strain curve for soil + 25% fly ash

UCS test results for soil treated with 20% fly ash & varying percentage of enset fiber

Table H-6 UCS test result for (Soil + 20% FA + 0.5% EF, 15mm)

Weight (g) = 156.1			Moisture content (%) = 27.8		
Volume (cm³) = 86.19			Dry density (g/cm³) = 1.42		
Bulk density (g/cm³) = 1.81					
Sample Deformation ΔH (mm)	Strain ε = (ΔH/H)	Axial Strain (%)	Corrected Area Ac = Ao/(1-ε) [m²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.03018	26.54
0.4	0.0053	0.526	0.001140	0.04026	35.31
0.6	0.0079	0.789	0.001143	0.05255	45.97
0.8	0.0105	1.053	0.001146	0.06229	54.35
1	0.0132	1.316	0.001149	0.07334	63.82
1.2	0.0158	1.579	0.001152	0.08276	71.82
1.4	0.0184	1.842	0.001155	0.09313	80.60
1.6	0.0211	2.105	0.001159	0.10457	90.26
1.8	0.0237	2.368	0.001162	0.11479	98.82
2	0.0263	2.632	0.001165	0.12333	105.88
2.2	0.0289	2.895	0.001168	0.13237	113.34
2.4	0.0316	3.158	0.001171	0.14273	121.88
2.6	0.0342	3.421	0.001174	0.15162	129.12
2.8	0.0368	3.684	0.001177	0.15956	135.51
3	0.0395	3.947	0.001181	0.16721	141.62
3.2	0.0421	4.211	0.001184	0.17368	146.69
3.4	0.0447	4.474	0.001187	0.18022	151.80
3.6	0.0474	4.737	0.001191	0.18775	157.71
3.8	0.0500	5.000	0.001194	0.196	164.18
4	0.0526	5.263	0.001197	0.20219	168.90
4.2	0.0553	5.526	0.001200	0.20885	173.98
4.4	0.0579	5.789	0.001204	0.21266	176.66
4.6	0.0605	6.053	0.001207	0.21613	179.04
4.8	0.0632	6.316	0.001211	0.2191	180.99
5	0.0658	6.579	0.001214	0.22119	182.20
5.2	0.0684	6.842	0.001217	0.22322	183.36
5.4	0.0711	7.105	0.001221	0.22482	184.15
5.6	0.0737	7.368	0.001224	0.2224	181.65
5.8	0.0763	7.632	0.001228	0.21986	179.07

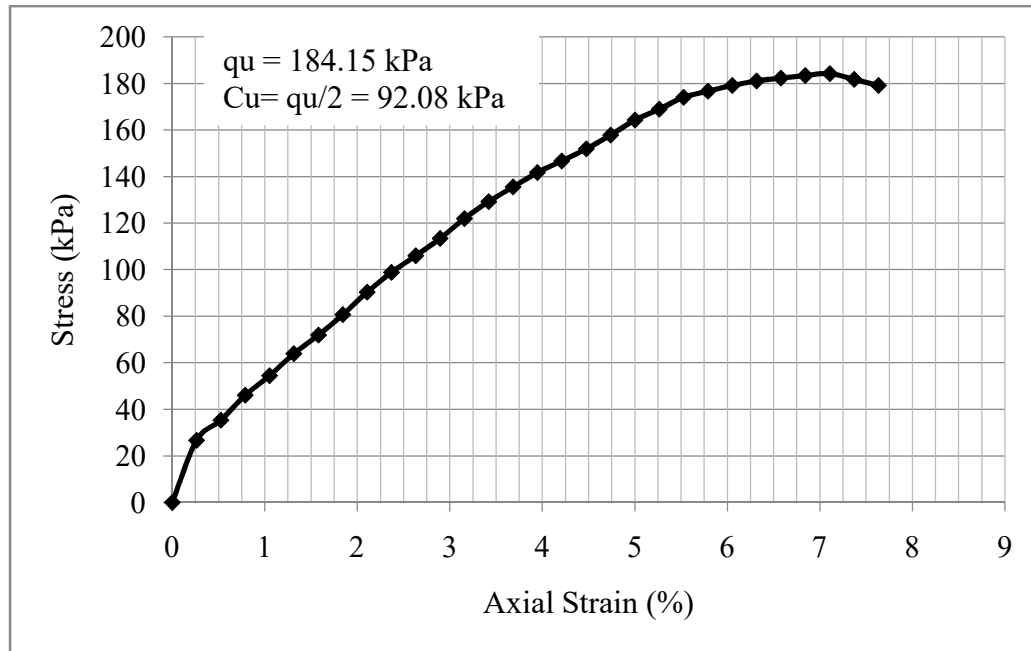


Figure H-6 UCS stress-strain curve for soil + 20% FA + 0.5% EF, 15mm length

Table H-7 UCS test result for (Soil + 20% FA + 1.5% EF, 15mm)

Weight (g) = 155.4			Moisture content (%) = 30		
Volume (cm ³) = 86.19			Dry density (g/cm ³) = 1.39		
Bulk density (g/cm ³) = 1.8					
Sample Deformation ΔH (mm)	Strain $\epsilon = (\Delta H/H)$	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\epsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.02247	19.76
0.4	0.0053	0.526	0.001140	0.03063	26.87
0.6	0.0079	0.789	0.001143	0.03784	33.10
0.8	0.0105	1.053	0.001146	0.04415	38.52
1	0.0132	1.316	0.001149	0.05036	43.82
1.2	0.0158	1.579	0.001152	0.05594	48.55
1.4	0.0184	1.842	0.001155	0.06349	54.95
1.6	0.0211	2.105	0.001159	0.06781	58.53
1.8	0.0237	2.368	0.001162	0.07645	65.81
2	0.0263	2.632	0.001165	0.08346	71.65
2.5	0.0329	3.289	0.001173	0.09998	85.26
3	0.0395	3.947	0.001181	0.11725	99.30
3.5	0.0461	4.605	0.001189	0.1356	114.06
4	0.0526	5.263	0.001197	0.15177	126.78

4.5	0.0592	5.921	0.001205	0.16647	138.09
5	0.0658	6.579	0.001214	0.17889	147.36
5.5	0.0724	7.237	0.001223	0.19667	160.86
6	0.0789	7.895	0.001231	0.21193	172.12
6.5	0.0855	8.553	0.001240	0.22586	182.12
7	0.0921	9.211	0.001249	0.23976	191.94
7.5	0.0987	9.868	0.001258	0.2501	198.76
8	0.1053	10.526	0.001268	0.25495	201.14
8.5	0.1118	11.184	0.001277	0.25926	203.03
9	0.1184	11.842	0.001286	0.26296	204.41
9.5	0.1250	12.500	0.001296	0.26849	207.15
10	0.1316	13.158	0.001306	0.27327	209.25
10.5	0.1382	13.816	0.001316	0.27698	210.48
11	0.1447	14.474	0.001326	0.28077	211.74
11.5	0.1513	15.132	0.001336	0.28345	212.11
12	0.1579	15.789	0.001347	0.28594	212.32
12.5	0.1645	16.447	0.001357	0.2881	212.25
13	0.1711	17.105	0.001368	0.29026	212.16
13.5	0.1776	17.763	0.001379	0.29188	211.65
14	0.1842	18.421	0.001390	0.2935	211.12

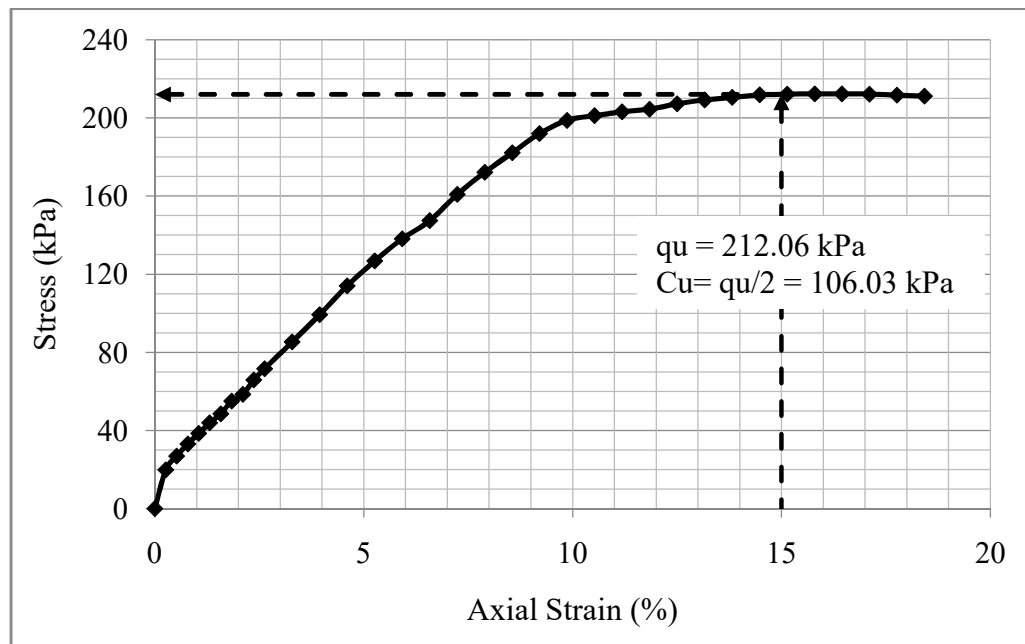


Figure H-7 UCS stress-strain curve for soil + 20% FA + 1.5% EF, 15mm length

Table H-8 UCS test result for (Soil + 20% FA + 2.0% EF, 15mm)

Sample Deformation ΔH (mm)	Strain $\varepsilon =$ ($\Delta H/H$)	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\varepsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.01974	17.36
0.4	0.0053	0.526	0.001140	0.026	22.80
0.6	0.0079	0.789	0.001143	0.03221	28.18
0.8	0.0105	1.053	0.001146	0.03909	34.10
1	0.0132	1.316	0.001149	0.04797	41.74
1.2	0.0158	1.579	0.001152	0.05645	48.99
1.4	0.0184	1.842	0.001155	0.06381	55.23
1.6	0.0211	2.105	0.001159	0.07324	63.22
1.8	0.0237	2.368	0.001162	0.08074	69.51
2	0.0263	2.632	0.001165	0.08661	74.36
2.5	0.0329	3.289	0.001173	0.09988	85.17
3	0.0395	3.947	0.001181	0.10852	91.91
3.5	0.0461	4.605	0.001189	0.12128	102.01
4	0.0526	5.263	0.001197	0.13262	110.78
4.5	0.0592	5.921	0.001205	0.14611	121.20
5	0.0658	6.579	0.001214	0.15852	130.58
5.5	0.0724	7.237	0.001223	0.17039	139.37
6	0.0789	7.895	0.001231	0.18335	148.90
6.5	0.0855	8.553	0.001240	0.1936	156.11
7	0.0921	9.211	0.001249	0.20277	162.32
7.5	0.0987	9.868	0.001258	0.21033	167.16
8	0.1053	10.526	0.001268	0.21842	172.32
8.5	0.1118	11.184	0.001277	0.22598	176.97
9	0.1184	11.842	0.001286	0.23246	180.70
9.5	0.1250	12.500	0.001296	0.23893	184.34
10	0.1316	13.158	0.001306	0.24487	187.50
10.5	0.1382	13.816	0.001316	0.2508	190.59
11	0.1447	14.474	0.001326	0.25512	192.39
11.5	0.1513	15.132	0.001336	0.26268	196.57
12	0.1579	15.789	0.001347	0.2686	199.44
12.5	0.1645	16.447	0.001357	0.27455	202.27
13	0.1711	17.105	0.001368	0.28157	205.81
13.5	0.1776	17.763	0.001379	0.28858	209.26
14	0.1842	18.421	0.001390	0.2956	212.63

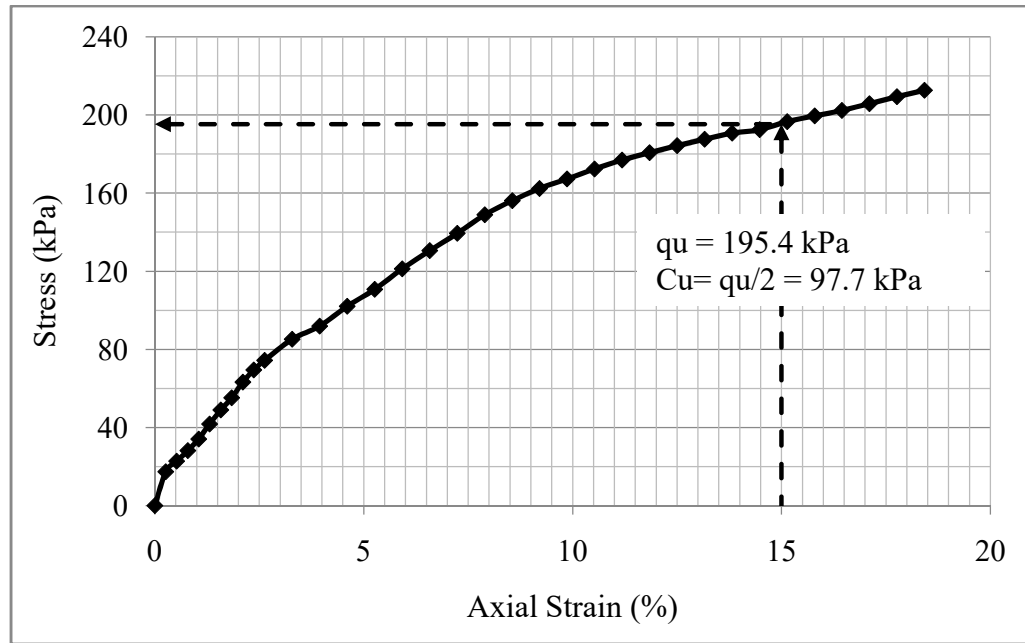


Figure H-8 UCS stress-strain curve for soil + 20% FA + 2.0% EF, 15mm length

Table H-9 UCS test result for (Soil + 20% FA + 0.5% EF, 20mm)

Weight (g) = 155.8			Moisture content (%) = 28.4		
Volume (cm³) = 86.19			Dry density (g/cm³) = 1.41		
Bulk density (g/cm³) = 1.81					
Sample Deformation ΔH (mm)	Strain ε = (ΔH/H)	Axial Strain (%)	Corrected Area Ac = Ao/(1-ε) [m²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.03067	26.97
0.4	0.0053	0.526	0.001140	0.04156	36.45
0.6	0.0079	0.789	0.001143	0.05181	45.32
0.8	0.0105	1.053	0.001146	0.0624	54.44
1	0.0132	1.316	0.001149	0.07441	64.75
1.2	0.0158	1.579	0.001152	0.08333	72.32
1.4	0.0184	1.842	0.001155	0.09257	80.12
1.6	0.0211	2.105	0.001159	0.10095	87.14
1.8	0.0237	2.368	0.001162	0.10998	94.68
2	0.0263	2.632	0.001165	0.11884	102.03
2.2	0.0289	2.895	0.001168	0.12911	110.55
2.4	0.0316	3.158	0.001171	0.13814	117.96
2.6	0.0342	3.421	0.001174	0.14886	126.77
2.8	0.0368	3.684	0.001177	0.15645	132.87

3	0.0395	3.947	0.001181	0.16431	139.16
3.2	0.0421	4.211	0.001184	0.17227	145.50
3.4	0.0447	4.474	0.001187	0.17879	150.59
3.6	0.0474	4.737	0.001191	0.18614	156.35
3.8	0.0500	5.000	0.001194	0.19388	162.41
4	0.0526	5.263	0.001197	0.20036	167.37
4.2	0.0553	5.526	0.001200	0.20763	172.96
4.4	0.0579	5.789	0.001204	0.21277	176.75
4.6	0.0605	6.053	0.001207	0.21651	179.35
4.8	0.0632	6.316	0.001211	0.21943	181.26
5	0.0658	6.579	0.001214	0.22158	182.52
5.2	0.0684	6.842	0.001217	0.22356	183.64
5.4	0.0711	7.105	0.001221	0.22534	184.57
5.6	0.0737	7.368	0.001224	0.22778	186.04
5.8	0.0763	7.632	0.001228	0.22946	186.88
6	0.0789	7.895	0.001231	0.23149	188.00
6.2	0.0816	8.158	0.001235	0.23224	188.07
6.4	0.0842	8.421	0.001238	0.23132	186.79

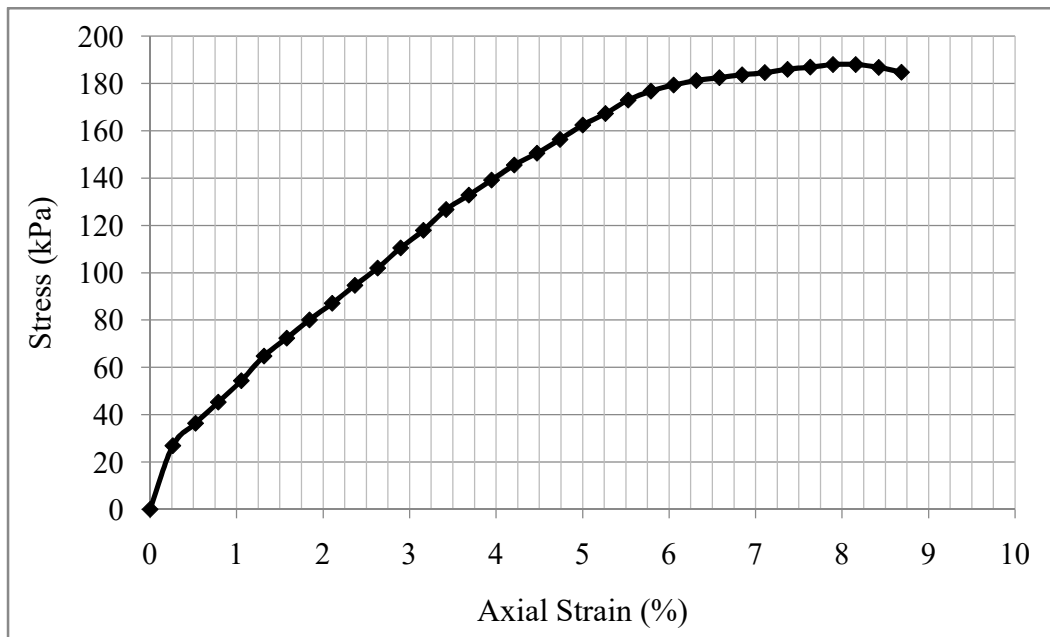


Figure H-9 UCS stress-strain curve for soil + 20% FA + 0.5% EF, 20mm length

Table H-10 UCS test result for (Soil + 20% FA + 1.0% EF, 20mm)

Sample Deformation ΔH (mm)	Strain $\varepsilon =$ ($\Delta H/H$)	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\varepsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.02046	17.99
0.4	0.0053	0.526	0.001140	0.02839	24.90
0.6	0.0079	0.789	0.001143	0.03536	30.93
0.8	0.0105	1.053	0.001146	0.04168	36.36
1	0.0132	1.316	0.001149	0.04777	41.57
1.2	0.0158	1.579	0.001152	0.05441	47.22
1.4	0.0184	1.842	0.001155	0.06035	52.23
1.6	0.0211	2.105	0.001159	0.06575	56.75
1.8	0.0237	2.368	0.001162	0.07384	63.57
2	0.0263	2.632	0.001165	0.0825	70.83
2.5	0.0329	3.289	0.001173	0.09883	84.28
3	0.0395	3.947	0.001181	0.11833	100.22
3.5	0.0461	4.605	0.001189	0.13755	115.70
4	0.0526	5.263	0.001197	0.15296	127.77
4.5	0.0592	5.921	0.001205	0.16727	138.76
5	0.0658	6.579	0.001214	0.18053	148.71
5.5	0.0724	7.237	0.001223	0.19519	159.65
6	0.0789	7.895	0.001231	0.21044	170.91
6.5	0.0855	8.553	0.001240	0.22429	180.85
7	0.0921	9.211	0.001249	0.23678	189.55
7.5	0.0987	9.868	0.001258	0.24737	196.59
8	0.1053	10.526	0.001268	0.25204	198.84
8.5	0.1118	11.184	0.001277	0.25609	200.55
9	0.1184	11.842	0.001286	0.25933	201.58
9.5	0.1250	12.500	0.001296	0.26257	202.58
10	0.1316	13.158	0.001306	0.26635	203.95
10.5	0.1382	13.816	0.001316	0.26905	204.46
11	0.1447	14.474	0.001326	0.27175	204.93
11.5	0.1513	15.132	0.001336	0.2739	204.97
12	0.1579	15.789	0.001347	0.2766	205.38
12.5	0.1645	16.447	0.001357	0.2793	205.77
13	0.1711	17.105	0.001368	0.28092	205.33
13.5	0.1776	17.763	0.001379	0.28195	204.45
14	0.1842	18.421	0.001390	0.28362	204.01

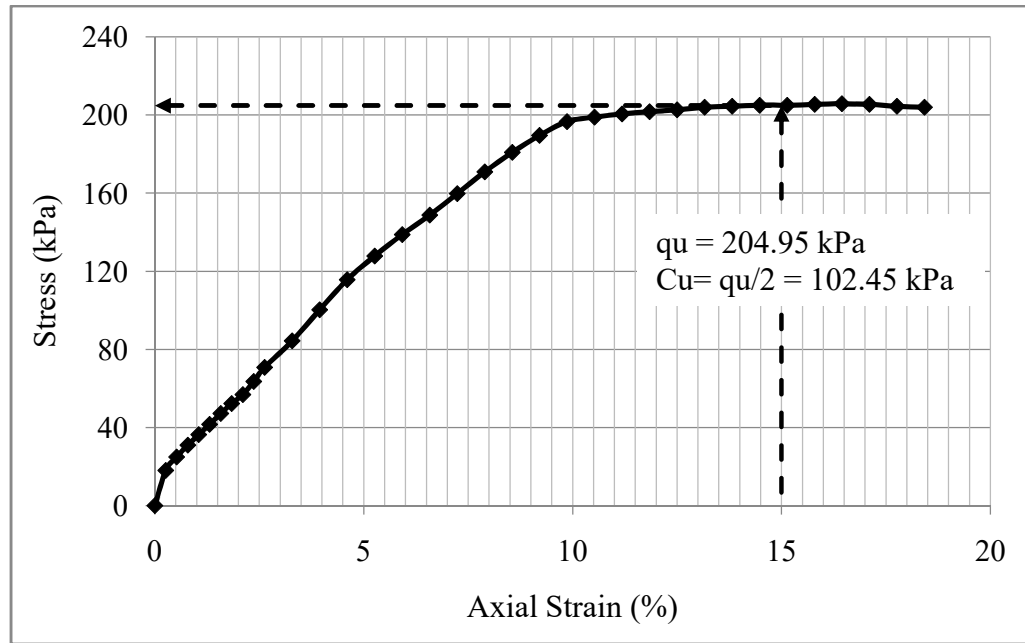


Figure H-10 UCS stress-strain curve for soil + 20% FA + 1.0% EF, 20mm length

Table H-11 UCS test result for (Soil + 20% FA + 1.5% EF, 20mm kerosene coated fiber)

Weight (g) = 155.2			Moisture content (%) = 31		
Volume (cm³) = 86.19			Dry density (g/cm³) = 1.38		
Bulk density (g/cm³) = 1.8					
Sample Deformation ΔH (mm)	Strain ε = (ΔH/H)	Axial Strain (%)	Corrected Area Ac = Ao/(1-ε) [m²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.02509	22.06
0.4	0.0053	0.526	0.001140	0.03143	27.57
0.6	0.0079	0.789	0.001143	0.03947	34.53
0.8	0.0105	1.053	0.001146	0.04648	40.55
1	0.0132	1.316	0.001149	0.05242	45.61
1.2	0.0158	1.579	0.001152	0.05835	50.64
1.4	0.0184	1.842	0.001155	0.06537	56.58
1.6	0.0211	2.105	0.001159	0.07185	62.02
1.8	0.0237	2.368	0.001162	0.0794	68.35
2	0.0263	2.632	0.001165	0.0875	75.12
2.5	0.0329	3.289	0.001173	0.108	92.10
3	0.0395	3.947	0.001181	0.12852	108.85
3.5	0.0461	4.605	0.001189	0.14902	125.35
4	0.0526	5.263	0.001197	0.16845	140.71

4.5	0.0592	5.921	0.001205	0.1868	154.96
5	0.0658	6.579	0.001214	0.20407	168.10
5.5	0.0724	7.237	0.001223	0.21648	177.07
6	0.0789	7.895	0.001231	0.22943	186.33
6.5	0.0855	8.553	0.001240	0.23969	193.27
7	0.0921	9.211	0.001249	0.25032	200.39
7.5	0.0987	9.868	0.001258	0.26042	206.96
8	0.1053	10.526	0.001268	0.26443	208.62
8.5	0.1118	11.184	0.001277	0.27199	213.00
9	0.1184	11.842	0.001286	0.27792	216.04
9.5	0.1250	12.500	0.001296	0.28494	219.84
10	0.1316	13.158	0.001306	0.29088	222.73
10.5	0.1382	13.816	0.001316	0.29681	225.55
11	0.1447	14.474	0.001326	0.30383	229.13
11.5	0.1513	15.132	0.001336	0.31084	232.61
12	0.1579	15.789	0.001347	0.31678	235.22
12.5	0.1645	16.447	0.001357	0.32272	237.75
13	0.1711	17.105	0.001368	0.32919	240.61
13.5	0.1776	17.763	0.001379	0.33621	243.79
14	0.1842	18.421	0.001390	0.34322	246.88

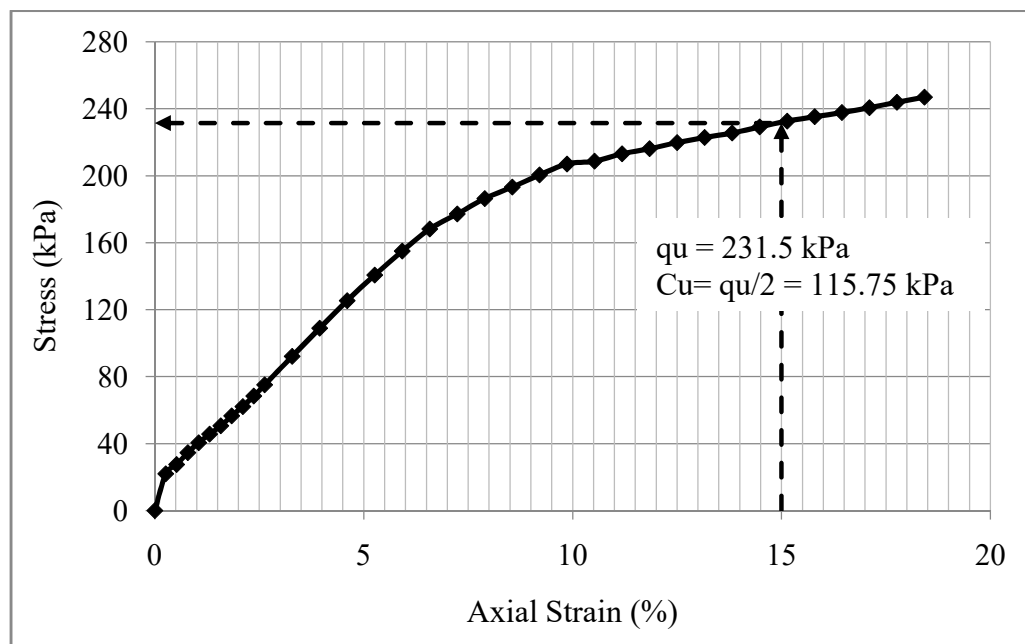


Figure H-11 UCS stress-strain curve for soil + 20% FA + 1.5% coated EF, 20mm length

Table H-12 UCS test result for (Soil + 20% FA + 1.5% EF, 20mm Uncoated fiber)

Sample Deformation ΔH (mm)	Strain $\varepsilon =$ ($\Delta H/H$)	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\varepsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.018369	16.15
0.4	0.0053	0.526	0.001140	0.025108	22.02
0.6	0.0079	0.789	0.001143	0.032012	28.00
0.8	0.0105	1.053	0.001146	0.038399	33.50
1	0.0132	1.316	0.001149	0.045191	39.32
1.2	0.0158	1.579	0.001152	0.050114	43.49
1.4	0.0184	1.842	0.001155	0.057267	49.56
1.6	0.0211	2.105	0.001159	0.064282	55.49
1.8	0.0237	2.368	0.001162	0.070219	60.45
2	0.0263	2.632	0.001165	0.075615	64.92
2.5	0.0329	3.289	0.001173	0.093556	79.78
3	0.0395	3.947	0.001181	0.11197	94.83
3.5	0.0461	4.605	0.001189	0.13438	113.03
4	0.0526	5.263	0.001197	0.15434	128.93
4.5	0.0592	5.921	0.001205	0.17053	141.46
5	0.0658	6.579	0.001214	0.18611	153.31
5.5	0.0724	7.237	0.001223	0.19806	162.00
6	0.0789	7.895	0.001231	0.20931	169.99
6.5	0.0855	8.553	0.001240	0.2191	176.67
7	0.0921	9.211	0.001249	0.2272	181.88
7.5	0.0987	9.868	0.001258	0.23475	186.56
8	0.1053	10.526	0.001268	0.24231	191.17
8.5	0.1118	11.184	0.001277	0.24825	194.41
9	0.1184	11.842	0.001286	0.25472	198.00
9.5	0.1250	12.500	0.001296	0.26382	203.54
10	0.1316	13.158	0.001306	0.270423	207.07
10.5	0.1382	13.816	0.001316	0.27464	208.71
11	0.1447	14.474	0.001326	0.27843	209.97
11.5	0.1513	15.132	0.001336	0.28217	211.15
12	0.1579	15.789	0.001347	0.28413	210.97
12.5	0.1645	16.447	0.001357	0.28737	211.71
13	0.1711	17.105	0.001368	0.28845	210.83
13.5	0.1776	17.763	0.001379	0.29061	210.73
14	0.1842	18.421	0.001390	0.29167	209.80

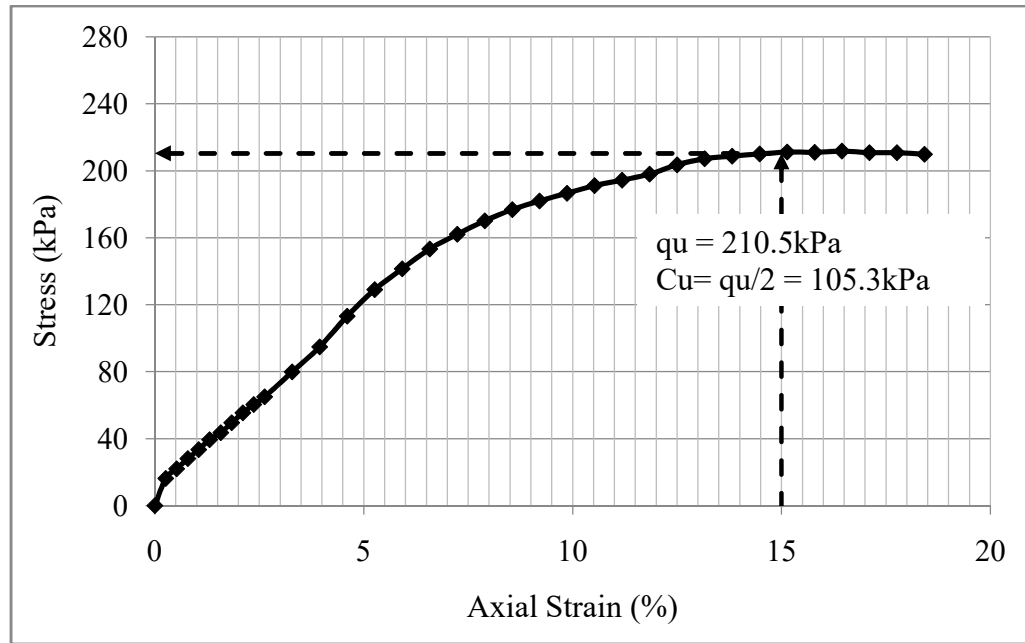


Figure H-12 UCS stress-strain curve for soil + 20% FA + 1.5% uncoated EF, 20mm length

Table H-13 UCS test result for (Soil + 20% FA + 2.0% EF, 20mm)

Sample Deformation ΔH (mm)	Strain $\epsilon = (\Delta H/H)$	Axial Strain (%)	Corrected Area $A_c = A_o/(1-\epsilon)$ [m ²]	Load [kN]	Stress [kPa]
0	0	0	0.001134	0	0
0.2	0.0026	0.263	0.001137	0.02742	24.11
0.4	0.0053	0.526	0.001140	0.03428	30.07
0.6	0.0079	0.789	0.001143	0.04225	36.96
0.8	0.0105	1.053	0.001146	0.0515	44.93
1	0.0132	1.316	0.001149	0.06154	53.55
1.2	0.0158	1.579	0.001152	0.07104	61.65
1.4	0.0184	1.842	0.001155	0.07806	67.56
1.6	0.0211	2.105	0.001159	0.08759	75.61
1.8	0.0237	2.368	0.001162	0.0952	81.95
2	0.0263	2.632	0.001165	0.10024	86.06
2.5	0.0329	3.289	0.001173	0.11426	97.43
3	0.0395	3.947	0.001181	0.12344	104.55
3.5	0.0461	4.605	0.001189	0.13512	113.65
4	0.0526	5.263	0.001197	0.14753	123.24
4.5	0.0592	5.921	0.001205	0.15994	132.68
5	0.0658	6.579	0.001214	0.17397	143.31
5.5	0.0724	7.237	0.001223	0.18584	152.01

6	0.0789	7.895	0.001231	0.19718	160.14
6.5	0.0855	8.553	0.001240	0.20797	167.69
7	0.0921	9.211	0.001249	0.21768	174.26
7.5	0.0987	9.868	0.001258	0.22578	179.43
8	0.1053	10.526	0.001268	0.23333	184.08
8.5	0.1118	11.184	0.001277	0.23927	187.38
9	0.1184	11.842	0.001286	0.24629	191.45
9.5	0.1250	12.500	0.001296	0.2533	195.43
10	0.1316	13.158	0.001306	0.25978	198.92
10.5	0.1382	13.816	0.001316	0.2657	201.91
11	0.1447	14.474	0.001326	0.27057	204.04
11.5	0.1513	15.132	0.001336	0.27705	207.32
12	0.1579	15.789	0.001347	0.28406	210.92
12.5	0.1645	16.447	0.001357	0.28946	213.25
13	0.1711	17.105	0.001368	0.29648	216.70
13.5	0.1776	17.763	0.001379	0.304	220.44
14	0.1842	18.421	0.001390	0.31051	223.36

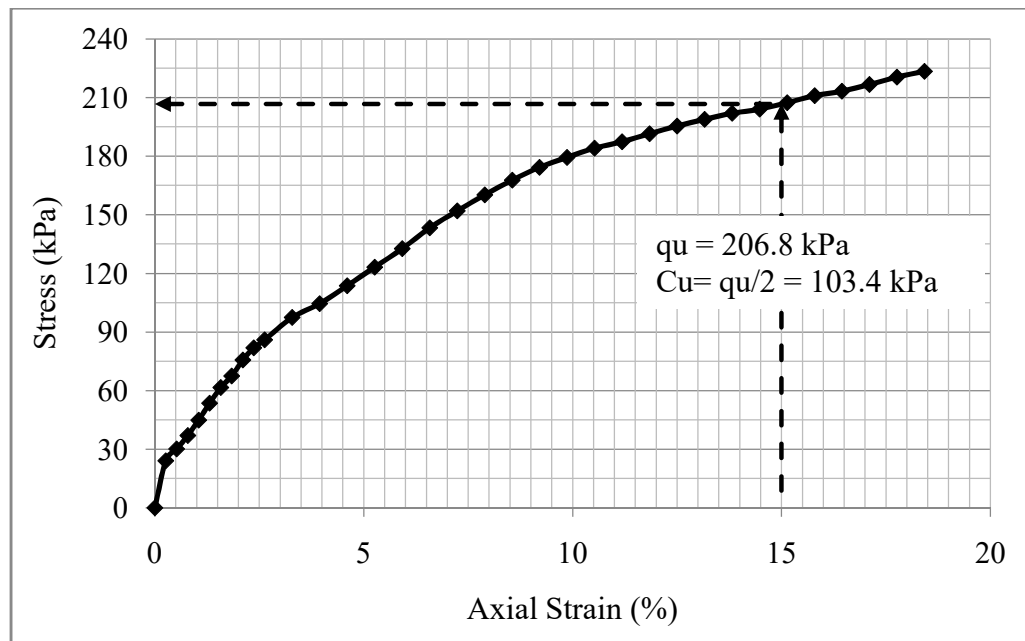


Figure H-13 UCS stress-strain curve for soil + 20% FA + 2.0% EF, 20mm length

Appendix I - Test result for Enset fiber

Table I-1 Specific gravity test result of coated enset fiber

1. Trial No.	1	2
2. Mass of Pycnometer + Enset fiber	56.3	58.5
3. Mass of dry enset fiber	10	10
4. Mass of Pycnometer with full of Water	151.4	153.8
5. Mass of Pycnometer + Enset fiber + Water	151.9	154.4
6. Mass of equal volume of water as the fiber sample, (3+4-5)	9.5	9.4
7. Specific Gravity at 22°C (3/6)	1.05	1.06
8. Conversion factor K	0.9996	0.9996
9. Specific gravity of enset fiber at 20 °c	1.05	1.06
Average Specific Gravity	1.06	

Table I-2 WAC test result for uncoated Enset fiber

Uncoated Enset fiber	
Mass of dry uncoated enset fiber + container (gm)	94.5
Mass of wet uncoated enset fiber + container (gm)	129.2
Mass of water (gm)	34.7
Mass of container (gm)	82.5
Mass of dry uncoated enset fiber (gm)	12
Moisture content (%)	289.2

Table I-3 WAC test result for kerosene coated Enset fiber

Kerosene coated Enset fiber	
Mass of dry kerosene coated enset fiber + container (gm)	96.5
Mass of wet kerosene coated enset fiber + container (gm)	122.1
Mass of water (gm)	25.6
Mass of container (gm)	84
Mass of dry kerosene coated enset fiber (gm)	12.5
Moisture content (%)	204.8