STRENGTH CHARACTERISTICS OF DISPERSIVE SOIL STABILIZED WITH FLY ASH

MOHAMMAD ZIAUL HOQUE

MASTER OF SCIENCE IN CIVIL ENGINEERING
(GEOTECHNICAL)

DEPARTMENT OF CIVIL ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)
DHAKA, BANGLADESH

March, 2022

STRENGTH CHARACTERISTICS OF DISPERSIVE SOIL STABILIZED WITH FLY ASH

By

Mohammad Ziaul Hoque

A Thesis Submitted to the Department of Civil Engineering in Partial Fulfillment of the Requirement for the Degree of Master of Science in Civil Engineering (Geotechnical)

DEPARTMENT OF CIVIL ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)

March, 2022

Dedicated

To

My Family Members and Supervisor for

Their Endless Inspiration

The thesis/project titled "Strength Characteristics of Dispersive Soil Stabilized with Fly Ash" submitted by Mohammad Ziaul Hoque, Roll No.: 1015042216, Session: October 2015, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Geotechnical) on March 5, 2022.

BOARD OF EXAMINERS

Dr. Mohammad Shariful Islam
Professor
Department of Civil Engineering
BUET, Dhaka-1000

Chairman
(Supervisor)

Dr. Md. Delwar Hossain
Professor and Head
Department of Civil Engineering
BUET, Dhaka-1000

Member
(Ex- officio)

Dr. Mohammed Kabirul Islam
Professor
Department of Civil Engineering
BUET, Dhaka-1000

Member

Brig Gen Md Moin Uddin
Project Director
24 Engineer Construction Brigade
Dhaka Cantonment, Bangladesh Army

Member
(External)

DECLARATION

It is hereby declared that this thesis has been composed solely by the author, and that it has not been submitted in whole or in part for the award of any degree (except for publication). Apart from where states otherwise by reference or acknowledgment, the work presented is entirely by the author.

Mohammad Ziaul Hoque
Student ID: 1015042216

ACKNOWLEDGEMENT

All praise to Almighty ALLAH for allowing me to complete my thesis work successfully and efficiently. It is indeed a huge blessing from Him to provide me with courage, opportunity, determination, and strength to complete my thesis work effectively.

I would like to express my heartfelt thanks and gratitude to my respected supervisor, Dr. Mohammad Shariful Islam, Professor, Department of Civil Engineering, BUET for his continuous guidance, constructive criticisms, encouragement, and enthusiastic support throughout the progress of the thesis work. Without his wholehearted support, it would not be possible for me to complete the thesis work.

Sincere appreciation to Dr. Md. Delwar Hossain, Professor and Head of the Department of Civil Engineering, BUET for his advice and support from the Department. My gratitude to Dr. Mohammed Kabirul Islam, Professor, Department of Civil Engineering, BUET for his valuable information, supervision and recommendations that made this work resourceful. I am also very grateful to Brig Gen Md Moin Uddin, Bangladesh Army for giving his valuable comments, thoughtful questions, and suggestions.

I want to express my gratitude to Mr. Mohammad Shahidul Islam, site engineer, Toma Enterprise for his support in collecting soil samples from Bhanga, Faridpur and transporting them to Dhaka with proper care. I am appreciative to Engr. Marzia Ashraf and Engr. Md. Omar Faruk, undergraduate students of the Department of Civil Engineering, BUET for their cordial help, participation in field, laboratory work, data collation and interpretations.

I am also grateful to all staffs of the Geotechnical Engineering Laboratory, Department of Civil Engineering, BUET for their help in the successful completion of all experiments. I also want to express my gratitude to the Head and laboratory staffs of the Department of Glass and Ceramic Engineering of BUET for obtaining the SEM images, which indeed helped me to conclude the research works.

I would like to acknowledge the research grant received for this study from the Committee for Advanced Studies and Research (CASR) of BUET, Dhaka.

My heartfelt gratitude to my spouse and children for their true sacrifice. Without their outstanding support, the dream would not come into reality. I am also grateful to my mother and siblings for their cordial support.

ABSTRACT

Dispersive soil is problematic soil that erodes or dislodges easily in the presence of flowing water or even stagnant water. The soil is highly susceptible to erosion due to the presence of a high percentage of exchangeable sodium ions in the soil particles, and that is why it is called sodic soil. This study aims to determine the effectiveness of fly ash in stabilizing dispersive soil. Fly ash is considered an industrial waste that is harmful to the environment and so requires proper disposal. In this study, the potential industrial waste fly ash (Type F) has been used to reduce the dispersivity of sodic or dispersive soil.

At first, to determine the degree of dispersivity crumb test, double hydrometer test, pinhole test and chemical tests are carried out. Compacted samples are prepared using three fly ash contents (3%, 6%, and 9% by weight). Stress-strain behavior of stabilized compacted samples is assessed by conducting unconfined compression tests on samples cured for different periods, i.e., 0, 7, 14 and 21 days. The microfabric arrangement before and after adding various contents of fly ash with dispersive soils is observed by scanning electron microscopy (SEM).

It is observed from the crumb test that dispersivity of soil is reduced with the addition of various percentages of fly ash contents. The dispersivity of soil reduces from Grade 4 to Grade 1, which is nondispersive. Compaction tests are carried out on both treated and untreated soil samples following the Standard Proctor specification. It is observed that due to the progressive addition of fly ash with the dispersive soil, the maximum dry density increases a little, and on the other hand, the optimum moisture content (OMC) decreases with the increasing fly ash. Addition of fly ash with 0%, 3%, 6% and 9% decreases the OMC to 19.9%, 19.8%, 18.4% and 14.5%, respectively.

The double hydrometer test reveals that the flocculation process has been improved with the addition of fly ash which acts as a binding agent. Additions of 3%, 6% and 9 % fly ash reduce the value of dispersion by 25%, 29% and 33%, respectively, from untreated soil. It is observed from the Pinhole test that the degree of soil dispersivity decreases significantly from the state ND4 to ND1with the increment of fly ash contents.

Unconfined compression test exhibits for soil sample prepared with 3% fly ash that failure strain of treated soil sample is reduced by 4% than that of untreated soil. Along with reducing the degree of dispersiveness of soil, fly ash content increases the overall unconfined compressive strength by 325 kPa in 21 days of curing of remolded soil samples which is 2.5 times of 0-day sample. It is also observed that with the increase of curing age, the water content of the soil sample reduces, which makes the sample brittle. Hence, a higher percentage of water content is required for proper hydration and pozzolanic reaction. SEM images of the treated sample show that fly ash reacts with the soil particles and forms calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels and improves compactness, cementation, and bonding among the soil particles. The microstructure of treated soil with fly ash reveals that the voids in between the soil particles are reduced. Hence, it provides resistance and improve~~s~~ the strength characteristics of dispersive soil.

TABLE OF CONTENTS

Page No.

Chapter One: INTRODUCTION

Chapter Two: LITERATURE REVIEW

Chapter Three: EXPERIMENTAL PROGRAM

Page No.

Chapter Four: RESULTS AND DISCUSSIONS

Chapter Five: CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

Page No.

Page No.

LIST OF TABLES

LIST OF ABBREVIATIONS

Symbol	Description
φ'	Angle of internal friction
c'	Cohesion
^{o}	Degree
$'$	Minute
BOFS	Basic oxygen furnace slag
BTPP	Barapukuria termal power plant
C-A-H	Calcium Aluminium Hydrate
CESB	Compressed stabilised earth block
CEC	Cation exchange capacity
C-S-H	Calcium Silicon Hydrate
DFPF	Discrete fibrillated polypropylene fibres
EC	Electrical conductivity
GBFS	Granulated blast furnace slag
G_s	Specific gravity
ha	Hectare
I_F	Flow index
I_T	Toughness index
LL	Liquid limit
LOI	Loss on ignition
M_1	Mass of empty pycnometer
M_2	Mass of pycnometer with dry soil
M_3	Mass of pycnometer, soil and water
M_4	Mass of pycnometer filled with water only
PBRLP	Padma bridge railway link project
PI	Plasticity index
PL	Plastic limit
PS	Percent sodium
SAR	Sodium absorption ratio
TDS	Total dissolved salt
w_S	Shrinkage limit

Chapter One

INTRODUCTION

1.1 General

Soil is a natural substance composed of organic and inorganic materials. The soil composition is quite different from the other civil engineering materials, i.e., steel, concrete, wood, etc. As a natural substance worldwide, soil demonstrates variables in physical and chemical properties from place to place, even from point to point. Despite variations, soil also reveals many geotechnical engineering problems, i.e., inadequate bearing capacity, less cohesion among particles, erosion, differential settlements, slope instability, etc. All these engineering issues are raised due to various problematic soils, and the most striking are dispersive soils, expansive soils, collapsible soils, organic soils etc.

Geotechnical engineers and designers must identify all the constraints associated with problematic soils to find a suitable solution for the limitations levied by the properties of the soil. In the face of the construction of any project, geotechnical engineers will consider an appropriate improving method considering soils properties. Improving soil properties may involve complicated processes like improving soil strength, soil stabilization, soil reinforcement, internal chemical changes, and other ground improvement techniques (Note-13, USDA, 1991). An engineer must consider the availability, suitability, and quality of ground improvement materials with the best economic and environmental issues.

Among the problematic soils, dispersive soils are clay soils that demonstrate mild to severe erosive behavior when in contact with flood or rainwater (Indraratna et al., 1991; Bhuvaneshwari et al., 2007; Vyas et at., 2011; Umesh et al., 2011; Belarbi et al., 2013; Ashraf and Islam, 2018; Faruk et al., 2019; Abbaslou et al., 2020). It is also observed that even in stagnant water, dispersive soils erode unnoticed and cause the failure of earthen structures (Hardie, 2009). Hence, the presence of dispersive soil poses critical challenges to civil engineers, construction firms and clients.

Dispersive soils are characterized by easily flocculated and erodible in water and by an unstable structure. Using dispersive soils in constructing roads, dams, embankments, and hydraulic structures can cause serious engineering problems. Therefore, dispersive soils must be appropriately identified, and necessary remedies to be taken before using such problematic soils. This problem is global and structural failures attributed to dispersive soils have occurred in many countries (Indraratna et al., 1991; Bhuvaneshwari et al., 2007; Vyas et at., 2011; Umesh et al., 2011; Vakili et al., 2012; Belarbi et al., 2013; Karthik et al., 2014; Abbaslou et al., 2016; Ashraf and Islam, 2018; Faruk et al., 2019; Abbaslou et al., 2020).

Visually and in normal dry weather conditions, dispersive soils cannot be identified very easily. Visual classification like Atterberg's limits and particle size analysis does not provide a sufficient basis to differentiate between dispersive clays and ordinary erosion-resistant clays (Umesha et al., 2011; Fattah et al., 2014; Maharaj et al., 2015; Ismael et al., 2021). Dispersive soils are identified by ASTM tests such as Pinhole Test, Crumb Test, Double Hydrometer Test and Chemical Test (Umesha et al., 2011; Belarbi et al., 2013; Fattah et al., 2014; Maharaj et al., 2015; Ismael et al., 2021).

In the last few decades, several research and studies have been undertaken by researchers to eradicate and stabilize the dispersivity of dispersive soils. However, it was witnessed that the chemical treatment reduces the dispersivity potential to a tolerable limit (Indraratna et al., 1991; Vakili et al., 2012; Karthik et al., 2014; Ashraf and Islam, 2018; Faruk et al., 2019). Therefore, in this thesis, the effects of adding different percentages of coal Fly Ash (pozzolanic) on dispersive soils available in Bangladesh were investigated with varying curing times.

1.2 Background of the Study

Dispersive soils are clay soils that are highly susceptible to erosion and contain a high percentage of exchangeable sodium ions. In earth dams and embankments, dispersive clays may cause a piping failure. Dispersive soils have existed in various types of climates in various locations in Australia, Brazil, Iran, New Zealand, the United States, Thailand, Mexico, Vietnam, South Africa, and many other countries. Recently, a railway embankment has collapsed due to the presence of dispersive soils at Bhanga, Faridpur of Bangladesh. As such, the need for understanding the causes of erosion and finding the appropriate remedies to eradicate the problems of dispersive soils become an essential issue from the geotechnical point of view.

A visual inspection was carried out to the damaged site of the railway embankment and observed that the side canals or borrow pits of soils are full of turbid water. A simple field crumb test also indicated the area had dispersive soils. Recently, research revealed that much of those erosions are associated with sodic or dispersive soil. When the percentage of sodium in the soil seems excessively high, then it is termed sodic or dispersive soil (Indraratna et al., 1991; Bhuvaneshwari et al., 2007; Vyas et at., 2011; Umesh et al., 2011; Vakili et al., 2012; Belarbi et al., 2013; Karthik et al., 2014; Abbaslou et al., 2016; Ashraf and Islam, 2018; Faruk et al., 2019; Abbaslou et al., 2020). So, the sodic or dispersive soil displays high erosion phenomena and thus becomes a common problematic issue in Bangladesh.

The extent of dispersion depends on clay chemistry and mineralogy of soil particles, as well as the Total Dissolved Salts (TDS), Percent Sodium (PS), Sodium Absorption Ratio (SAR), and Electrical Conductivity (EC). In dispersive soils, the attractive forces of soil particles are less than the repulsive forces under saturated conditions. Hence, the soil particles become segregated and move in suspension (Note 13, USDAS, 1991; Frenkel et al., 1992; Hardie et al., 2007; DAF Farm Note 386, 2009; DAF, Farm Note 387, 2010; Vakili et al., 2012).

Geotechnical engineers did not document the problems related to dispersive soils until 1960. As a result, most of the construction work was carried out without much knowledge of the damaging effects of dispersive soils, even after recognizing such problematic soils in various countries. This ignorance also hampers the durability of embankments in Bangladesh. For example, the 215.22 km long Padma Bridge Railway Link Project (PBRLP) is being constructed from Central Dhaka to the Jashore district of Bangladesh. Dispersive soil has been identified in different locations such as Faridpur and Shariatpur district to Jashore. In the past, the use of such soils was not recommended at all, but nowadays, the improvement of dispersive soils is highly advised due to the increasing construction of earth structures and the uneconomical replacement of dispersive soils with borrowed nondispersive soils (Belarbi et al., 2013; Ashraf and Islam, 2018; Faruk et al., 2019).

The researchers have developed many techniques to reduce the associated problems of dispersive soils. The most common treatment applied for stabilization of dispersive soil is the use of chemical additives such as alum, bioengineering with plants and plant roots, biological methods with *Bacillus sphaericus* and *Bacillus pasteurii*, basic oxygen furnace slag (BOFS), cement, fly ash, granulated blast furnace slag (GBFS), pond ash, rice husk ash, polymers, lime, and ZELIAC (Indraratna et al., 1991; Bhuvaneshwari et al., 2007; Vyas et at., 2011; Umesh et al., 2011; Vakili et al., 2012; Belarbi et al., 2013; Beetham et al., 2014; Puppala et al., 2015; Karthik et al., 2014; Premkumar et al., 2016; Abbaslou et al., 2016; Rani et al., 2017; Ashraf and Islam, 2018; Faruk et al., 2019; Abbaslou et al., 2020; Ismael et al., 2021). In addition, soil stabilization using fly ash can reduce shrink-swell potential, and increase workability, soil strength and stiffness. In recent research, fly ash has been introduced successfully in reducing dispersivity in clay (Indraratna et al., 1991; Vakili et al., 2012; Premkumar et al., 2016; Abbaslou et al., 2016; Rani et al., 2017; Ashraf and Islam, 2018; Faruk et al., 2019).

In Bangladesh, fly ash is recognized as one of the common residues produced from coal combustion at Barapukuria Thermal Power Plant (BTPP), Dinajpur, Bangladesh. In the past, fly ash was unconditionally released into the atmosphere. However, recent concerns about environmental pollution led to the prohibition of its atmospheric release. Various mechanisms are mandated to trap it before releasing it into the atmosphere (Arfien et al., 2013; Khan et al., 2013; Tamim et al., 2013). Presently in Bangladesh, it is estimated that 37,000 cum of fly ash is produced per annum for dumping from thermal power plants. The dumping of fly ash can reach up to 2,70,000 cum. Subsequently, the storage and recycling of this massive quantity of fly ash have become a new concern. Again, if fly ash can be used as a soil stabilizer, no extra cost will be required for producing soil stabilizer. For all those reasons, utilization of fly ash is anticipated to be very advantageous in the stabilization of dispersive soils both economically and environmentally (Arfien et al., 2013; Khan et al., 2013; Tamim et al., 2013; Masud et al., 2014; Ashraf and Islam, 2018; Faruk et al., 2019; Elahi et al., 2020; Elahi et al., 2021).

1.3 Objectives of the Research

The main objectives of the research are:

(1) To determine the geotechnical and chemical properties of selected dispersive soil.
(2) To study the effectiveness of fly ash in stabilizing dispersive soil.
(3) To study the microstructure of fly ash stabilized dispersive soil.

1.4 Research Methodology

The whole research methodology can be described as follows:

(1) First, index properties of the soil samples collected from Bhanga, Faridpur were determined. Index tests included liquid limit, plastic limit, shrinkage limit, plasticity Index (ASTM D 4318) and specific Gravity test (ASTM D 854).

(2) To determine optimum moisture content and maximum dry density standard proctor test (ASTM D1557) was performed for both untreated and treated samples with varying percentages of (3%, 6% and 9%) fly ash.

(3) To recognize, a dispersive soil crumb test (ASTM D 6572) was performed as a preliminary test on two sets of soil samples. When the results obtained was up to mark as expected, the same test was performed for sample mixed with 3%, 6%, and 9% fly ash (w/w).

(4) To determine the degree of dispersivity, chemical and physical tests such as the pinhole test (ASTM D 4647-93), crumb test (ASTM D 6572), double hydrometer test (ASTM D 4221-99) and chemical tests (ASTM D 4542-95) were also performed because dispersive soils cannot be identified by the standard laboratory index tests such as particle size analysis, specific gravity or Atterberg's limits. When the results obtained were up to mark as expected, the same tests were performed for samples mixed with 3%, 6%, and 9% fly ash to check whether the characteristic behavior would have been improved.

(5) Unconfined Compression Test (ASTM D 2166) was conducted on both untreated and treated soil. For all percentages of fly ash mixed with soil, one set of specimens was tested immediately after compaction. Other sets (3%, 6%, 9% by weight) were cured for 7 days, 14 days and 21 days for Unconfined Compression tests are conducted.

(6) The Scanning Electron Microscopy (SEM) test was conducted on both untreated and treated soil samples. The microlevel improvement of soil particles are observed for all percentages of fly ash mixed with dispersive soil (3%, 6%, and 9% by weight).

1.5 Thesis Layout

Chapter 1 consists of an introduction. It states the background to the study, the reasons for carrying out this research, the objective and possible outcome of the study and the methodology carried out for this thesis.

Chapter 2 reviews the literature related to dispersive soils and their stabilization. It focuses on the problems associated with these problematic soils and alternative solutions using the chemical additives technique. In addition, some application cases of fly ash such as CESB, slope protection, and embankment stabilization for various engineering purposes are mentioned, focusing on soil treatment carried out by researchers. At the end of this chapter, the research gap is presented.

Chapter 3 describes the methodology followed to achieve the objective of the study. The tests to be performed during this research to meet the objectives of this study are also discussed. Various tests are carried out on dispersive soils before stabilization and then repeated on stabilized dispersive soils.

Chapter 4 focuses on the experimental program analyzing obtained data, test results, and discussions. The results of treated soils are compared with the results of untreated soils. The inner mechanism and strength characteristics are described when dispersive soils are stabilized with fly ash at various percentages of mixed ratios.

Chapter 5 presents the conclusions of the study and recommendations for future research.

Chapter Two
LITERATURE REVIEW

2.1 Introduction

During construction, geotechnical engineers often experience problems due to various problematic soils, such as dispersive, collapsible, and expansive soil. Therefore, engineers adopt different techniques and methods to develop the site soil condition to meet the desired construction specifications. Worldwide, the mindset of engineers varies with the availability of suitable materials for the stabilization of problematic soils.

Infield condition identification of dispersibility is a little easier based on visual and simple field tests but exceedingly difficult to quantify in the laboratory condition. Visual classification, Atterberg limits, and particle size analysis do not provide a sufficient basis to differentiate between dispersive soil and ordinary erosion-resistant soil. Hence, the Crumb, Pinhole, and Double Hydrometer tests are the only tests suitable for identifying dispersive soils.

This literature review focuses on the dispersive soils, which are highly susceptible to erosion and contain a high percentage of exchangeable sodium ions, the problems instigated by dispersive soils and various standard techniques and methods applied earlier for stabilization. This section reviews the factors influencing the dispersive phenomena and research gap based on erosion potential in Bangladesh and the associated problems.

2.2 Origin of Dispersive Soils

Dispersive soil can be found anywhere in the arid, semi-arid region of the world. Weathering of sedimentary rocks transfers sodium ions from the rock components to the soil. In dry climates, the vaporisation of water induces a high sodium content in the top layer, especially in the case of low permeability in the underlying layers (Heinzen and Arulanandan, 1977).

Generally, saline soil becomes sodic through the leaching of salts (e.g., sodium chloride), usually over many thousands of years. As salt is washed down through the soil, it leaves some sodium behind bound to clay particles displacing other elements such as calcium. When there is excess sodium, soil swells and clay particles disperse when in contact with water rather than sticking together, causing the soil structure to slump and collapse. On the other hand, the presence of water will overcome and eliminate the interparticle forces, and the particles will move apart, forming a dispersed colloidal solution. The separated particles would move even with a slow water flow (Davies and Lacey, 2009; Qadir et al., 2007).

Most studies reported in the literature have shown that failures of structures built on dispersive clay soils occurred on first wetting. All failures were associated with water and fractures by shrinkage, construction failure or differential arrangement. These failures draw attention to the importance of early identification and recognition of dispersive clay soils. Otherwise, the problems they cause can result in abrupt, irreversible, and disastrous failures. Therefore, a comprehensive investigation is required for the identification of dispersive soils, problems and improvement in the soil engineering properties using different soil stabilization procedures (Faulkner, 2006; Abbaslou et al., 2016)

2.3 Extent of Dispersive Soils

FAO/UNESCO (1976) soil map of the world estimated that globally the total area of sodic soil or Dispersive soil is 434 million hectares (Table 2.1). Sodic soils occur within the boundaries of at least 75 countries, and their extent has increased steadily in several major irrigation schemes throughout the world. Dispersive soils are found in alluvial plains and lacustrine environments and shales under the sea. Sodic soils are also found in humid regions like Brazil, Vietnam, Australia, Mexico, Thailand, India, Venezuela, and the southern US (Sherard et al., 1976; Qadir et al., 2007).

Bangladesh is a land of rivers and canals. In the north-eastern part of South Asia, it is between $20^{o}34'$ and $26^{o}38'$ north latitudes and $88^{o}01'$ and $92^{o}41'$ east longitudes. The country is located between the Bay of Bengal in the south and the Himalayas in the north. Bangladesh is one of the highest disaster-prone areas of the world. The low-lying delta regions of the country are subject to different degrees of flooding from monsoon rains, cyclones and tidal waves with significant crop damage and high loss of lives. The

Sundarbans mangrove forests in the country's south serve as a natural defense against cyclonic storms and tidal surges.

Table 2.1: Extent of Dispersive Soils in the World (FAO/UNESCO, 1976)

Regions	Total area (ha)	Saline Soils	%	Sodic Soils	%
Africa	1899.1	38.7	2.0	33.5	1.8
Asia, Pacific, and Australia	3107.2	195.1	6.3	248.6	8.0
Europe	2010.8	6.7	0.3	72.7	3.6
Latin America	2038.6	60.5	3.0	50.9	2.5
Near East	1801.9	91.5	5.1	14.1	0.8
North America	1923.7	4.6	0.2	14.5	0.8
Total	12781.3	397.1	3.1	434.3	3.4

The soils of Bangladesh are quite varied, and more than 465 soil series have been identified. This wide soil variation is mainly due to the physiography and microclimatic variation. Although most of the country’s soil is developed on alluvial deposits, hilly formations and soils are formed under evergreen and deciduous forest vegetation. The whole country has been subdivided into seven physiographic units. Soils developed under each of these units are identified with them. Examples are Himalayan piedmont soil, hill soils, acid-basin clay soils, calcareous alluvium soils, noncalcareous alluvium soils, peatland soils, mangrove soils etc. (Huq and Shoaib, 2013).

Bangladesh's extent of dispersive soil (Figure 2.1) is not entirely familiar. Most research in Bangladesh is based on agricultural and geological points of view. The scope of past research for dispersive soil and its associated problems in Bangladesh was not standard. The economy of the country is thriving day by day. It has one of the fastest-growing economies in Southeast Asia. Hence, an enormous number of mega projects are undertaken frequently to build infrastructures all over the country.

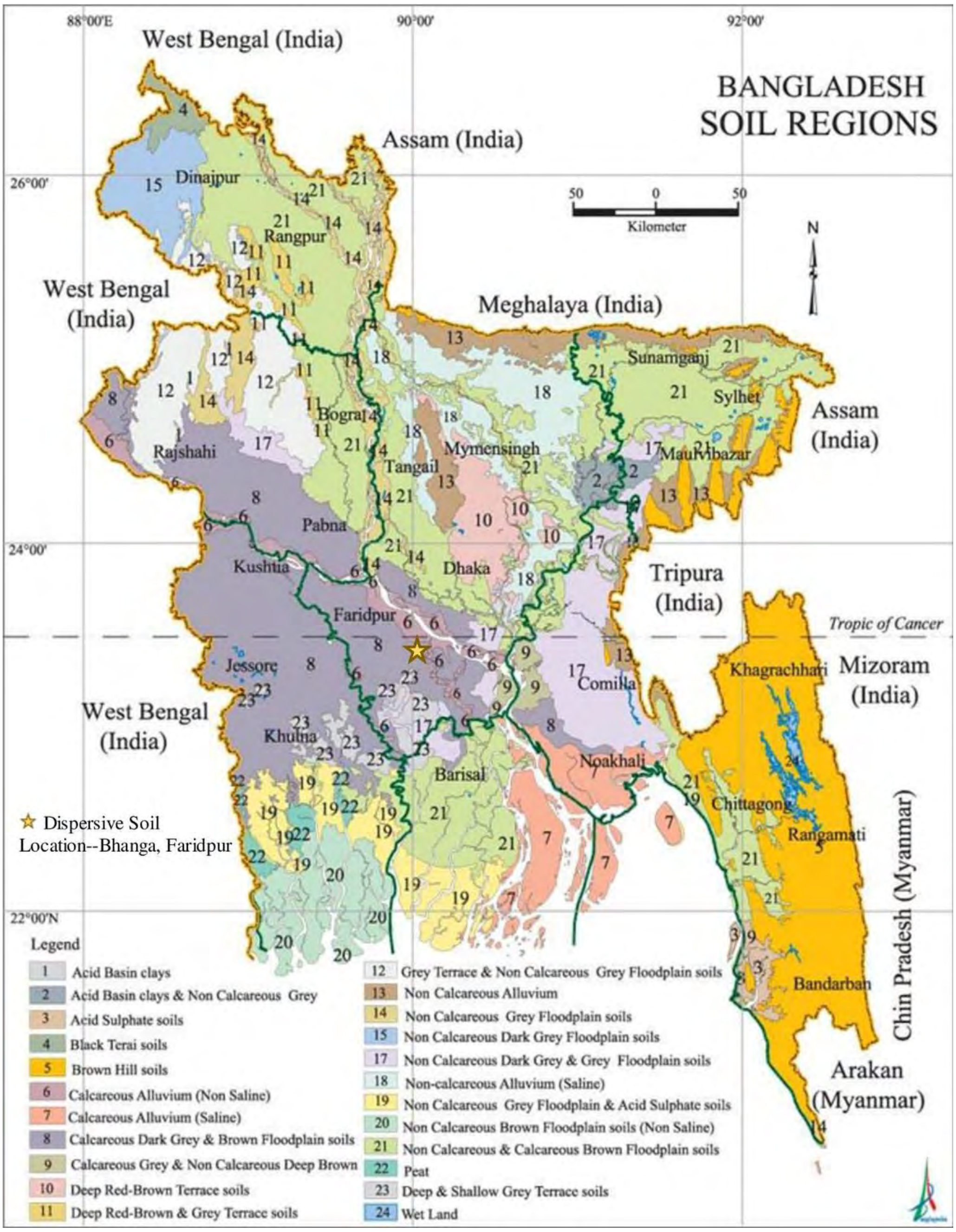


Figure 2.1: Soil Map of Bangladesh Focused on Dispersive Soils (Source: https://en.banglapedia.org/index.php/Bangladesh_Soil)

The Padma Bridge Rail Link Project (PBRLP) is one of the superstructures connecting the capital Dhaka with the southern part of the country. During the railway embankment construction, sodic soils posed enormous difficulties to sustain the structure during high flood water. Figure 2.2 shows the collapsed pattern of the railway embankment at Bhanga, Faridpur. Figure 2.3 illustrates the cross-section of the collapsed railway embankment.

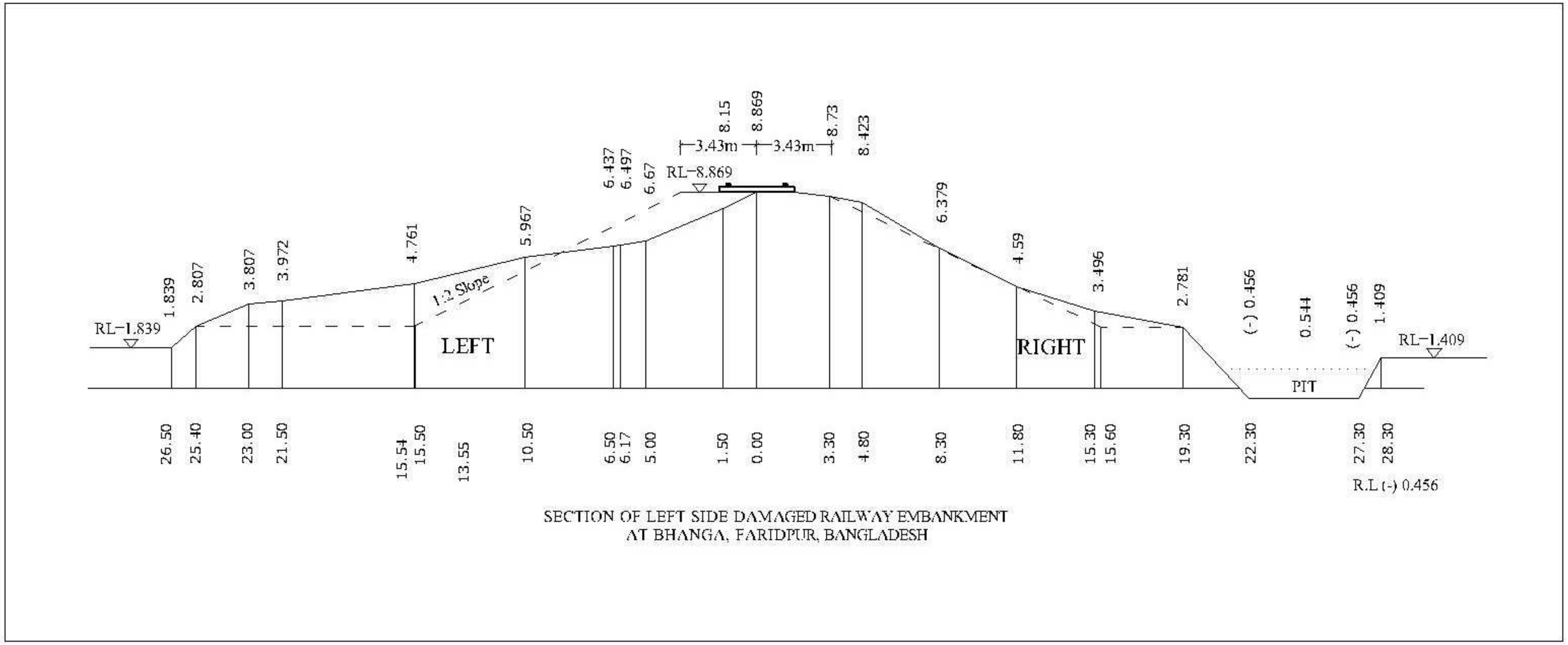
(a)

(b)

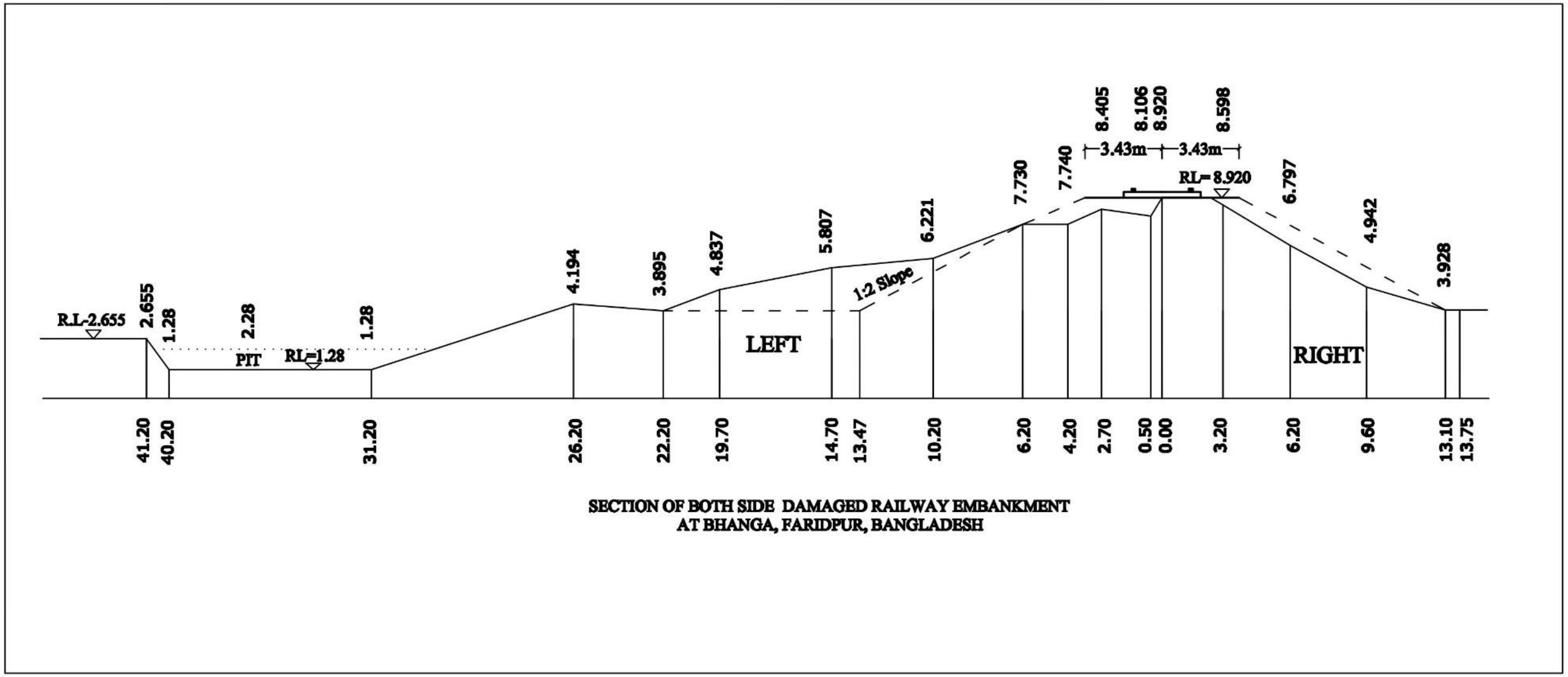
(c)

(d)

Figure 2.2: (a) Collapsed railway embankment at Bhanga, Faridpur, (b) turbid canal water represents probable dispersive soil location, (c) hanging railway line bottom part, (d) hanging railway line the upper part


SECTION OF LEFT SIDE DAMAGED RAILWAY EMBANKMENT
AT BHANGA, FARIDPUR, BANGLADESH
LEFT
RIGHT
PIT
1:2 Slope
RL-1.839
RL-8.869
RL-1.409
R.L (-) 0.456
3.43m
3.43m
1.839
2.807
3.807
3.972
4.761
5.967
6.437
6.497
6.67
8.15
8.869
8.73
8.423
6.379
4.59
3.496
2.781
(-) 0.456
0.544
(-) 0.456
1.409
26.50
25.40
23.00
21.50
15.54
15.50
13.55
10.50
6.50
6.17
5.00
1.50
0.00
3.30
4.80
8.30
11.80
15.30
15.60
19.30
22.30
27.30
28.30

(a)



(b)

Figure 2.3: (a) Section of left side damaged railway embankment at Bhanga, Faridpur, Bangladesh, (b) section of both side damaged railway embankment at Bhanga, Faridpur, Bangladesh

2.4 Behavior of Dispersive Soils

Dispersive soils are a key contributing factor to the piping failure of embankments dams constructed without filters (Fell et al., 1992; Faulkner, 2006; Hardie et al., 2007; Hardie, 2009). Foster et al. (2000) conducted a statistical study on 11,192 hydraulic structures and found 136 structures collapsed, among which 6% collapsed by landslides, 46% by internal erosion and 48% by overflow.

The erosion occurs when shearing stress generated by water flow is large enough to cause particles to be removed from the surface. The resistance to erosion for non-cohesive soils depends mainly on the sediment's gravity forces. On the other hand, the structure of the soil particles and the interface between pore and eroding fluids at the surface are the causes of erosion for cohesive soils (Figure 2.4). The amount and type of clay, pH, organic matter, temperature, water content, thixotropy and type and concentration of ions in the pore and eroding fluids are the factors that affect the critical shear stress required to initiate erosion (Bhuvaneshwari et al., 2007; Umesh et al., 2011; Marchuk and Rengasamy, 2012; Heinz, 2012; Suresh et al., 2013).

(a) (b)

Figure 2.4: (a) Washed away embankment, (b) piping failure of embankment constructed on dispersive soil (Mississippi, USA) (source: www.fema.gov)

Dispersive clays are a particular type of soil in which the clay fraction erodes in the presence of water by the process of deflocculating (Forrest, 1980). These soils are highly erodible and tend to crumble in the presence of water and erode under a low flow rate, which leads to stability problems in earthworks. Erosion due to soil dispersion depends on clay's mineralogy and chemical composition and the salts dissolved in interstitial water. Dispersive clays are highly erosive because they contain more dissolved sodium cations than ordinary clays. Sodium cations increase the thickness of the diffused double water layer surrounding the individual clay particles, which causes the repulsive forces to exceed the attractive forces. Hence, the particles readily go into suspension in the presence of water (McElroy, 1987). Anon (1999) stated that dispersive soil contains a high exchangeable sodium percentage, and the sodium is adsorbed onto the surface of the clay. Its ions are large but weakly charged. The positive ions bind the negatively charged clay particles together. When water is added, it attracts sodium. The ions are hydrated and force the plates apart. As a result, the clay particles swell and then disperse with water. From Figure 2.5, dispersive soil floats in the presence of water significantly.

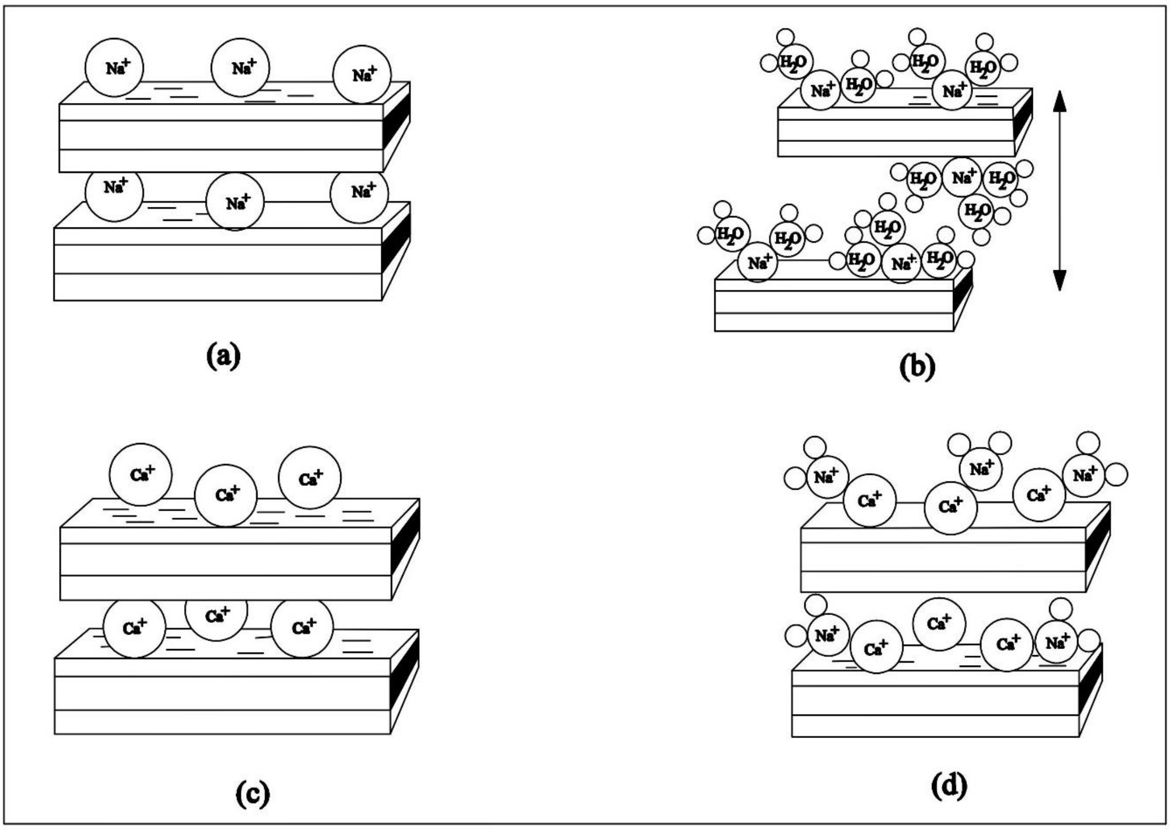


Figure 2.5: Behavior of non-sodic and sodic soils in water (Anon, 1999)

Anon (1999) also stated that calcium is adsorbed onto clay's surface in nondispersive soil, which is a small-sized ion but strongly charged. As a result, water cannot go into the platelets, and swelling does not happen. It happens because water ions cannot overcome the binding forces of calcium ions, and the soil does not disperse (Figure 2.5).

2.5 Problem Associated with Dispersive Soil

Dispersiveness of soil was first noticed by agronomists over 100 years back. The phenomena were understood by soil scientists and agricultural engineers nearly 70 years before. However, the importance of the subject in civil engineering practice was not recognized until the early 1960s, when research on piping failure came into existence in Australia because of many failures of small clay dams.

Figures 2.6 and 2.7 present that dispersivity has severe impacts such as surface crusting, reduced seedling emergence, reduced soil aeration, increased run-off and erosion risk, less groundcover and organic matter, less microbial activity, quality of the storage water, instability of the retaining wall and the containing slopes, gully and tunnel erosion etc. (Faulkner, 2006; Hardie et al., 2007; Hardie, 2009).

(a) (b)

Figure 2.6: (a) Dribble pattern of dispersive soil, (b) spew holes created in dispersive soil (Tasmania, Australia) (Hardie, 2009)

(a)

(b)

Figure 2.7: Some problems associated with dispersive soil: (a) piping and internal erosion failure, Tanbridge Dam, Tasmania, (b) gully erosion due to dispersive soil, Pavrud Irrigation Network, Iran (Source: https://www.geoengineer.org/gallery)

Figure 2.8 shows that tunnel erosion is one of the significant problems of dispersive soil. When an embankment is constructed without proper soil compaction, air voids will result within the wall. When water seeps in and leaches out the clay particles, it causes narrow piping. The piping quickly develops into tunnels and results in the destruction of the embankment. Due to piping, many slopes, earth dams, foundations and pavement failures have been observed in dispersive soil. The erosion starts upstream, forming a tunnel-shaped passage or pipe until it reaches the water sources, where a rapid catastrophic failure may result (Hardie et al., 2007; Hardie, 2009; Nadal-Romero et al., 2011).

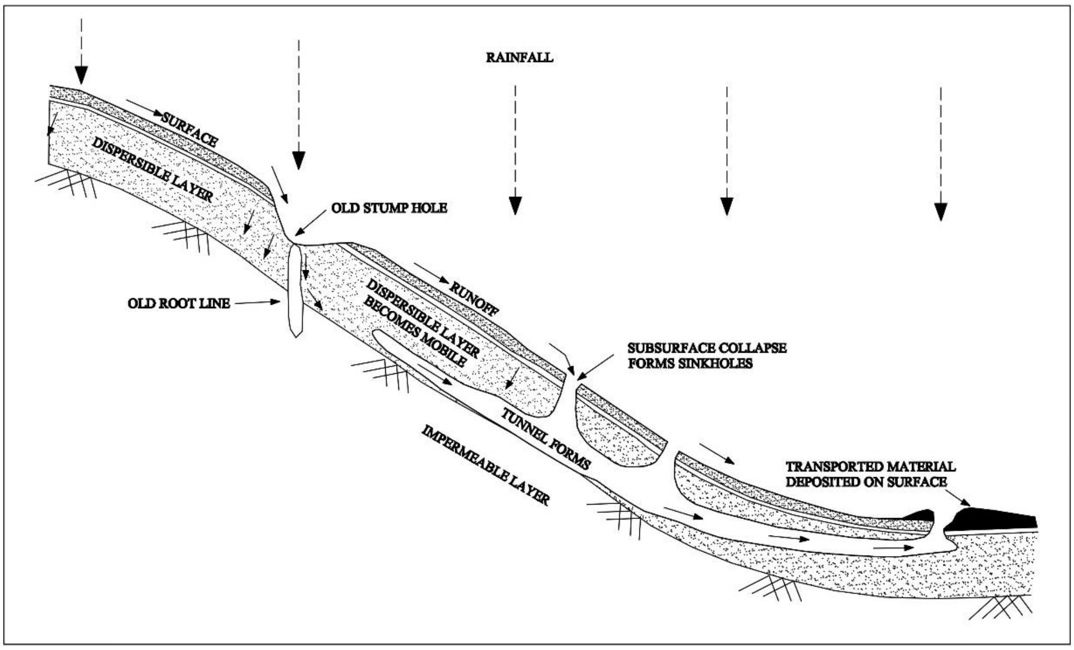


Figure 2.8: Tunnel erosion at the slope constructed with dispersive soil (Source: http//www.vro.agriculture.vic.gov.au)

Dispersive soil has a significant variation in index properties and physical properties such as relative density, particle size distribution, Atterberg limits, field moisture content, degree of compaction, ductility, permeability etc. This nature of variation names the soil as problematic soil. Dispersive soil loses attractive forces among the particles when it comes in contact with water. Surface erosion, severe rain cut, tunnel erosion, gully formation, sinkholes, differential settlement of building foundations and roads, etc., are associated with dispersive soil problems (Batool et al., 2015).

2.6 Stabilization of Dispersive Soil

Soil stabilization is the permanent physical and chemical alteration of soil to enhance its physical properties like strength, durability, and resistance to deformation of in situ soil. It is now one of the most convenient and economical techniques for improving soil conditions. Stabilization is the process of blending and mixing a specific additive with soil to enhance certain soil properties.

Dispersive soil is improved based on three stabilization mechanisms; chemical additives, mechanical reinforcement, and a combination of chemical and mechanical stabilization. However, soil biology and biochemistry researchers have developed plant roots and deep banded nutrient-rich amendments in recent years, which influence aggregation and dispersion in a dispersive clay subsoil. Still, the suitability of this process is unknown for civil construction works.

Mechanical stabilization by including Discrete Fibrillated Polypropylene Fibres (DFPF) is known for use in pavement subgrades. The addition of polypropylene fiber reinforcement can improve remolded soils. Mechanical reinforcement materials are mostly made from polymers and plastics but can also be made from wood or glass fibers. Polymers show a remarkable soil stabilization effect because of the bond between clay mineral and polar end groups of polymers.

Additive based stabilization is achieved by adding a proper percentage of fly ash, lime, cement, bitumen, alum or a combination of these materials. Since dispersibility is primarily a chemical reaction, chemical stabilizers are appropriate for dispersive soils. In addition, these chemicals improve the engineering properties of soil by forming a bond with clay minerals present in the soil.

The selection of type and determination of the percentage of additive to be used depends on the soil classification and the degree of improvement desired in soil quality. This research paper will focus on the strength characteristics of dispersive soil with pozzolanic fly ash. The reason behind choosing this ingredient and the relative comparisons are described in the subsequent sections.

2.6.1 Selection of Additives

The additive based stabilization technique is widely used worldwide to construct roads, airports, embankments etc. The additives are mixed with clay soils to improve their workability, strength, stiffness, swelling characteristics, and bearing capacity (Puppala et al., 2007; Puppala et al., 2009). The stabilizer selection is carried out based on the plasticity index (PI) value because it directly impacts the selection of the additives. However, sometimes PI is not enough for the selection of the additives. In that case, the optimum moisture content (OMC) and maximum dry density (MDD) need to be determined in the laboratory for the further selection process (Puppala et al., 2015).

The preliminary selection of the appropriate additives for soil stabilization should consider the following:

(i) Soil consistency and gradation.
(ii) Soil mineralogy and composition.
(iii) Desired engineering properties.
(iv) Purpose of treatment.
(v) Required strength and durability.
(vi) Mechanism of stabilization.
(vii) Environmental condition and engineering economics.

2.6.2 Stabilization with Fly Ash

In the present research, changes in dispersivity potential and other properties of the dispersive soil samples were investigated using pozzolanic fly ash. The reduction in the dispersibility potential was significantly changed upon the curing time and percentage of selected fly ash. The results proved that adding pozzolan followed by curing reduces the dispersibility potential of the samples. Furthermore, samples stabilized by pozzolan were found to have increased unconfined compressive strength (UCS), decreased plasticity index, decreased percent sodium, and increased electrical conductivity. Various researchers used fly ash as the most suitable and green technology to eradicate the dispersiveness of soil from 2% to 20%. Some established that the soil becomes brittle when the fly ash contents are greater than 8%. The results indicate that the least dispersivity potential corresponds to the application of 6% pozzolan, and better results were obtained with an increasing number of curing days (Indraratna et al., 1991; Vakili et at., 2012; Karthik et al., 2014; Premkumer et al., 2016).

Figure 2.9 illustrates alterations in the percent dispersion of stabilized samples with fly ash with different curing times. The samples with 5% pozzolan in a 90-day curing time demonstrate the least dispersion compared to other stabilized samples. The 90-day percent dispersion is 25.79% which indicates the soil is non-dispersive. It is observed that 5% gives the best result in reducing percent dispersion based on the Double Hydrometer test, and percent dispersion is reduced with curing days. At 90 days of curing, percent dispersion decreased to less than 30% (Vakili et al., 2012).

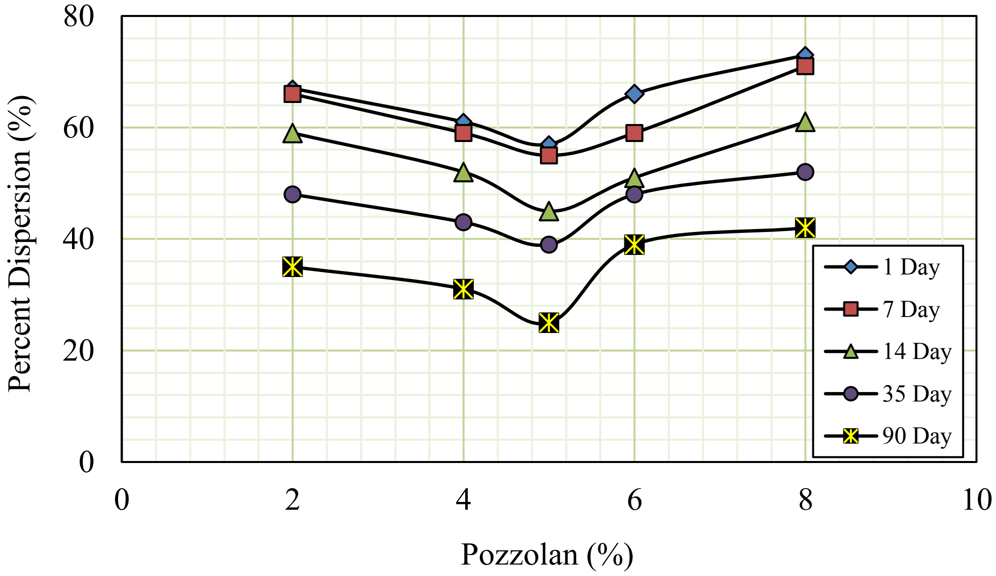


Figure 2.9: Percent dispersion of samples treated with pozzolanic fly ash contents and different curing times (Vakili et al., 2012)

The Pinhole test is one of the most popular tests for identifying the dispersion potential of dispersive soil. Figure 2.10 shows that the final flow rate decreased with an increase in curing time, and the lowest amount of dispersion happened with 5% pozzolan. Therefore, the treated samples were mostly categorized as semi-dispersive and dispersive soils. This figure also shows that the flow rate decreases with the increase of pozzolanic fly ash. Figure 2.11 illustrates changes in the electrical conductivity and sodium percentage in the treated samples with pozzolanic fly ash (Vakili et al., 2012).

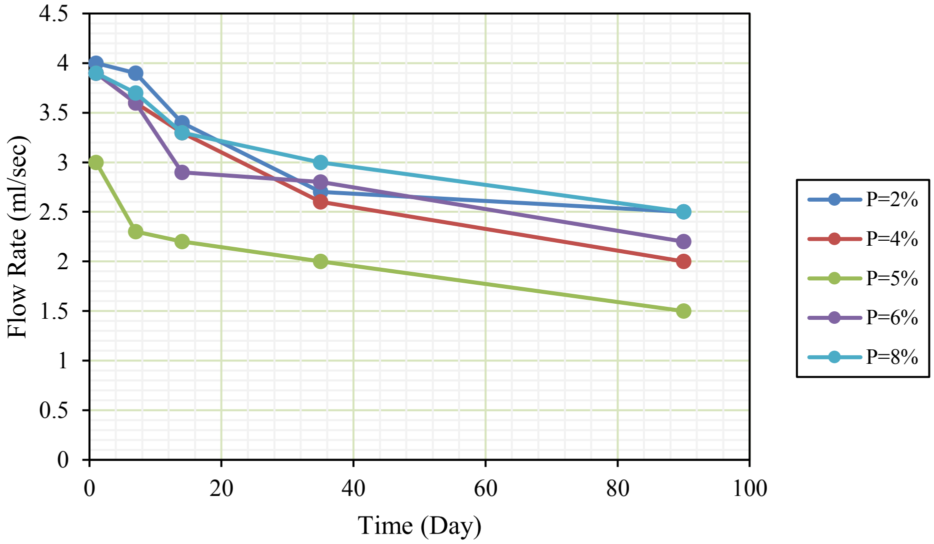


Figure 2.10: Flow rate for treated samples with different pozzolanic fly ash content (Vakili et al., 2012)

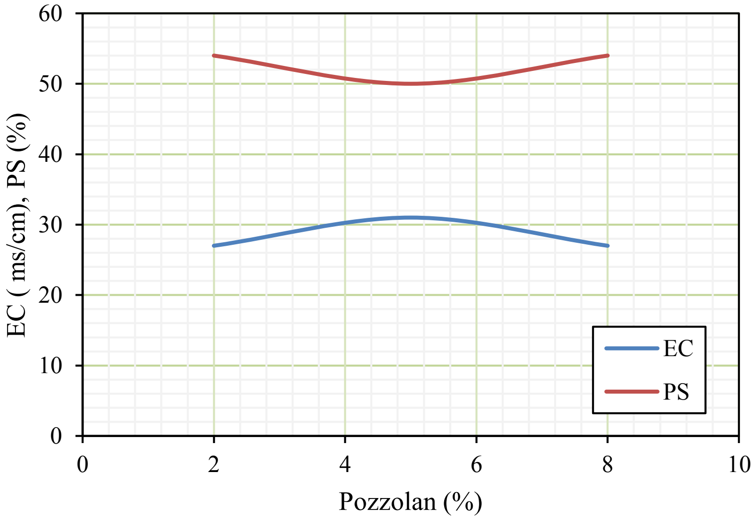


Figure 2.11: Percent sodium and electrical conductivity for treated samples with different fly ash content after 35 days of curing (Vakili et al., 2015)

Premkumar et al. (2016) tested different treated and untreated dispersive soil samples following the Standard Proctor Specification with various soil-fly ash mixtures. Figure 2.11 shows the standard compaction curves established for both natural soil and samples blended with different fly ash contents. The average maximum dry density and optimum moisture content for the natural soil were 1760 kg/m^3 and 16%, respectively. The Proctor relationships for the soil-fly ash mixtures revealed that the maximum dry density decreases and the optimum moisture content increase with increasing fly ash content. The reasons were that the selected fly ash contained a higher percentage of free lime (CaO), which needed more water for the hydration process. Figure 2.12 shows that with 12% fly ash, the least dry density and higher optimum moisture content are obtained.

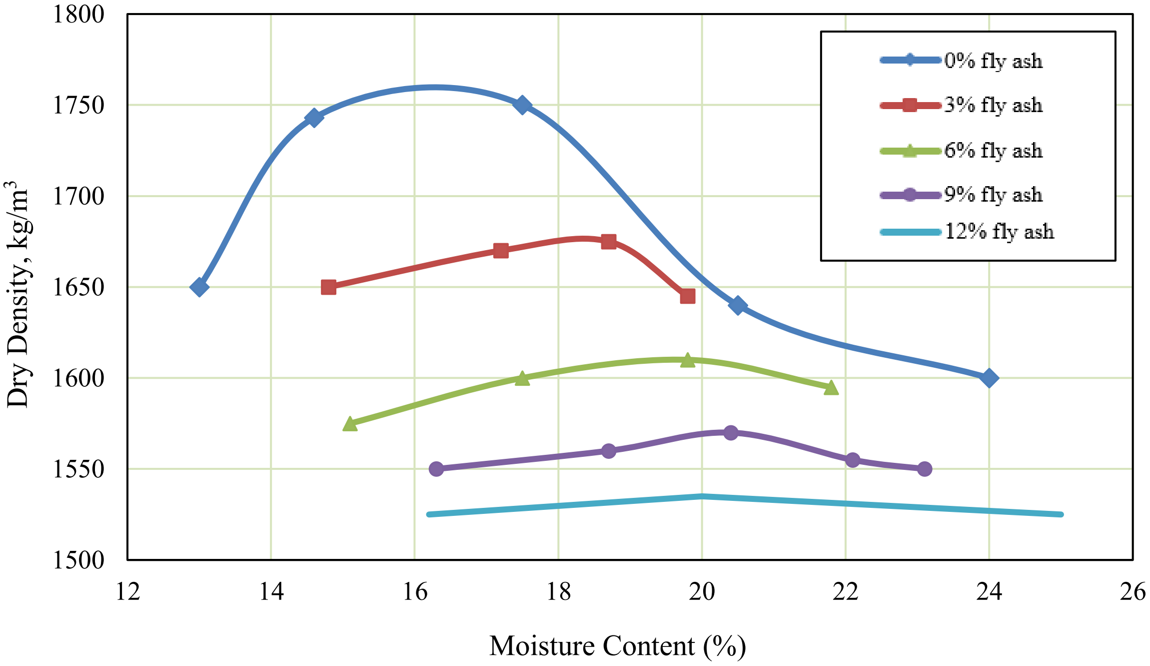


Figure 2.12: Influence of brown coal fly ash on moisture density relationship of selected soil (Premkumar et al., 2016)

Premkumar et al. (2016) carried out Unconfined Compression (UC) tests on the dispersive soil samples both treated and untreated with coal fly ash with different curing times. The UC test results revealed that the compressive strength increased with the curing time and the increment of fly ash content. The variations of fly ash content were from 0%, 3%, 6%, 9% and 12%. Significant strength improvement was achieved after 90 days of curing. The compressive strengths at 90 days were 0.69 MPa, 0.90 MPa, 1.27 MPa, and 1.32 MPa, respectively. Figure 2.13 proved that without fly ash, compressive strength was unchanged with curing days. The main reason was that the selected fly ash reacted with calcium ions and formed C-A-H (Calcium Aluminium Hydrate) and C-S-H (Calcium Silicon Hydrate), which caused more strength to be obtained.

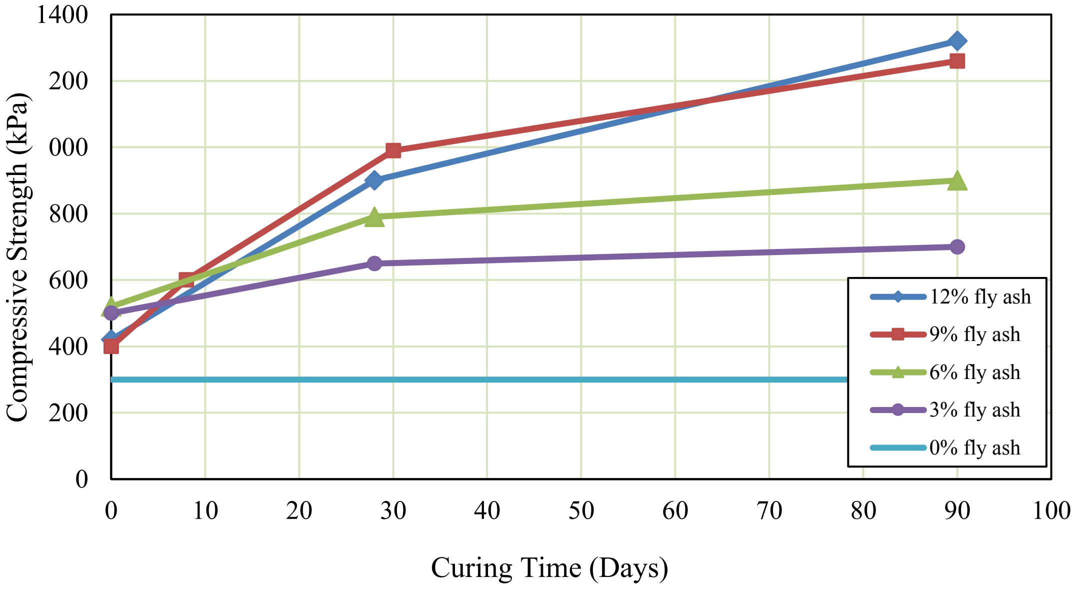


Figure 2.13: UC test for treated samples with different fly ash contents and different curing times (Premkumar et al., 2016)

The variation of liquid limit, plastic limit and specific gravity with fly ash contents are shown in Figures 2.14, 2.15 and 2.16, respectively (Karthik et al., 2016)

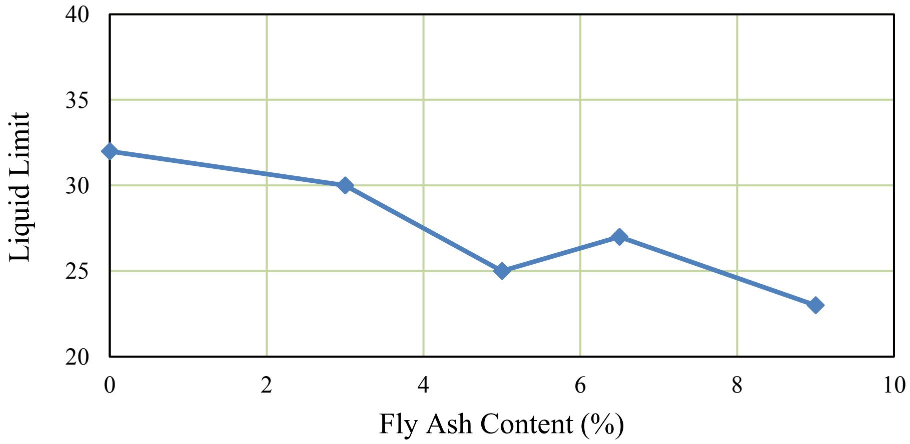


Figure 2.14: Effect of fly ash on the liquid limit (Kartik et al., 2016)

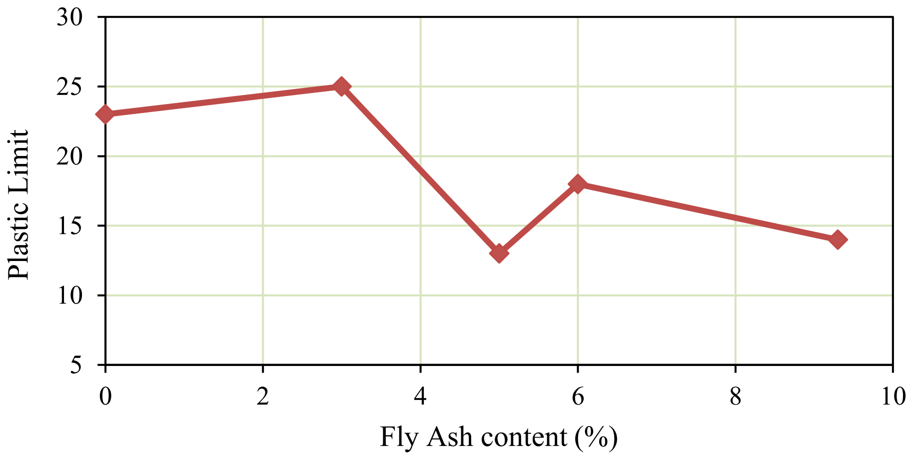


Figure 2.15: Effect of fly ash on the plastic limit (Karthik et al., 2016)

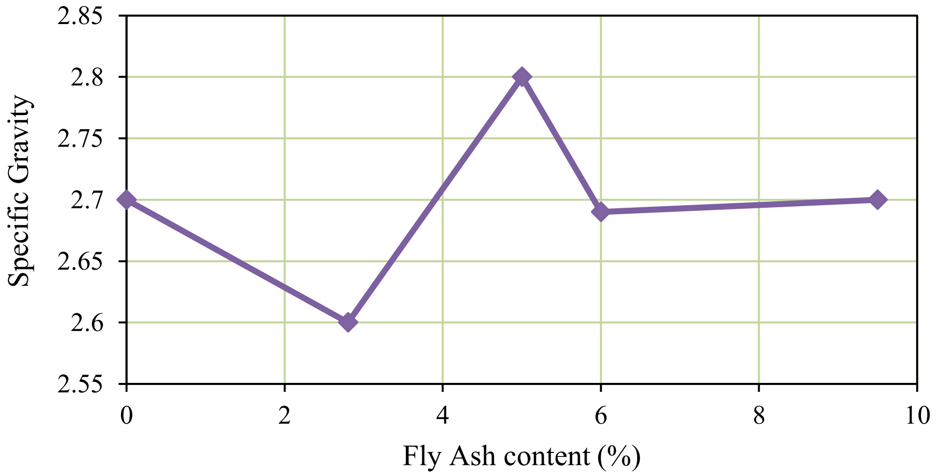


Figure 2.16: Effect of fly ash on specific gravity (Karthik et al., 2016)

Fly ash is one of the by-products in thermal power plants when coal is used as fuel for combustion (Arfien et al., 2013; Khan et al., 2013; Tamim et al., 2013). According to ASTM standard C593 (ASTM International, 1994), fly ash is classified as either Class C or Class F (Table 2.2), depending on its source. Class F fly ash is the by-product of bituminous or anthracite coal burning, and Class C fly ash is the by-product of burning sub-bituminous or lignite coals. The main difference between these two types is the amount of calcium, silica, alumina, and iron content (Khan et al., 2013; Tamim et al., 2013; Puppala et al., 2015).

Table 2.2: Chemical Requirements for Fly Ash Classification (Puppala et al., 2015)

Properties	Class F (%)	Class C (%)
Silicon dioxide (SiO_2) + Aluminium Oxide (Al_2O_3) + Iron Oxide (Fe_2O_3) (Minimum)	70.0	50.0
Sulphur Trioxide (SO_3) (Maximum)	5.0	5.0
Moisture Content (Maximum)	3.0	3.0

Barapukuria Thermal Power Plant (BTPP) is Bangladesh's only coal-based power plant. BTPP produces 300 metric tons of coal combustion fly ash per day by burning 2,400 metric tons of coal to generate 250 MW of electricity. The massive amount of fly ash disposed of in the open air is a serious threat to the environment (Arfien et al., 2013; Khan et al., 2013).

The Physico-chemical properties (Table 2.3) of BTTP fly ash have a pH value of 6.2, which is almost neutral. The presence of unburnt carbon is around 2% which is favorable for cement production. The bulk density is 0.9 g/cm^3, indicating that the fly ash can be used for embankments and road construction. The liquid limit is around 47%, suggesting that the sample is suitable for other construction works (Khan et al., 2013; Tamim et al., 2013).

Table 2.3: Physico-Chemical Characteristics of BTTP Fly Ash (Khan et al., 2013)

Parameters	Average ± SD
pH	6.20 ± 0
Conductivity (ms/cm)	0.40± 0
Moisture content (%)	1.08 ± 0.106
Unburnt carbon content (%)	2.00 ± 0.101
Bulk density (gm/cm^3)	0.90± 0.014
Specific gravity	2.12± 0.007
Water holding capacity (%)	78.76 ± 0.647
Liquid limit (%)	47.00 ± 1.414
Plastic limit (%)	Nil

The qualitative analysis shows that the BTTP coal fly ash in Bangladesh is classified as Class F Fly ash (Tamim et al., 2013). The chemical composition of BTTP fly is shown in Table 2.4, where the percentage of silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3) is around 93.62% indicating the fly ash is Class F type (Khan et al., 2013).

Table 2.4: Chemical Composition of the BTTP Fly Ash (Khan et al., 2013)

Composition	Percentage by Weight
SiO_2	50.20
Al_2O_3	40.10
Fe_2O_3	3.32
TiO_2	2.38
CaO	1.92
MgO	0.20
Na_2O	0.06
K_2O	0.93
P_2O_5	0.66
SO_3	0.45
MnO	0.05
NiO	0.01
CuO	0.0158
ZnO	0.0068
PbO	0.0073
Loss on Ignition (LOI)	2.00

From Table 2.4, the major component of fly ash is alumina (Al_2O_3) and silica (SiO_2), which indicate the components are useful for alumina and aluminum recovery, agrochemicals, construction materials, carbothermal reduction process etc. In addition, various trace elements of the fly ash are useful for plant growth in agriculture fields. The sulfur trioxide (SO_3) content is significantly less and not hazardous to the environment. The chemical composition also revealed that the fly ash of BTTP in Bangladesh is pozzolanic and will be useful for cement and concrete manufacturing and stabilization of various problematic soils (Khan et al., 2013; Tamim et al., 2013).

2.6.3 Effect of Other Stabilizers on Dispersive Soil

2.6.3.1 Lime Stabilization

The use of lime for stabilizing soil, sand, and ancient structures has been one of the most practical methods for the past 5000 years. In Thailand, the lime Stabilization technique is very familiar. The major advantages are attributed to the Physico-chemical stabilizing effects due to soil-lime reactions (Nagy et al., 2016). Hence, lime is suitable for construction materials for earth-fill typed infrastructures such as dams, embankments, etc. (Belarbi et al., 2012; Beetham et al., 2014; Puppala et al., 2015)

Stabilization of soil by lime is achieved through cation exchange, flocculation, agglomeration, lime carbonation and pozzolanic reaction. Cation exchange, flocculation and agglomeration reactions take place rapidly and cause immediate changes in soil properties such as strength, plasticity, and workability. On the other hand, the pozzolanic reactions are time-dependent. These pozzolanic reactions of lime are achieved through cation exchange, flocculation, agglomeration, lime carbonation and pozzolanic reaction (Puppala et al., 2015).

The lime additives are three types, i.e. Calcium Oxide (CaO), Calcium Hydroxide, $Ca(OH)_2$ and Calcium Carbonate ($CaCO_3$). The chemical reactions are as follows (Sherwood, 1995):

$$CaCO_3 + \text{heat} \longrightarrow CaO + CO_2 \tag{2.1}$$

$$CaO + H_2O \longrightarrow Ca(OH)_2 + \text{heat} \tag{2.2}$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O \tag{2.3}$$

The four basic pozzolanic reactions can be described as follows (Schoute, 1999; Nelson and Miller, 1992; Little, 1995; Puppala et al., 2015):

(1) Cation exchange:

$$Ca(OH)_2 = Ca^{2+} + 2(OH)^- \tag{2.4}$$

(2) Flocculation/agglomeration

(3) Carbonation: Equation 2.3

(4) Pozzolanic reactions:

$$Ca^{2+} + 2[OH]^- + SiO_2 \rightarrow \text{C-S-H (gel)} \tag{2.5}$$

$$Ca^{2+} + 2[OH]^- + Al_2OH \rightarrow \text{C-A-H (gel)} \tag{2.6}$$

2.6.3.2 Cement Stabilization

Soil stabilization with cement is currently one of the most widely used methods. Portland cement and soil mix of proper moisture content produce soil-cement, a structural material that is hard and durable. However, geotechnical problems arise in modern urban construction in soft clay owing to its low strength, low durability, and high compressibility. In such circumstances, cement is often used as an additive to improve in situ soft clay soils' strength, durability, volume stability, and compressibility (Nelson and Miller, 1992; Puppala et al., 2015).

The soil cement mixing has been used for many diverse applications, including building and bridge foundations, retaining structures, liquefaction potential mitigation, temporary support of excavation, water control and structures to protect the natural environment, pollution control by using stabilization/solidification (S/S) techniques that aim to immobilize the source of cement.

Cement can also be used for dispersive soil stabilization because of the presence of calcium and aluminum ions which can replace the sodium ion responsible for dispersibility. When cement is mixed with soil, generally, there is a reduction in liquid limit, plastic limit and the potential for volume change of soils. However, there will be an increase in the shrinkage limit and shear strength. The increase in strength of cement-treated soil is by primary and secondary cementitious reactions in the soil-cement matrix. The primary cementation is due to hydration products of Portland cement. Hydration reactions form a variety of compounds and gels. The Portland cement is a heterogeneous substance containing tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetra calcium alumino-ferrite (C_4AF). The hydrous silica and alumina slowly react with calcium ions liberated from the hydrolysis of cement to form insoluble compounds that harden on curing to stabilize the soil (Vakili et al., 2012)

2.6.3.3 Alum Stabilization

Alum {aluminum sulfate ($Al_2(SO4)_3 \cdot 18H_2O$)} is commonly used for the treatment of these types of soils. The interaction of soil–additives during the treatment process is a Physico-chemical phenomenon. Double hydrometer testing indicates that the application of 1.5% aluminum sulfate caused a noticeable decrease in dispersivity potential (Beetham et al., 2014). The results obtained indicate that the addition of alum causes a decrease in the pH level of dispersive bentonite. In this process, a distinguishable change in the engineering properties of soil occurred, including a reduction in liquid limit and an increase in hydraulic conductivity. The replacement of sodium ions with aluminum ions in the double layer of the clay particles resulted in a decrease in the thickness of the particles' double layers. Two different phenomena were responsible for overcoming soil dispersivity, ion exchange and pH effects (Ouhadi and Goodarzi, 2006).

2.3.6.4 Stabilization with ZELIAC

ZELIAC is considered a new stabilizer in treating dispersive clay. It consists of zeolite, activated carbon, limestone, rice husk ash, and Portland cement (Mojiri et al., 2014a). The ZELIAC was investigated for treating Malaysian dispersive clay soil, where an appreciable decrease in dispersivity was achieved due to treatment with 8% ZELIAC. After 28 days of curing, the initially dispersive samples became non-dispersive. Furthermore, due to the treatment, the samples had increased unconfined compressive strength (UCS), permeability, optimum moisture content, and decreased fines content, plasticity index, maximum dry density, and compressibility index (Vakili et al., 2015; Vakili et al., 2017). In any soil stabilization project, the sustainability and nonhazardous nature of the additive must be ensured. ZELIAC is qualified as a nonhazardous composite material produced using naturally existing low-cost ingredients such as zeolite, activated carbon, calcium carbonate, rice husk ash and Portland cement (Mojiri et al., 2014a; Vakili et al., 2017). These materials improve the cementing properties and have been used to reduce the cement content in the composite.

2.7 Past Researches

Indraratna et al. (1991) researched the influence of pozzolanic fly ash to stabilize dispersive soil. It was noted that the addition of fly ash reduced erosion and dispersive behavior significantly. However, it was also noted that excessive use of fly ash more than 8% causes segregation again due to insufficient cohesion. Note 13, USDA (1991) described that dispersive soil differs from ordinary erosion-resistant soil because of the preponderance of sodium in the pore water. The note described four tests to determine the dispersive soils: crumb test, double hydrometer test, pinhole test, and chemical test. Engineering Field Handbook (EFH) Notice 210-WI-62 (1992) listed that the plasticity of dispersive soil is low to medium, and it was classified as CL in the Unified Soil Classification System (USDA). The note also described that soil color is not a suitable distinguishing feature for identifying dispersive soils.

Ouhadi and Goodarzi (2005) found that dispersive soil was the leading cause of failure for geotechnical and geoenvironmental projects. The problems were overcome by chemical treatments using alum {aluminum sulfate ($Al_2(SO_4)_3.18H_2O$)}, and the application of 1.5% of aluminum sulfate reduced the dispersibility significantly.

DAF, Farm Note 386 (2009) and DAF, Farm Note 387 (2010) stated that clay particles are negatively charged on their surface and stabilized with charged cations such as Ca^{+2}, Mg^{+2}, K^+ and Na^+. When Na^+ ions are higher than the other ions, the clay particles are less tightly bound and quickly disperse in the presence of water. For ameliorating dispersive soils, the notes suggested applying lime or gypsum, the addition of organic matter and the use of waterlogging tolerant crops.

Hardie et al. (2007) and Hardie (2009) found the relations between dispersive soil and tunnel erosion in southern and northern Tasmania, Australia. It was revealed that tunnel erosion in dispersive soils mostly occurs in the areas with Triassic sandstone or Permian mudstone and deep sedimentary soils. However, tunnel erosion occurs when the slope is over 10 degrees near drainage lines and vegetation, soils, and local hydrology have been disturbed. The initial identification of dispersive soil can be identified by dribble patterns and the development of spew holes. This paper described that the risk of tunnel erosion or piping failure for small earth dams could be minimized by adequate compaction, chemical ameliorants with gypsum, hydrated lime, sand filters, and construction of the dams with nondispersive clay and topsoiling (Faulkner, 2006).

Bhuvaneshwari et al. (2007) researched stabilization and microstructural modification of dispersive soil with various lime and fly ash percentages. The paper discovered that dispersive soil has high swell shrink potential, low resistance to erosion and low permeability in an intact state. The strength development occurs with the addition of suitable additives and the alteration in the microstructure and mineralogy. The amount of dispersion decreased with the addition of 5% lime and 2% lime + 15% fly ash mixture. However, the researchers did not find significant changes when adding fly ash alone.

Vyas et al. (2011) tried to be stabilized dispersive soil by blending polymers from Dundiya Dam, Udaipur, Rajasthan, India. Dispersive soils are unsuitable for hydraulic earth structures due to dissolved Na^+ instead of Ca^{+2} and Mg^{+2} in the pore water. Therefore, it is mandatory to stabilize these problematic soils either mechanically or chemically before using them for construction. The blending of polymers like polyvinyl alcohol, urea, formaldehyde, polyurethane, epoxy resin and styrene butadiene rubber latex with dispersive soil showed a remarkable soil stabilization effect due to the formation of a bond between clay mineral and polar end groups of polymers.

Umesh et al. (2011) characterized the dispersive soils with various standardized tests such as shrinkage limit and UC test other than pinhole and double hydrometer tests. The dispersivity of soils can be identified with some simple tests in the field and laboratory but very difficult to quantify dispersivity. It was observed that quantifying the dispersivity from the strength test is more reliable.

Vakili et al. (2012) investigated that adding pozzolan followed by curing time reduces the dispersivity of soils remarkably. Dispersive soil stabilized by pozzolan increased unconfined compressive strength (UCS), decreased plasticity index (PI), decreased percent sodium, and increased electrical conductivity (EC). In addition, sodium cation (Na^{+}) in between soil pallets is replaced by Aluminium (Al^{+2}), and calcium ions (Ca^{+2}) that have higher valences cause the decrease of swelling properties of dispersive soils.

Clays are considered watertight and erosion resistant materials. Generally, clays are used for flood protection and dikes. However, if the clays are dispersive soil, the surface of hydraulic structures erodes in the presence of water or rainfall and ultimately destroys the structure. The laboratory tests showed that most dispersive soil has pH values higher than 8.2 and percent sodium values higher than 2.3, respectively, the lower and upper limit of soil salinity (Nagy et al., 2016).

Dispersive soil can be treated with granulated blast furnace slag (GBFS) and basic oxygen furnace slag (BOFS). In the laboratory, two types of slags are used separately from 2.5% to 30% with dispersive soils and experiments are carried out to study the physicochemical, mechanical and microstructural changes of soil samples. It was observed that with the increase in curing time, the potential of dispersivity was decreased and improved the strength of composite samples. Furthermore, the SEM micrographs of soil samples revealed the cementations products in between the soil particles (Goodarzi and Salimi, 2015).

The researchers listed the following tests and experiments to recognize the dispersive soils:

(i) Field observation (color and variety of eroded forms).

(ii) Physical tests (double hydrometer test, pinhole test and crumb test).

(iii) Chemical Measurements by Sodium Adsorption Ratio (SAR), Exchangeable Sodium Percentage (ESR), and Cation Ratio of Soil Structural Stability (CROSS) (Marchuk and Rengasamy, 2012).

(iv) Mechanical tests (Atterberg limits, compression strength, shear strength, compaction, and density)

The potential dispersivity can be reduced by chemical reaction, mechanical reinforcement, or combining chemical and mechanical methods. For example, lime, gypsum and cement are common chemical materials (Abbaslou et al., 2016).

Dispersive soils are vulnerable to severe erosion even in quiet water. The soils were treated with chemical additives such as lime, cement, pozzolans, polymers and fly ashes. The brown coal fly ash from Hazelwood Power Station, Australia, is high in Calcium Sulphate, Calcium Oxide and Magnesium Oxide. The researchers used brown coal fly ash with lime as a secondary binder for stabilizing the dispersive soils. The obtained test results showed that brown coal fly ash effectively reduces the dispersivity of soils with the addition of lime (Premkumer et al., 2016). A few researchers found that fly ash did not cause any significant changes in the dispersion of dispersive soil. However, the addition of lime with fly ash imparts changes in the dispersive characteristics (Rani et al., 2017).

Ashraf and Islam (2018) stated that soil dispersion behavior happened due to the presence of exchangeable Sodium (Na^+). It was observed that the attractive forces between the soil particles are less than the repulsive forces, which cause the ultimate dispersivity. It was revealed that only the use of fly ash in various percentages reduced the dispersivity of soils significantly.

Wang et al. (2019) tried to stabilize the dispersive soil with bioengineering methods. To ameliorate the effect of dispersivity, the researchers used nutrient-rich organic amendments to improve the physical structure of dispersive soils. Researchers found that wheat (*Triticum aestivum*) plants and roots effectively reduce the dispersivity of soil. However, the test results need further review of bioengineering methods.

Faruk et al. (2019) studied the effects and influence of fly ash on dispersive soils available in Bangladesh. The use of optimum percentages of fly ash reduces the dispersivity significantly. Fly ash is the common residue produced from the combustion of coal. At various coal power plants, fly ash was released into the atmosphere unconditionally, which is a matter of great concern for environmental pollution. These situations pose an imminent threat in a densely populated country like Bangladesh (Tamim et al., 2013). Therefore, many researchers in Bangladesh have emphasized the waste management of fly ash. The effectiveness of fly ash and cement are studied for compressed stabilized earth blocks (CSEB) construction, and the results are very satisfactory for sustainable construction materials (Islam et al., 2020; Elahi et al., 2020).

The dispersivity of soil mostly depends on mineralogy and clay chemistry. It has been discussed that various additives are used to reduce the dispersivity of dispersive soil, and the ultimate results are satisfactory. Stabilizing dispersive soil using biological methods is a new and uncommon phenomenon. The researchers used bacteria named *Bacillus sphaericus* and *Bacillus pasteurii* to assess the impact of bacteria strains on the improvement parameters of soils. Biological stabilization can be an alternative soil improvement method as an eco-friendly and effective way for sustainable development (Abbaslou et al., 2020).

In Bangladesh, the use of fly ash is increasing for research purposes. Recently engineering characteristics of CSEB with cement and fly ash were studied. The results of fly ash were as follows:

(i) The addition of fly ash increased the compressive strength of the blocks.
(ii) The inclusion of fly ash increased the flexural strength of the blocks.
(iii) Fly ash showed a significant effect on the shear strength of the stabilized mix.
(iv) Fly ash was very effective to increase the value of cohesion c' and angle of internal friction φ'.

As such, fly ash is considered one of the suitable and sustainable construction materials in Bangladesh (Elahi et al., 2021).

2.8 Research Gaps

From the above discussions, the research gaps can be identified as follow:

(1) The number of deliberate research for sodic or dispersive soil is less worldwide.

(2) Only a few research were carried out on the dispersive soil available in Bangladesh.

(3) Researchers from last decades opined for Physico-chemical methods to stabilize the dispersive soil. Physical stabilization was the choice of researchers at the end of the last century. The chemical stabilization was very popular among the researchers using alum, cement, fly ash, gypsums, polymers, ZELIAC etc.

(4) However, as a stabilizing agent for dispersive soil, fly ash has mixed results, both favor and disfavor.

(5) The use of fly ash to stabilize dispersive soil in Bangladesh has very little research.

(6) The waste management and environmental use of fly ash are less thought out in Bangladesh. Hence, the commercial use of fly ash in construction works will open a new horizon for waste management and a pollution free environment.

2.9 Summary

Dispersive soils demonstrate mild to severe erosive behavior when in contact with water. These soils erode unnoticed and cause the failure of earthen structures. These soils are characterized by an unstable structure, easily flocculated in water, and very erodible. Using this type of soil in hydraulic structures, embankment dams, or other roadway embankments can cause serious engineering problems if these soils are not identified and used appropriately. Visually and in normal dry weather conditions, dispersive soils cannot be identified very easily. The soil is highly susceptible to erosion and contains a high percentage of exchangeable sodium ions.

Many techniques have been developed to reduce the associated problems related to dispersive soils. The most common treatment applied for stabilization of dispersive soil is the use of chemical additives such as alum, bioengineering with plants and plant roots, biological methods with *Bacillus sphaericus* and *Bacillus pasteurii*, basic oxygen furnace slag (BOFS), cement, fly ash, granulated blast furnace slag (GBFS), pond ash, rice husk ash, polymers, lime, ZELIAC etc.

It was observed that a few research were carried out for the dispersive soil, which is available in Bangladesh. Researchers mainly depended on physicochemical methods. The use of fly ash for stabilizing dispersive soil has a mixed response. Previously Bhuvaneshwari et al. (2007) stated that only the addition of fly ash alone does not significantly reduce dispersivity. On the other hand, Elahi et al. (2021) found fly ash as a suitable and sustainable construction material in Bangladesh. Besides, Ashraf and Islam (2018) and Faruk et al. (2019) found the suitability of fly ash over dispersive soils stabilization. Therefore, fly ash available in Bangladesh is considered to determine the strength characteristics of dispersive soil.

Chapter Three

EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter describes various tests and test methods used in this study. Different techniques are used to investigate the degree of dispersion and engineering properties of soil. In addition, the strength characteristics of dispersive soil stabilized with Barapukuria Thermal Power Plant (BTPP) fly ash is taken for the experimental program. This chapter also discusses the procedure of various laboratory tests and criteria for dispersiveness.

3.2 Materials

The core two materials used for this research are dispersive soil and fly ash. Dispersive soil was collected in disturbed conditions from Bhanga, Faridpur District of Bangladesh. Fly ash was collected from the Barapukuria Thermal Power Plant (BTPP) of the Dinajpur District of Bangladesh. Locations of dispersive soil and fly ash are presented in Figure 3.1a and Figure 3.1b, respectively.

(a) (b)

Figure 3.1: Location of: (a) dispersive soil sample, Bhanga, Faridpur, (b) fly ash, Barapukuria Thermal Power Plant (BTPP), Dinajpur

3.2.1 Dispersive Soil Sample

Dispersive soil sample was collected in disturbed conditions from the location shown in Figure 3.1a. Using a spade, soil samples were collected from 0.8 m below the ground surface. Collected soil samples were put into plastic bags to prevent moisture loss. All the samples were transported to the Geotechnical Engineering Laboratory of Bangladesh

University of Engineering and Technology (BUET), Dhaka. Collected soil samples were air dried and crushed using a wooden hammer. All the foreign materials were removed before doing the tests.

3.2.2 Fly Ash

When coal is burned at a high temperature inside the furnace of a power plant, it produces hazardous gases like SO_2, NO_2, CO_2, and NH_2 along with fly ash as waste and potentially hazardous material. The microparticles of fly ash create several pollution problems in the air, soil surface, and groundwater around the power plant area. Rainwater absorbs the gases of fly ash and produces toxic substances like H_2SO_4, HNO_3, H_2CO_3, NH_4OH etc. In addition, the rainwater increases the acidity of soil nearby the power plant and damages the surrounding crops field devastatingly. In this study, fly ash was collected from Barapukuria (Figure 3.1b). Properties of the fly ash used in this investigation are given in Table 4.2 of Chapter 4.

3.3 Test Methods

According to the standards, a series of laboratory tests, including Standard Proctor Compaction Test, Unconfined Compression Test, Pinhole Test, Crumb Test, Double Hydrometer Test, Chemical Test and SEM, are conducted on both treated and untreated soil to evaluate the potential of a stabilizer to reduce the dispersivity. The Standard Test procedure followed in determining the properties of the soil is given in Table 3.1.

3.4 Atterberg Limit Test

The Atterberg limits are an essential measure of the critical water contents of a fine-grained soil to find out shrinkage, plastic, and liquid limits. In dry conditions, clay soil takes on increasing amounts of water and undergoes distinct changes in behaviour and consistency. Depending on the water content of the soil, it may appear in four states: solid, semi-solid, plastic and liquid. In each state, the consistency and behaviour of soil are different and, consequently, the engineering properties. The Atterberg limit tests are conducted in accordance with ASTM D 4318. Liquid limit (LL) is the limit of water content beyond which the soil acts as if it is in a liquid state. It is the water content at the transition of liquid state to plastic state below which it gains a certain small shearing strength.

Table 3.1: Details of Laboratory Test Performed on Dispersive Soil with Fly Ash Contents

Type of Test	Sample Type	No of Test	Test Method
Liquid Limit and Plastic Limit	Untreated soil	1	ASTM D 4318
Shrinkage Limit	Untreated soil	1	ASTM D 427
Specific Gravity of Soil	Untreated soil	1	ASTM D 854
Standard Compaction Test	Untreated soil	1	ASTM D 698
	Treated soil with fly ash	3	
Pinhole Test	Untreated soil	2	ASTM D 4647
	Treated soil with fly ash	3	
Double Hydrometer Test	Untreated soil	1	ASTM D 422
	Treated soil with fly ash	3	
Crumb Test	Untreated soil	2	ASTM D 6572
	Treated soil with fly ash	3	
Chemical Test	Untreated soil	1	ASTM D 4324
Scanning Electron Microscopy (SEM)	Untreated soil	1	ASTM E 2809
	Treated soil with fly ash	3	
Unconfined Compression Test	Untreated soil	4	ASTM D 2166
	Treated soil with fly ash	12	

Plastic limit (PL) is the minimum moisture content at which the soil can be deformed plastically. It can be taken as the smallest water content at which the soil began to crumble when rolled into a thread of 3 mm in diameter. At the plastic limit, soil gains some minimum stiffness. Shrinkage limit is the water content of the soil when the water is just sufficient to fill all the pores of the soil, and the soil is just saturated. The shrinkage limit test was carried out according to ASTM D 427. Plasticity index (PI) is the size of the range of water contents where the soil exhibits plastic properties. It is the numerical difference between liquid and plastic limits, PI=LL-PL. To identify the engineering properties of soil, the criteria are described in Tables 3.2, 3.3, and 3.4.

Table 3.2: Typical Values of Liquid and Plastic Limit (Atkins,1997)

Soil	Liquid Limit, LL	Plastic Limit, PL
Silt Clay mixture	25-40	20-30
Kaolinite clay	40-70	20-40
Montmorillonite clay	300-600	100-200

Table 3.3: Plasticity of Soil (Atkins,1997)

Plasticity Index (%)	Description	Dry Strength	Field Test
0-3	Non plastic	Very low	Grains fall apart easily
4-6	Slightly plastic	Low	Easily crushed by fingers
7-12	Moderately plastic	Low to medium	Slight pressure is required to crush
16-35	Plastic	Medium to high	Difficult to crush
Over 35	High plastic	High	Impossible to crush with fingers

Table 3.4: Swelling against Shrinkage Limit and other Index Properties (Whitlow, 1996)

Shrinkage Limit (%)	Liquid Limit (%)	% Colloids (<0.001 um)	Plastic Index (%)	Swelling Potential
>15	<39	<15	<18	Low
10-16	39-50	13-23	15-28	Medium
7-12	50-63	20-31	25-41	High
<11	>63	28	>35	Very high

3.5 Specific Gravity Test

The knowledge of specific gravity is required to calculate soil properties such as void ratio and degree of saturation. The specific gravity ($G_{s)}$ is the ratio of the density of an object divided by the density of water. In this study, the specific gravity test provided an important parameter of the soil sample, and the result was used for calculating percent dispersion in the Double Hydrometer Test. A pycnometer was used to determine the specific gravity of soil particles, followed by ASTM D 854. The following relation (Eqn. 3.1) determines the specific gravity of soil.

$$G=\frac{M2-M1}{(M2-M1)-(M3-M4)} \tag{3.1}$$

Where M_1=Mass of empty Pycnometer, M_2= Mass of the Pycnometer with dry soil, M_3= mass of the Pycnometer and soil and water, M_4 = mass of Pycnometer filled with water only.

3.6 Compaction Test

To determine the relationship between moisture contents and densities, a series of Standard Proctor Tests (SPT) were conducted on treated and untreated materials according to ASTM D 698-07. Optimum Moisture Contents (OMC) determined during compaction of treated and untreated soil samples with different fly ash contents (0%, 3%, 6% and 9%) were used to prepare specimens for Unconfined Compression (UC) tests, crumb test, pinhole test, chemical test and Scanning Electron Microscopy (SEM).

Treated and untreated soil samples were compacted in three layers with an automatic standard compactor with varying moisture contents. Moisture content and dry density determinations were made on each compacted sample. Fly ash treated samples were mixed thoroughly with varying amounts of water. Standard Proctor Compaction tests were conducted for 0%, 3%, 6%, and 9% fly ash stabilized soil to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).

3.7 Crumb Test

This test has been developed as a simple procedure to identify dispersive soil behaviour in the field. Nowadays, it is performed in the laboratory. The crumb test is a relatively accurate positive indicator of the presence of dispersiveness in soil. However, it can seldom be relied upon as a sole test method for determining the presence of dispersive clays. The double hydrometer test and pinhole test are the methods that provide valuable additional insight into the probable dispersive behaviour of clay soils.

3.7.1 Crumb Test Procedure

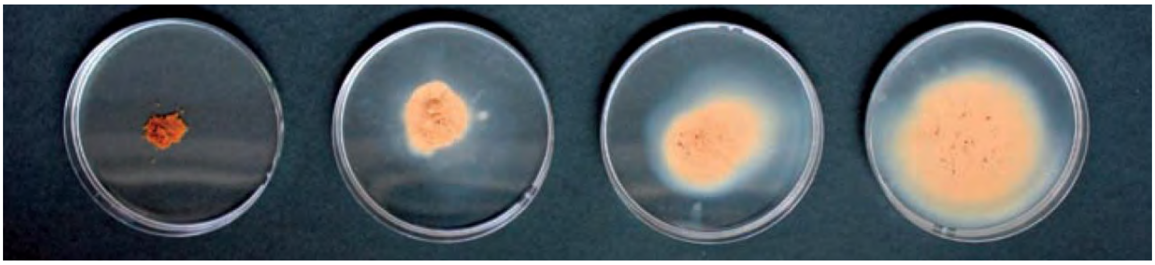
It consists of preparing a cubical specimen of about 15 mm at a natural moisture content. In this study, the soil was firstly air-dried and made soil crumble at OMC following the "Test Method B" stated in ASTM D 6572. Then, the specimen was carefully placed in 250 ml of distilled water and gently released only after placing it directly on the bottom of the dish. The tendency of colloidal-sized particles to deflocculate and go into the suspension was observed with an elapsed period. In this study, crumb tests were performed twice for each sample.

3.7.2 Crumb Test Criteria

Crumb test results are interpreted after 1 hour, and there are four grades of a possible reaction. Table 3.5 describes the four grades with their interpretation. Figure 3.2 presents grades of reaction in the crumb test.

Table 3.5: Interpretations of Crumb Test Results (ASTM D 6572; Maharaj et al., 2015)

Types of Grades	Reaction Criteria	Descriptions
Grade 1	No Reaction	The soil may crumble, slake, diffuse, spread out, and there is no turbid water.
Grade 2	Slight Reaction	A faint, barely visible colloidal suspension causes turbid water near soil to crumble.
Grade 3	Moderate Reaction	An easily visible cloud suspension clay colloids are seen all around the crumb.
Grade 4	Strong Reaction	A dense, profuse cloud of suspended clay colloids is seen around the entire bottom of the dish.



No Reaction	Slight Reaction	Moderate Reaction	Strong Reaction

Figure 3.2: Grades of reaction in crumb test of dispersive soil (Source: DAF, Farm Note 386, 2009)

3.8 Double Hydrometer Test

A double hydrometer test is performed to identify the dispersiveness of soil. This test is performed in the laboratory. When this test is performed in conjunction with the standard hydrometer test method ASTM D 422 on the same soil sample, this test method indicates the natural dispersivity of the soil sample. The test compares the measured percentage of clay in a sample artificially dispersed to that of a companion sample with no artificial dispersing agent added. In this method, two hydrometer tests are performed: (1) standard hydrometer test (2) hydrometer test with no mechanical agitation and chemical dispersing agent. According to ASTM D 4221, the degree of dispersion is given in Table 3.6, and the dispersion calculation is expressed in the Eqn. 3.2.

$$\text{Dispersion}=\frac{\%\text{ clay }(0.005)\text{without dispersing agent}}{\%\text{ clay }(0.005)\text{ with dispersing agent}}\times 100 \qquad (3.2)$$

3.8.1 Double Hydrometer Test Procedure

A 50 gm (passing No 40 sieve) of well pulverized and oven-dried soil sample is mixed with 4% Sodium Hexametaphosphate {$(NaPO_3)_6$} as a deflocculating agent. A 125 ml solution is prepared and mixed with distilled water to make 1000 ml of solution in a graduated jar. The jar is shaken vigorously, and immediately after placing the hydrometer jar on the table, the hydrometer is inserted into the soil water suspension, the timer starts, and the hydrometer readings at elapsed times of 0.25, 0.5, 1, and 2 minutes are noted carefully. The timer is to be continued at elapsed times of 4, 8, 15, 30, 60 minutes, and 2, 4, 8, 16, and 24 hours. While taking a reading, the hydrometer is placed separately in a 1000 ml cylindrical jar for obtaining temperature and zero correction, in the same amount of deflocculating solution as used in the test {125 ml of 4% $(NaPO_3)_6$} mixed with water. The reading difference between the jars gives zero correction. Figure 3.3 shows the double hydrometer test arrangement. The same procedure applied with the same amount of soil sample with no artificial dispersing agent was carried out simultaneously. This method determined the number of particles smaller than 5 µm determined without dispersing agent, compared with the total amount of particles smaller than 5 µm following the test method ASTM D 422. Same tests are carried out on the soil samples stabilized with 3%, 6% and 9% fly ash contents. The results and observations are discussed in Chapter 4.

3.8.2 Double Hydrometer Test Result Criteria

Table 3.6 describes the general guidelines for the degree of dispersion:

Table 3.6: Degree of Dispersion from Double Hydrometer Test (ASTM D 4221; Maharaj et al., 2015; EFH, USDA, 1992; Note 13, USDA, 1991)

Percent Dispersion	Degree of Dispersion
<30%	Non-dispersive
30% to 50%	Intermediate
>50%:	Dispersive

(a) (b)

Figure 3.3: Double hydrometer test: (a) with dispersing agent, (b) without dispersing agent

3.9 Pinhole Test

Pinhole test presents a direct and qualitative measurement of dispersivity of soil and consequent colloidal erodibility by causing water to flow through a small hole punched in the soil specimen. This method relates the turbidity of a cloud of suspended clay colloid, flow rates and final diameter after water flow as indicators of dispersivity. In this study, the method described in ASTM D 4647 has been followed to classify the soil samples. Pinhole test gives the most reliable value in identifying dispersion among all the tests.

3.9.1 Pinhole Test Procedure

Pinhole test method starts with preparing the sample by compacting the sample into the apparatus cylinder on top of the coarse sand and wire screen which was previously placed in the cylinder. The coarse sand must be such that it passes through the #4 sieve. The purpose of using coarse sand is to ensure proper drainage. Again, wire mesh was used at the coarse sand and soil sample interface so that the clay soil does not get washed away into the coarse sand.

Distilled water flowing horizontally under a hydraulic head of 50 mm through a 1 mm hole punched in a soil specimen under the initial 50 mm head provides the principal difference between dispersive and nondispersive soil. Then the water flow was carried out under the heads of 180 mm and 380 mm. If the colour of the flowing water is moderately dark, the test for the 1020 mm head is not carried out. It is to be noted that flow from slightly to moderately dispersive soil will be slightly dark with a constant hole size and flow rate. On the other hand, flow from nondispersive clays will be completely clear with no measurable increase in hole size, and the flow rate will be less than 3.0 ml/s at 1020 mm head. The schematic diagram of the pinhole apparatus is given in Figure 3.4.

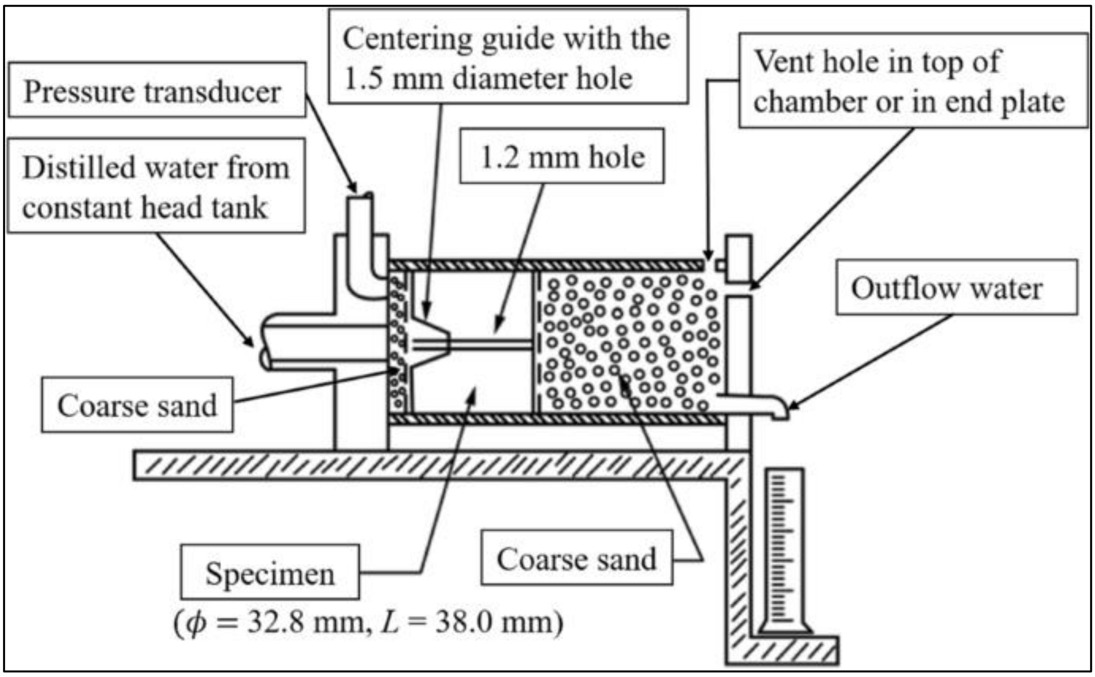


Figure 3.4: Schematic diagram of pinhole test apparatus (ASTM D 4647)
(Source: https://link.springer.com/article/10.1186)

3.9.2 Pinhole Test Result Criteria

Table 3.7 describes the evaluation procedure of pinhole test results. The categories are defined as follows.

D1: the sample rapidly eroded at 50 mm head. The pinhole enlarges at least twice the diameter. The flow rate exceeds 1.4 ml/s after 5 minutes.

D2: severe erosion of the hole occurs at 50 mm head. 10 minutes is required for the flow rate to increase by more than 1.4 ml/s. The eroded hole has a diameter of 1.5 mm.

ND4: the flow rate at 50 mm head does not exceed 1.0 ml/s. The turbidity of collected water is at least slightly dark. The hole diameter is less than 1.5 mm, and the flow rate is more than 1.4 ml/s. The soil is classified as ND4.

ND3: at a 180 mm head after 5 minutes of flow, the turbidity is slightly dark, the flow rate is at least 1.4 ml/s, and the hole diameter is greater than 1.5 mm.

ND2: at a 1020 mm head, if any turbidity is observed, the soil is classified as ND2.

ND1: no erosion is observed even with a 1020 mm head causing flow through the specimen. The collected water remains free from any colloidal cloud.

Table 3.7: Criteria for Evaluating Pinhole Test Result According to ASTM D 4647 (Nadal-Romero et al., 2009; Nadal-Romero et al., 2011)

Dispersive Classification	Head (mm)	Test time for given head, (min)	Final Flow rate through the specimen, ml/s	Cloudiness of flow at the end of the test		Hole Size After the Test (mm)
				From Side	From Top	
D1	50	5	1.0-1.4	Dark	Very dark	≥2.0
D2	50	10	1.0-1.4	Moderately dark	Dark	>1.5
ND4	50	10	0.8-1.0	Slightly dark	Moderately dark	≤1.5
ND3	180	5	1.4-2.7	Barely visible	Slightly dark	≥1.5
	380	5	1.8-3.2			
ND2	1020	5	>3.0	Clear	Barely	<1.5
ND1	1020	5	≤ 3.0	Perfectly clear	Perfectly clear	1

3.10 Chemical Test

Chemical test consists of the extraction of pore water from saturated soil. This test identifies the Exchangeable Sodium Percentage (ESP) and Sodium Absorbent Ratio (SAR) in dispersive Soil. As previously discussed, the dispersivity of soil is caused by excessive repulsive forces due to the presence of Sodium. Hence, the chemical test provides a molecular view of dispersivity. First, 5 gm of well pulverized sample was taken into a beaker, and 7.5 ml HCl and 2.5 ml HNO_3 were added and preserved for 24 hours. Then the mixture was boiled for about 3 hours. Boiling is done to extract pore water from the saturated slurry of the soil sample. After boiling, water was added to make the volume of 500 ml solution, and the mixture was filtered. Afterwards, 9 ml of demineralized water and 1 ml of filtered samples were mixed. Thus, a ten thousand times diluted sample was prepared. Finally prepared sample was put into an analyser to get the amount of sodium, magnesium, calcium, and potassium. The estimation procedure of ESP is presented in Eqn. 3.3. Table 3.8 presents the relation between the degree of dispersion and ESP.

$$\text{ESP}=\frac{Na}{TDS}\times 100 \tag{3.3}$$

Where, TDS= Ca + Mg + K + Na

Table 3.8: Relation between Degree of Dispersion and ESP (DAF, Farm Note 386, 2009)

Rating	Exchangeable Sodium Percentage (ESP)	Soil Dispersion Test
Non-sodic	<6	No dispersion is evident after 24 hours. Aggregates slaked but not dispersed clay.
Slightly Sodic	6 to 10	Dispersion is evident after 24 hours. Soil aggregates slightly disperse.
Moderately Sodic	10 to 15	Dispersion is evident after several hours. Soil aggregates partially disperse.
Highly Sodic	>15	Dispersion is evident in less than 30 minutes. Soil aggregates highly disperse.

3.11 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) provides detailed high-resolution images of the sample by restoring a focussed electron beam across the surface and detecting secondary or backscattered electron signals. An Energy Dispersive X-Ray Analyser is also used to provide elemental identification and quantitative compositional information. SEM provides images with magnifications up to ~X50000, allowing sub-micron scale features to be seen, i.e., well beyond the range of optical microscopes. In this research, SEM tests are performed using the facilities available at the Department of Glass and Ceramic Engineering (GCE), BUET for treated and untreated samples stabilized with 3%, 6% and 9% fly ash contents to check whether the soil fabric gets flocculated or not.

Figure 3.5: Scanning Electron Microscopy Machine at the Department of GCE, BUET (Source: www.buet.ac.bd)

3.12 Unconfined Compression Test

A series of Unconfined Compression (UC) tests were conducted on treated and untreated soil samples stabilized with 0%, 3%, 6% and 9% fly ash following the ASTM D 2166. However, the focus of this study is to minimise dispersion phenomena of soil with varying percentages of fly ash. The influence of fly ash on the strength behaviour based on the compressive strength is obtained from the UC test.

3.12.1 Sample Preparation for Unconfined Compression Test

In Section 3.6, it is mentioned that compaction tests were carried out on treated and untreated soil samples to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each soil sample stabilized with 0%, 3%, 6% and 9% fly ash contents. After compaction, the specimens from standard compaction moulds were ejected by a hydraulic ejector. Then the samples were cut into four parts and carved to make specimens of 76 mm diameter and 153 mm height using a spatula and a sharp metallic mould. Four specimens without defects were prepared; one was tested immediately after preparation, and others were kept for curing. The same procedure was applied for the treated soil samples stabilized with 3%, 6%, and 9% fly ash contents. Thus 12 samples were prepared, and 3 samples of 3%, 6%, and 9% fly ash mixed samples were tested immediately, and rests were kept for curing.

3.12.2 Curing of Samples

Both treated and untreated samples were cured in a desiccator for 7 days, 14 days and 21 days to observe the variation of strength with time. Curing is also carried out to ensure the proper bondage and pozzolanic reaction (Eqns. 2.4-2.6, Chapter 2) between the ash elements and soil. The samples were never cured with direct water spray or keeping samples in submerged conditions. The samples were always protected from free water for specified curing days. Samples were kept in a desiccator to sustain the initial moisture content at which the samples were prepared.

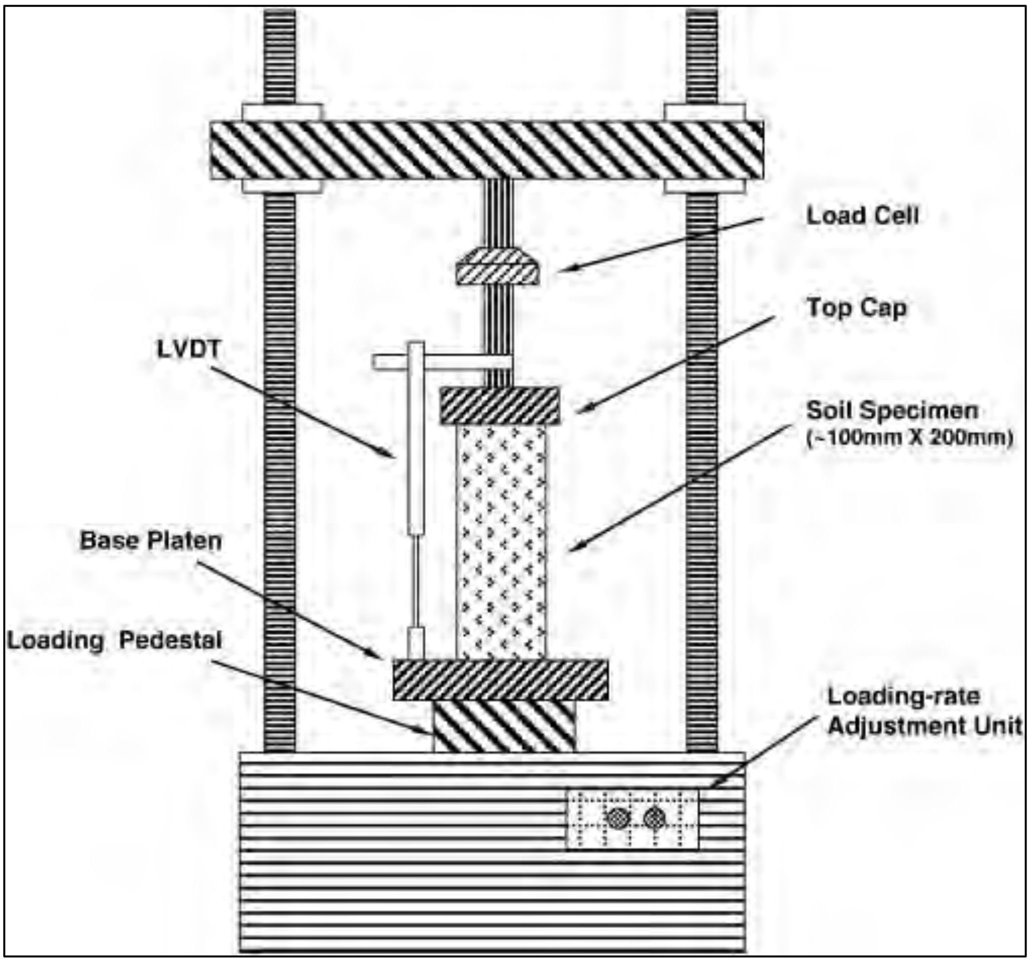


Figure 3.6: Schematic diagram of the unconfined compression test set-up (Source: www.sciencedirect.com)

Chapter Four
RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the laboratory tests results and their interpretation. At first, different tests were conducted to identify the dispersive soil and its dispersivity. Then untreated and fly ash treated soil samples were examined. Finally, the obtained data were collected, collated, and interpreted with knowledge of past research.

4.2 Index Properties of Untreated Dispersive Soil

Table 4.1 presents the index properties such as liquid limit, plastic limit, shrinkage limit and specific gravity of dispersive soil. From index properties, it is difficult to distinguish between dispersive soil and ordinary clay soil. Hence, index properties and specific gravity tests were not conducted for treated and untreated soil with varying percentages of fly ash. Instead, tests were carried out for untreated dispersive soil to understand the engineering parameters of soil index properties.

Table 4.1: Index Properties of Soil Sample

Parameters	Value
Specific Gravity	2.73
Liquid Limit, LL (%)	43
Plastic Limit, PL (%)	26
Shrinkage Limit, w_s (%)	18
Plasticity Index, PI (%)	17
Toughness Index, I_T	1.5
Flow Index, I_F	11

4.2.1 Engineering Properties According to Index Parameter

Various criteria related to index properties are described in Section 3.4. Properties of the tested soil (Table 4.1) for different index parameters are interpreted below:

(1) The liquid limit (LL) and the plastic limit (PL) values are 43% and 26%, respectively. According to Table 3.5, the range of liquid limit is within 40-70, and the range of plastic limit is within 20-40. It means that the soil is Kaolinite clay.

(2) The value of plasticity index (PI) has been obtained 17%. According to Table 3.6, the value falls in the range of 16-35, which means the soil is plastic in nature, has medium to high dry strength and is difficult to crush.

(3) The plasticity index (PI) <18, liquid limit (LL) <39 and shrinkage limit >15 means the swelling potential of the soil is low (Table 3.7). The plasticity index (PI) also indicates that the soil is extremely fine-grained.

(4) Toughness index is the ratio of the plasticity index (PI) to the flow index (I_F) of soil. The toughness index varies between 0 to 3. The results provide an idea of the shear strength of soil at its plastic limit. The toughness index of the soil is 1.5, which indicates that the soil has a low percentage of colloidal clay containing the mineral Kaolinite.

4.3 Compaction Test

Dispersive soils were treated with 3%, 6%, and 9% type F fly ash (w/w). Compaction tests were carried out on both treated and untreated soil samples in accordance with the Standard Proctor specification. The change in moisture content with dry density for all soil samples are given in Table 4.3 and Figure 4.1. Due to the progressive addition of fly ash with the dispersive soil, the maximum dry density increased a little, and on the other hand, the optimum moisture content (OMC) decreased with the increasing fly ash contents. Most importantly, OMC has been decreased sharply for the soil sample stabilized with 9% fly ash. It means that 9% fly ash is optimum for stabilizing the dispersive soil. Dry density vs moisture content of treated and untreated soil samples have been presented in Figure 4.1. The evaluations from the test results are as follows:

(1) The maximum dry density increases slightly with the increase of the fly ash content.

(2) The OMC decreases with the addition of fly ash. It is seen that OMC falls sharply with the addition of 9% fly ash with the dispersive soil. Due to the reduction of OMC, the ductility of the soil sample is lowered. Hence, this fact should be considered during dispersive soil stabilization using higher percentages of fly ash contents.

(3) The OMC decreases with the increase of fly ash due to the presence of free lime (CaO) in the fly ash, which is 5.80% (Table 4.2). In addition, the ductility of prepared soil samples decreases due to the hydration process and heat formation by free lime (CaO) as the water gets absorbed by fly ash.

Table 4.2: Comparison of Chemical Composition for Fly Ash

Compound	Chemical Composition (%) (Elahi et al., 2021)	Chemical Composition (%) (Khan et al., 2013)
SiO_2	51.20	50.20
Al_2O_3	23.80	40.10
Fe_2O_3	8.90	3.32
CaO	5.80	1.92
MgO	1.70	0.20
K_2O	0.20	0.93
Na_2O	0.30	0.06
SO_3	0.40	0.45
Others	4.30	0.82
LOI	3.40	2.00

Table 4.3: OMC and MDD of Dispersive Soil with Different Fly Ash Contents

Fly Ash Content	0%	3%	6%	9%
Optimum Moisture Content (%)	19.9	19.8	18.4	14.5
Maximum Dry Density (kN/m^3)	15.50	16.00	16.20	16.34

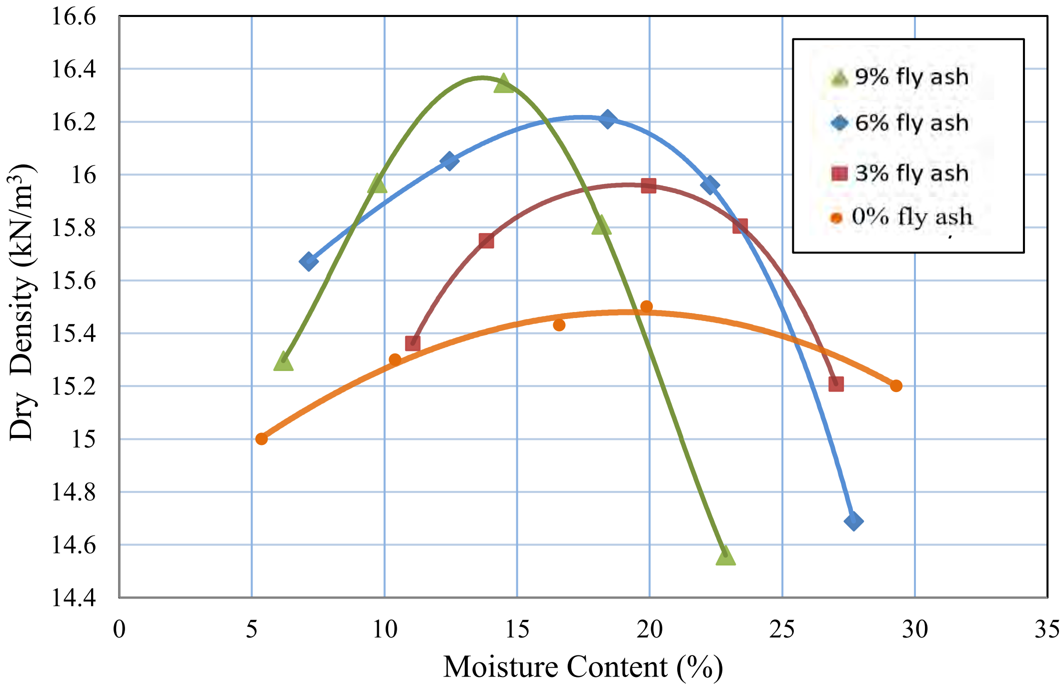


Figure 4.1: Moisture content and dry density relationship for untreated and treated soil samples with 3%, 6% and 9% of fly ash by weight

4.4 Degree of Dispersion of the Soil

As discussed before, the colour and texture of dispersive soils are like ordinary clay soil unless it comes in contact with stagnant, flood, or rainwater. When these types of soils come in contact with water, it starts eroding quickly. Most importantly, soil index properties do not distinguish between dispersive and nondispersive soils. Therefore, the recommended tests for identifying dispersive soils are pinhole test, crumb test, double hydrometer test and chemical test. These tests are conducted to anticipate the efficiency of fly ash in reducing the dispersibility of soil.

4.4.1 Crumb Test

Two crumb tests (Table 4.4) are carried out for dispersive soil samples without fly ash. The samples were observed instantly, after 15 minutes and after 1 hour. The conditions of the samples are shown in Figures 4.2 and 4.3.

The observations of soil Sample 1 were as follows:

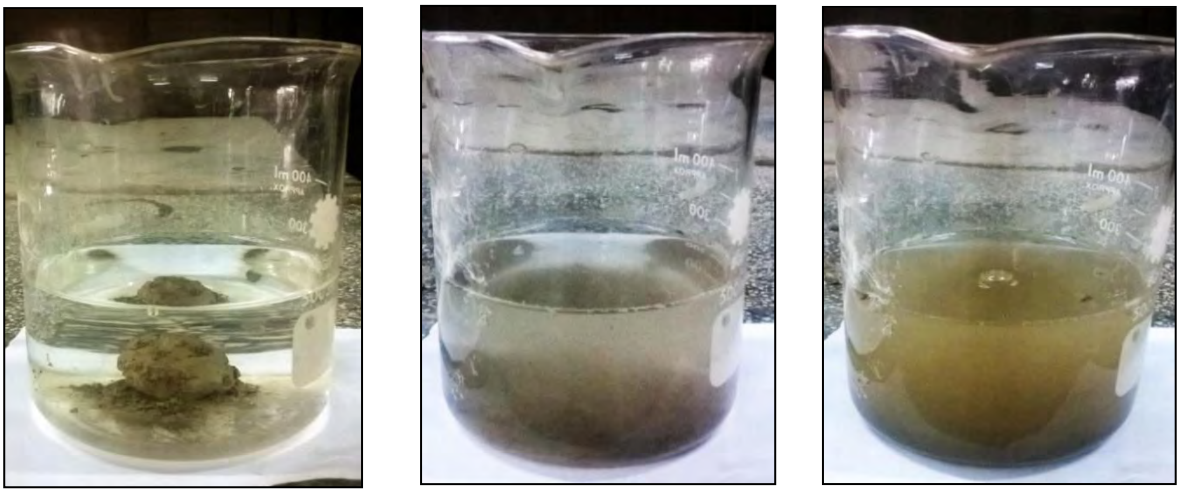
(1) The sample crumbled and slaked instantly after 1 minute.
(2) The less colloidal suspension was formed around the sample after 15 minutes.
(3) A dense, profuse cloud of suspended clay colloids formed at the bottom of the beaker.
(4) It indicates that the soil sample is highly dispersive and can be graded as Grade 4, as mentioned in Section 3.7.2.

The observations of soil Sample 2 were as follows:

(1) The sample started slaked after 1 minute.
(2) The sample crumbled and formed significantly less colloidal suspension after 15 minutes.
(3) An easily visible cloud of suspension clay colloids is seen at the beaker's bottom.
(4) It indicates that the soil sample is moderately dispersive and can be graded as Grade 3, as mentioned in Section 3.7.2.

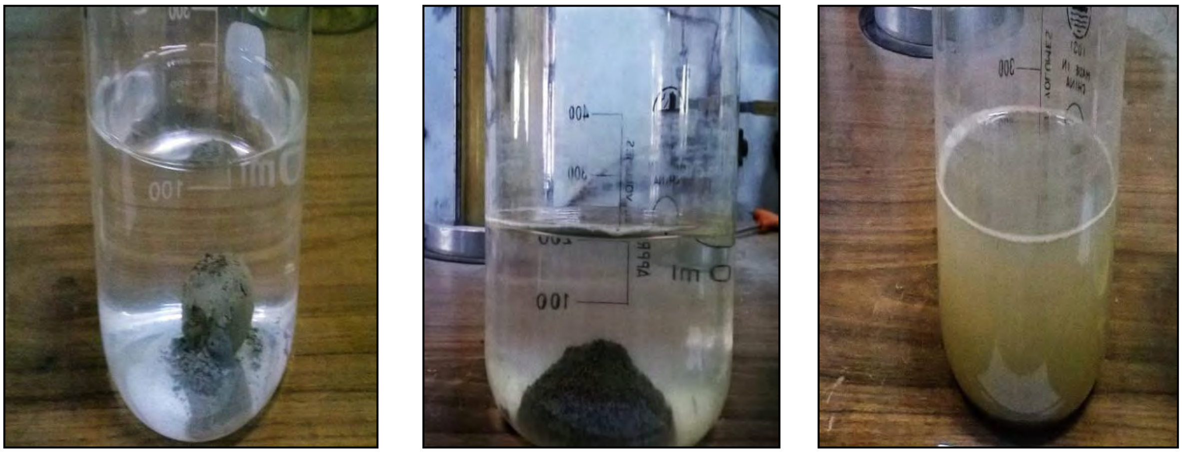
Table 4.4: Results of Crumb Test for Soil Samples

Sample No	Observation at instant	Observation after 15 minutes	Observation after 1 hour
Sample 1	Grade 1	Grade 3	Grade 4
Sample 2	Grade 1	Grade 2	Grade 3



(a) (b) (c)

Figure 4.2: Observation from crumb test of Sample 1: (a) instant, (b) after 15 minutes, (c) after 1 hour



(a) (b) (c)

Figure 4.3: Observation from crumb test of Sample 2: (a) instant, (b) after 15 minutes, (c) after 1 hour

Finally, based on all the observations, the soil can be considered moderate to high dispersive.

4.4.2 Double Hydrometer Test

A double hydrometer test is conducted for a dispersive soil sample, and the results are plotted in the graph in Figure 4.4. The percentage of clay particles without dispersing agent is obtained at 16, and using a dispersing agent is at 36. The percent dispersion (Eqn. 4.1) is calculated as follows:

$$\text{Dispersion}=\frac{\%\ \text{clay}\ (0.005)\text{without dispersing agent}}{\%\ \text{clay}\ (0.005)\ \text{with dispersing agent}}\times 100=\frac{16}{36}\times 100 = 44.44\% \qquad (4.1)$$

The percent dispersion of the selected soil sample is 44.44%. As mentioned in Table 3.7, the percent dispersion is in the range of 30% to 50%. Hence, the degree of dispersion of the soil sample is intermediate.

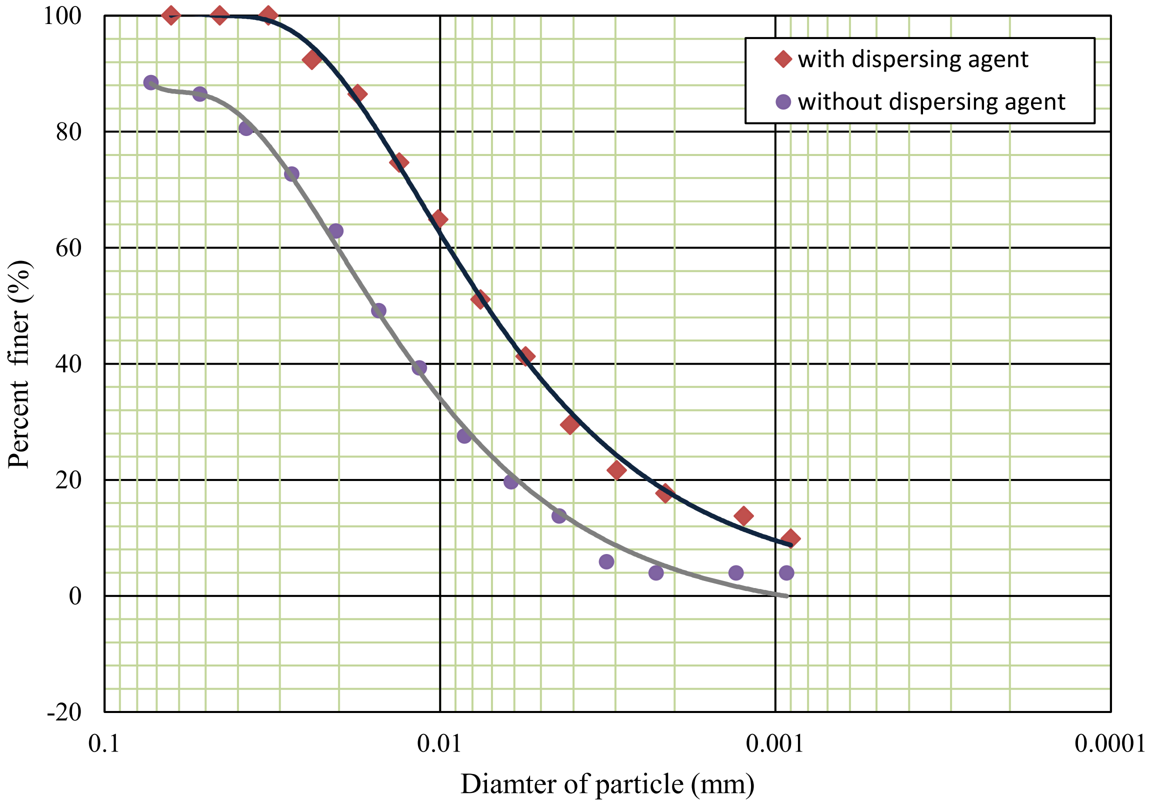


Figure 4.4: Double hydrometer test for dispersive soil

4.4.3 Pinhole Test

The results obtained from the tests are based on observation of turbidity of collected water and flow rate as discussed in Section 3.9.2. In addition, the enlargement of the 1 mm diameter hole inside the soil sample is measured afterwards to evaluate the test results as per ASTM D 4647.

The observations from Sample 1 (Figure 4.5 and Table 4.5) are as follows:

(1) Water collected has moderate turbidity and a light brown colour.

(2) Pinhole diameter increased four times the initial diameter.

(3) The soil sample falls in the category of ND4 as the flow is above 2.5 ml/s, which is more than 1.4 ml/s.

(4) The flow is moderately turbid, and the final diameter of the pinhole was about 6.5 mm at the top and 3.5 mm at the middle.

Table 4.5: Data Obtained from Pinhole Test of Sample 1

Head (mm)	Flow		Flow rate, ml/s	Turbidity from sides						Completely clear from the top	Remarks
	ml	sec		Very dark	Dark	Moderately dark	Slightly dark	Barely visible	Completely clear		
50	120	60	2.00						√		The final hole diameter is 3 to 4 times the initial diameter, and the soil corresponds to ND4
	130	60	2.17						√		
	75	60	1.25						√		
	100	60	1.67						√		
	100	60	1.67						√		
	70	60	1.17						√		
	50	60	0.83					√			
	80	60	1.33					√			
	70	60	1.17					√			
	65	60	1.08					√			
180	175	60	2.92				√				
	175	60	2.92				√				
	150	60	2.50				√				
	160	60	2.67				√				
	160	60	2.67				√				
	150	60	2.50			√					
	140	60	2.33			√					
	160	60	2.67			√					

The observations from the Sample 2 (Figure 4.6 and Table 4.6) are as follows:

(1) The sample is completely slaked out during the test.

(2) The average water flow was 2.5 ml/s, and the colour was cloudy.

(3) The pinhole diameter of the sample could not be detected, as the sample is completely eroded at the side.

(4) The soil sample falls in the category of ND3 based on the flow of water and colour.

Table 4.6: Data Obtained from Pinhole Test of Sample 2

Head (mm)	Flow		Flow rate, ml/s	Turbidity from sides						Completely clear from the top	Remarks
	ml	sec		Very dark	Dark	Moderately dark	Slightly dark	Barely visible	Completely clear		
50	80	60	1.33						√		The soil corresponds to ND3
	80	60	1.33						√		
	70	60	1.17						√		
	60	60	1.00						√		
	70	60	1.17						√		
	60	60	1.00						√		
	60	60	1.00					√			
	70	60	1.17					√			
	50	60	0.83					√			
	50	60	0.83					√			
180	250	60	4.167				√				
	250	60	4.167				√				
	180	60	3				√				
	160	60	2.667				√				
	160	60	2.667				√				

(a) (b) (c)

Figure 4.5: Pinhole test for Sample 1: (a) final condition of the sample after test, (b) final diameter is about 6.5 mm at the top face, (c) collected turbid water at 180 mm head


(a) (b)

Figure 4.6: Pinhole test for Sample 2: (a) eroded soil inside the tube of pinhole apparatus at 180 mm head, (b) diameter of soil could not be measured as soil eroded from side

The soil can be termed moderately dispersive from the results, i.e., ND3 and ND4.

4.4.5 Chemical Test

From the chemical test, the amount of Sodium, Calcium, Magnesium, and Potassium obtained in ppm (parts per million) unit is given in Table 4.7. The values of ESP need to be converted to meg/100 gm of soil as Cation Exchange Capacity (CEC) is expressed as meg/100 gm of soil.

Table 4.7: Elements from Chemical Test

Elements from the Chemical test	Amount (ppm)
Mg^+	168.8
Ca^+	365.04
Na^+	400.5
K^+	35.7
pH	7.6

From the periodic table of elements, the atomic weight of Calcium, Magnesium, Potassium and Sodium are 40, 24, 39 and 23, respectively. Calcium and magnesium have two positive charges, and Sodium and Potassium each have one positive charge. The atomic weight is divided by the number of valences (positive charges) to obtain the equivalent weight. So, the equivalent weight of Calcium, Magnesium, Potassium, and Sodium are 20, 12, 39 and 23, respectively. The equivalent weights are multiplied by ten to get meq/100 gm. The results obtained are presented in Table 4.8. According to Table 3.10, the soil is high sodic as ESP>15. Hence, the soil can be classified as highly sodic.

Table 4.8: Calculation of ESP of Untreated Sample

Elements from the Chemical test	Amount meq/100 gm	Calculation
Mg$^+$	$\frac{168.8}{120} = 1.41$	CEC = 1.41+1.83+ 1.74+0.092 = 5.072
Ca$^+$	$\frac{365.04}{200} = 1.83$	
K$^+$	$\frac{35.7}{390} = 0.092$	ESP = $\frac{Na}{CEC} \times 100 = 1.74 \div 5.072 \times 100 = 34.30$
Na$^+$	$\frac{400.5}{230} = 1.74$	

4.5 Variation of Degree of Dispersion of Soil Sample

The variations of the test results are presented in Table 4.9. The results show that the soil is dispersive and should be treated before using this soil in any construction work.

Table 4.9: Variation of Degree of Dispersion from Various Tests

Name of Test	Degree of Dispersion
Crumb Test	Highly Dispersive (Grade 4)
Double Hydrometer Test	Medium Dispersive (44.44%)
Pinhole Test	Moderately Dispersive (ND4 or ND3)
Chemical Test	Highly Sodic (34.30%)

4.6 Stabilization of Dispersive Soil with Fly Ash

In this study, the focus was to find the strength characteristics of dispersive soil when the soil is stabilized with coal fly ash. The various percentage of fly ash is added to the dispersive soil until the desired phenomena of nondispersiveness are obtained. At the same time, the strength characteristics of soils are observed with varying percentages of fly ash to understand the positive or negative impact on strength. The same tests, i.e., crumb, pinhole, and double hydrometer, are performed for the samples mixed with 3%, 6%, and 9% fly ash (w/w) contents. The results are discussed in subsequent sections.

4.6.1 Crumb Test for Fly Ash Stabilized Soil

The crumb tests were conducted for the soil samples mixed with 3%, 6% and 9% fly ash (w/w) contents. The samples are tested and observed as per the ASTM D 6572. The salient features are discussed below (Figures 4.7 and 4.8). The detailed results are presented in Table 4.10.

(1) From Table 4.4, the untreated soil sample is Grade 4 means the soil is highly dispersive.

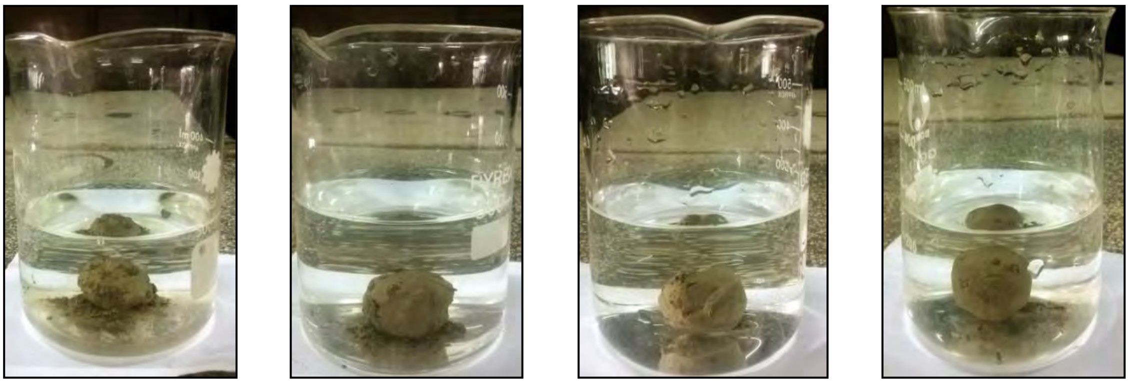
(2) The crumb of the soil sample stabilized with 3% fly ash, slaked little without forming suspension instantly. After 15 minutes, half of the crumb slaked into the water and remained the same after 1 hour. Therefore, the treated soil is termed Grade 2.

(3) The crumb of the soil sample stabilized with 6% fly ash does not show any reaction instantly. However, after 15 minutes, it slaked slightly and after 1 hour showed slight cloudiness. Therefore, the treated soil is termed Grade 2.

(4) The crumb of the soil sample stabilized with 9% fly ash does not show cloudiness after 1 hour. So, the treated soil is termed Grade 1.

Table 4.10: Observation of Crumb Test for Various Percentages of Fly Ash Mixed Sample

Fly ash (%)	Observation at instant	Observation at 15 minutes	Observation at 1 hour
0	Grade 1	Grade 3	Grade 4
3	Grade 1	Grade 2	Grade 2
6	Grade 1	Grade 1	Grade 2
9	Grade 1	Grade 1	Grade 1



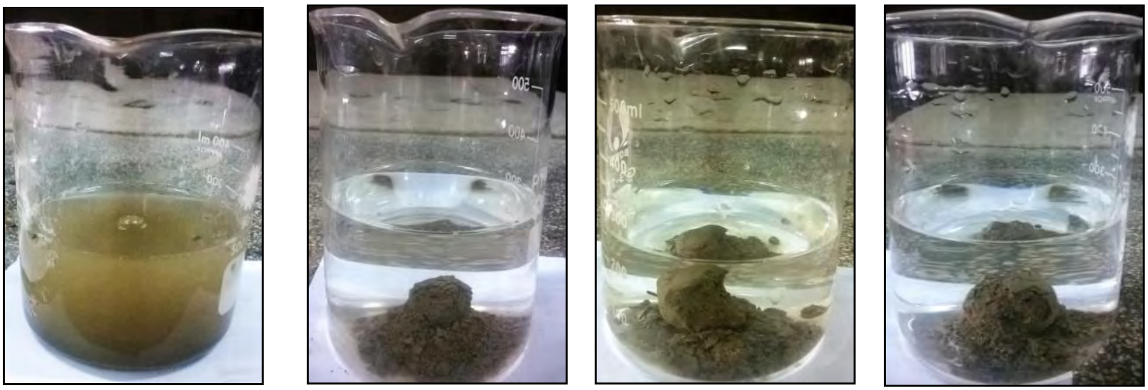
0% Fly Ash

3% Fly Ash

6% Fly Ash

9% Fly Ash

Figure 4.7: Observation of crumb test at instant for the samples prepared with 0%, 3%, 6% and 9% fly ash



0% Fly Ash

3% Fly Ash

6% Fly Ash

9% Fly Ash

Figure 4.8: Observation of crumb test at 1 hour for the samples prepared with 0%, 3%, 6% and 9% fly ash

The test results show that the addition of fly ash modifies the dispersive soil into nondispersive soil. The best result is obtained with 9% fly ash content.

4.6.2 Double Hydrometer Test with Fly Ash

Double hydrometer tests are performed for the dispersive soil treated with 3%, 6% and 9% fly ash contents. Double hydrometer test results for the specimens prepared with 3%, 6% and 9% fly ash are shown in Figures 4.9, 4.10 and 4.11, respectively. In addition, variations of percent dispersion with fly ash content have been presented in Figure 4.12. The findings from the tests are as follows:

(1) The addition of 3% fly ash reduces the dispersion value by 25% from untreated soil, which is 44%.

(2) Similarly, adding 6% and 9% fly ash reduces the dispersion value by 29% and 33%, respectively, from untreated soil.

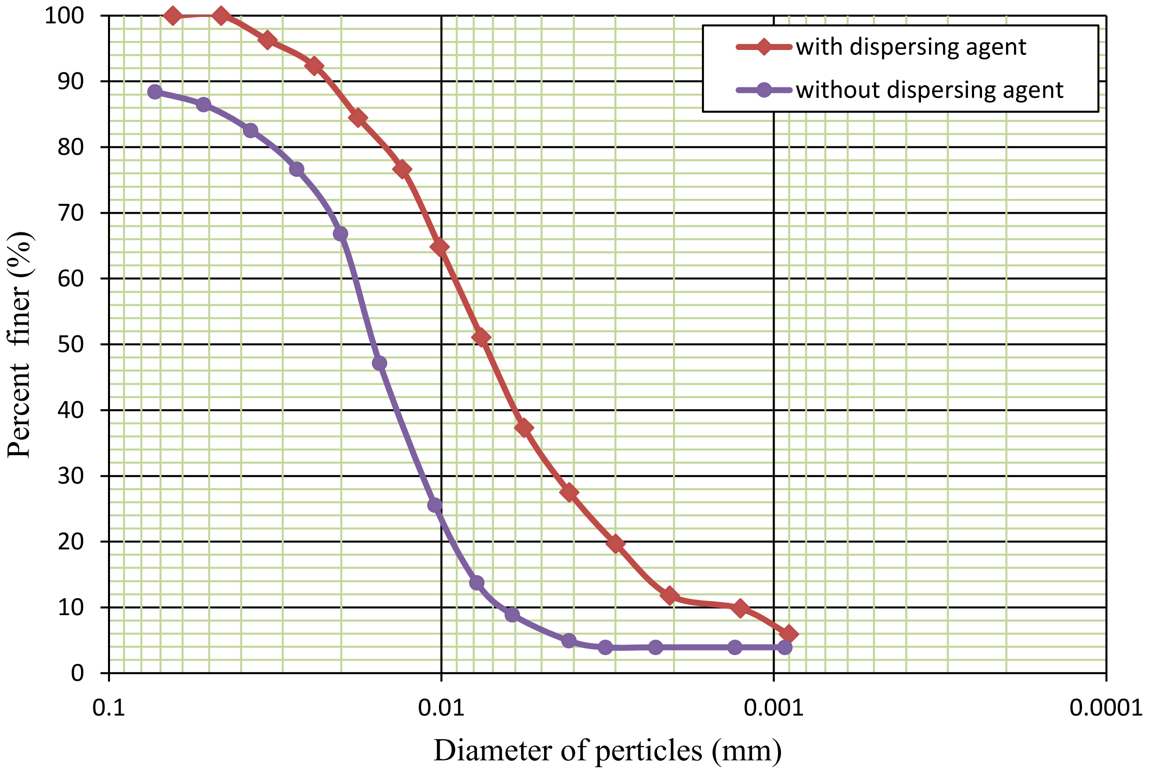


Figure 4.9: Double hydrometer test for dispersive soil treated with 3% fly ash

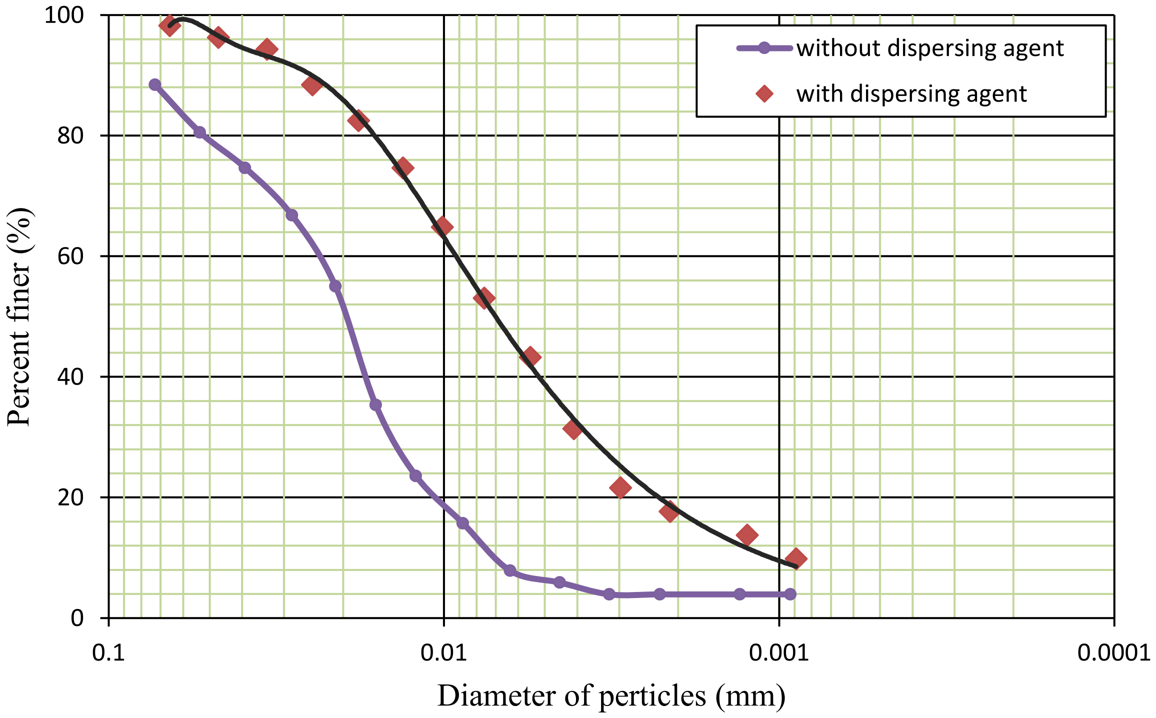


Figure 4.10: Double hydrometer test for dispersive soil treated with 6% fly ash

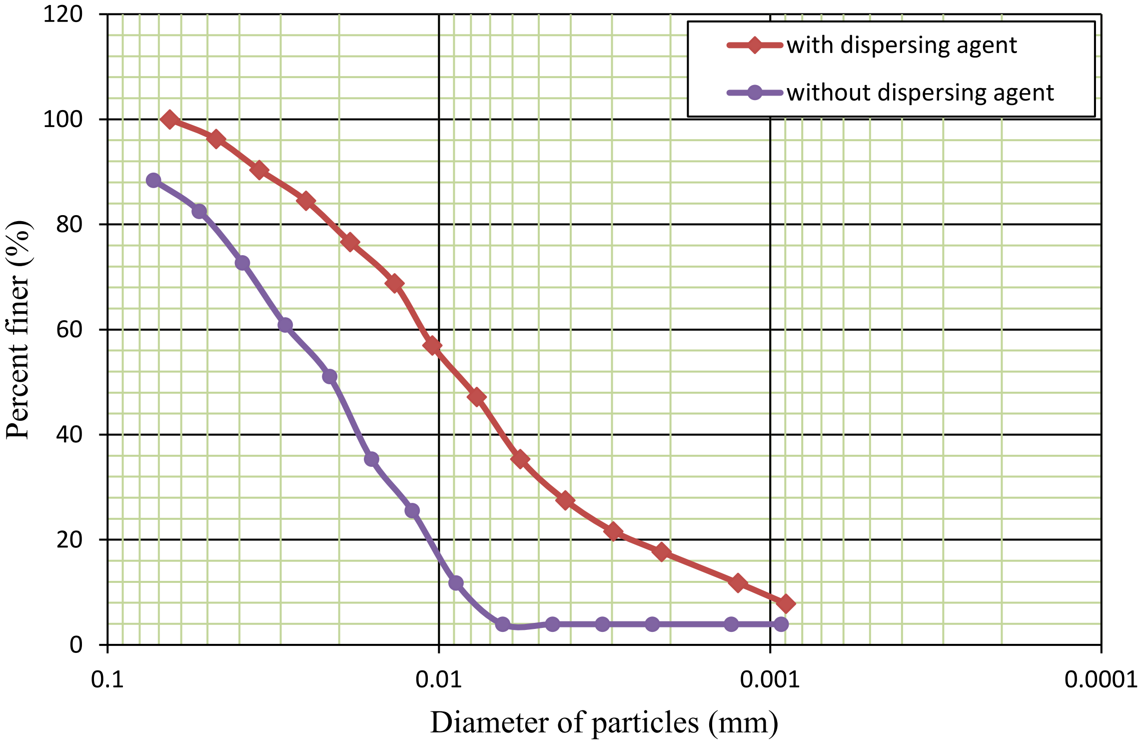


Figure 4.11: Double hydrometer test for dispersive soil treated with 9% fly ash

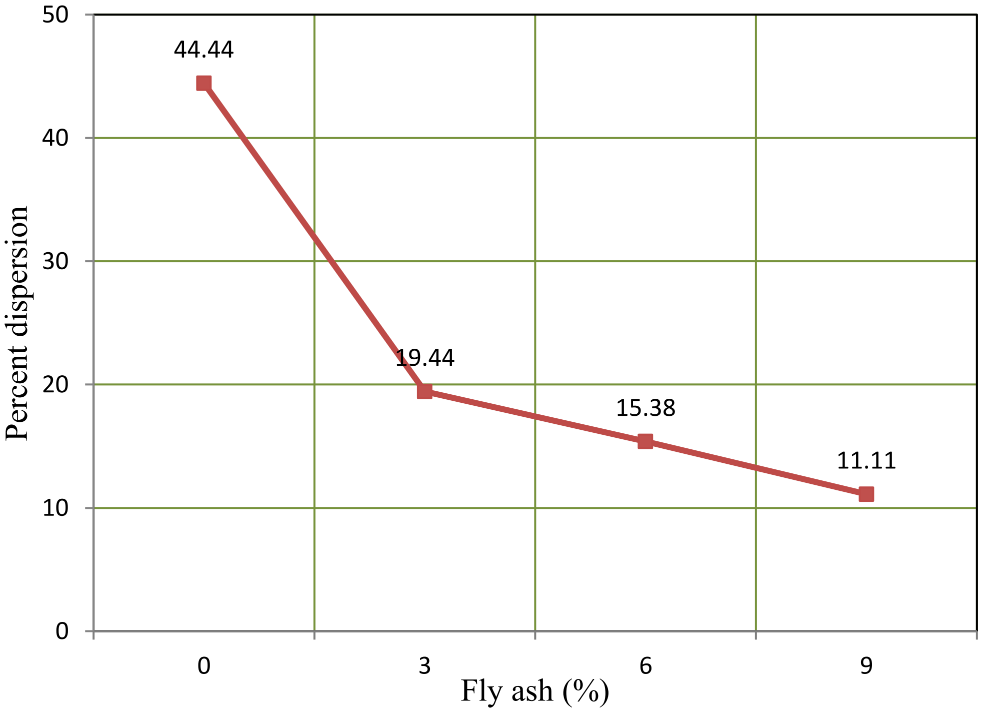


Figure 4.12: Variations of percent dispersion with fly ash content

The percent dispersion decreases with the increase of fly ash content. It is observed that the flocculation process has improved with the addition of fly ash which acted as a binding agent. It is clear from the tests that the addition of fly ash improves the properties of the dispersive soil.

4.6.3 Pinhole Test with Fly Ash

This study carried pinhole tests for the treated soil samples prepared with 3%, 6%, and 9% fly ash content. Pinhole test results are shown in Tables 4.11, 4.12 and 4.13.

Table 4.11: Data Obtained from Pinhole Test for the Sample Prepared with 3% Fly Ash

Head (mm)	Flow		Flow rate, ml/s	Turbidity from sides						Completely clear from the top	remarks
	ml	sec		Very dark	Dark	Moderately dark	Slightly dark	Barely visible	Completely clear		
180	100	60	1.67						√		The final hole diameter is about 1.5 to 2 times the initial diameter, and the soil corresponds to ND2
	120	60	2						√		
	100	60	1.667						√		
	100	60	1.667						√		
	100	60	1.667						√		
380	150	60	2.5						√		
	130	60	2.167					√			
	120	60	2					√			
	120	60	2					√			
	120	60	2					√			
1020	200	60	3.33					√			
	180	60	3					√			
	180	60	3					√			
	170	60	2.833					√			
	160	60	2.667					√			

Table 4.12: Data Obtained from Pinhole Test for the Sample Prepared with 6% Fly Ash

Head (mm)	Flow		Flow rate, ml/s	Turbidity from sides						Completely clear from the top	Remarks
	ml	sec		Very dark	Dark	Moderately dark	Slightly dark	Barely visible	Completely clear		
180	100	60	1.667						√		The final hole diameter is about 1.2 mm, and the soil corresponds to ND2
	95	60	1.583						√		
	90	60	1.583						√		
	80	60	1.33						√		
380	180	60	3.0						√		
	150	60	2.5						√		
	150	60	2.5						√		
	125	60	2.083						√		
	120	60	2						√		
	120	60	2						√		
1020	200	60	3.33					√			
	200	60	3.33					√			
	180	60	3					√			
	175	60	2.91					√			
	180	60	3.0					√			

Table 4.13: Data Obtained from Pinhole Test for the Sample Prepared with 9% Fly Ash

Head (mm)	Flow		Flow rate, ml/s	Turbidity from sides						Completely clear from the top	Remarks
	ml	sec		Very dark	Dark	Moderately dark	Slightly dark	Barely visible	Completely clear		
180	100	60	1.667						√		The final hole diameter is exactly 1.00 mm, and the soil corresponds to ND1
	70	60	1.167						√		
	80	60	1.33						√		
	80	60	1.33						√		
380	170	60	2.83						√		
	170	60	2.83						√		
	130	60	2.167						√		
	120	60	2.083						√		
	120	60	2						√		
	120	60	2						√		
1020	190	60	3.16						√		
	180	60	3.0						√		
	160	60	2.67						√		
	160	60	2.67						√		
	150	60	2.5						√		

The main findings from the test results are given below:

(1) The dispersive potential of soil samples significantly reduces with the increase of fly ash content.

(2) The flow was excessively slow and discharged water was clear at 50 mm head for all the soil samples treated with 3%, 6% and 9% fly ash. Therefore, the soils are classified as ND1, which is nondispersive.

(3) For 3% fly ash addition (Table 4.11), the final flow rate at 1020 mm head is less than 3 ml/s, collected water is barely dark, and the final diameter of the hole is about 1.5 to 2 times (Figure 4.13) than the initial diameter. Therefore, the stabilized soil is classified as ND2 or slightly dispersive.

(4) For 6% fly ash addition (Table 4.12), the final flow rate is 3 ml/s, and the turbidity of obtained water is barely visible from the outside. The final diameter of the hole is about 1.2 mm (Figure 4.14), and the soil corresponds to ND2 or is slightly dispersive.

(5) For 9% fly ash addition (Table 4.12), dispersivity of the soil has been reduced significantly. The final diameter of the hole is about 1.00 mm (Figure 4.15), and the flow rate at 1020 mm head is less than 2.5 ml/s. The collected water is completely clear both from the top and the side. Therefore, the soil is classified as ND1 or nondispersive.

From the above pinhole tests, it is observed that the flow of water reduces significantly with 6% and 9% fly ash contents. Furthermore, the samples containing 9% fly ash exhibited completely nondispersive characteristics, and the treated soil is termed ND1. Therefore, 9% fly ash is optimum to modify the soil from dispersive to nondispersive.

Figure 4.13: Condition of soil sample prepared with 3% fly ash after pinhole test (final diameter of the hole is about 2 mm)

Figure 4.14: Condition of soil sample prepared with 6% fly ash after pinhole test (final diameter of the hole is about 1.2 mm)

Figure 4.15: Condition of soil sample prepared with 9% fly ash after pinhole test (final diameter of the hole is about 1.00 mm)

4.7 Unconfined Compression Test Results

Unconfined compression (UC) tests are carried out for both treated and untreated soil samples with varying percentages of fly ash. First, four sets of samples are prepared, and one set of samples is tested just after the compaction. Then, for other sets of samples (treated with 3%, 6%, and 9% fly ash), the curing is done for 7, 14, and 21 days. Test results acquired for the samples cured for 0, 7, 14, and 21 days are given in Figures 4.16, 4.17, 4.18 and 4.19.

The outcomes of the UC test are described below:

(1) The compressive strength of soil samples increases with fly ash contents.

(2) After 14 days of curing, the soil sample with 3% fly ash exhibited slightly higher compressive strength than the sample with 9% fly ash.

(3) Brittleness is observed after 14 days of curing for the soil sample prepared with 9% fly ash. It means that the strength of the soil sample reduces with the increase of fly ash content by more than 9%.

(4) The increase in strength is considerable during the first two weeks for 6% and 9% fly ash mixed soil samples, beyond which the relative gain tends to reduce slightly. It implies that fly ash's self-hardening and pozzolanic activity peaked after two weeks.

(5) For treated and untreated samples, maximum stress increases with increasing fly ash contents up to 6% fly ash.

(6) The axial stress corresponds to the peak, and the maximum unconfined strength generally decreases. Hence, the treated soil sample with fly ash exhibits more brittleness than the untreated soil sample.

(7) From the axial stress vs axial strain graph (Figure 4.15) of the freshly prepared samples (at 0 day), it is observed that the failure strain for the untreated sample is 9%, while the failure strain of the samples treated with 3%, 6% and 9% fly ash is 10%, 9% and 7.5%, respectively. Although the addition of fly ash increases the strength, the addition of a higher percentage of fly ash, 9%, causes a reduction in failure strain. Adding a higher percentage of fly ash makes the soil sample brittle. Similarly, the test results of samples cured for different ages show a similar pattern. Variations of the failure strain with fly ash content and curing age are presented in Table 4.14. The results show that the failure strain reduces with the increase of curing age, and the failure strain decreases with the increase of fly ash contents. With the increase of curing age, the water content of the samples reduces, making the samples brittle. Increased fly ash requires higher water content for proper hydration and pozzolanic reaction. Since all the samples are prepared with the same initial water content as OMC, a higher percentage of initial water content could provide proper hydration.

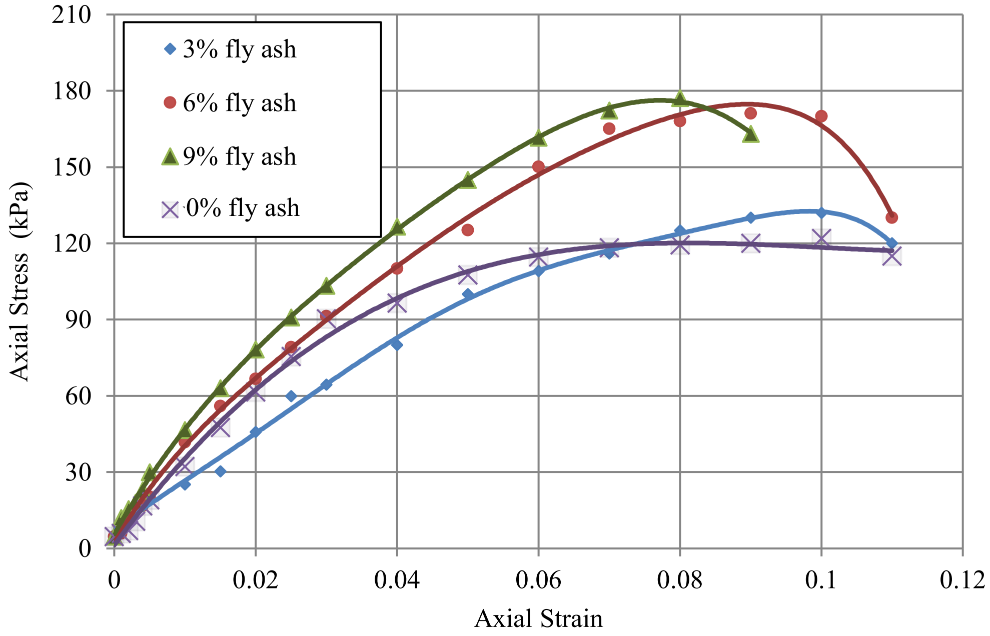


Figure 4.16: Axial stress vs axial strain for the samples without curing

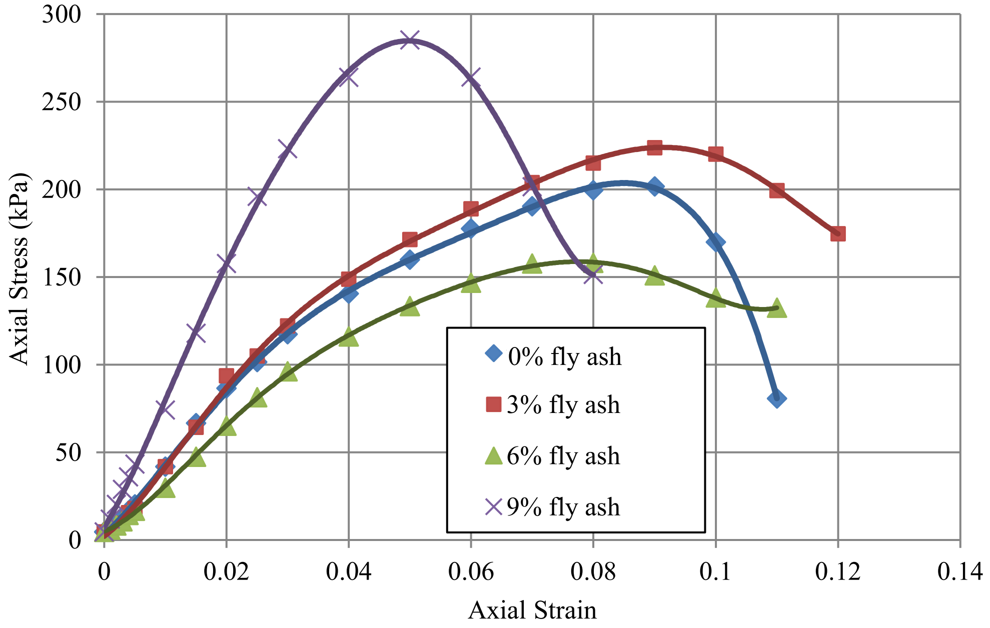


Figure 4.17: Axial stress vs axial strain for the samples cured for 7 days

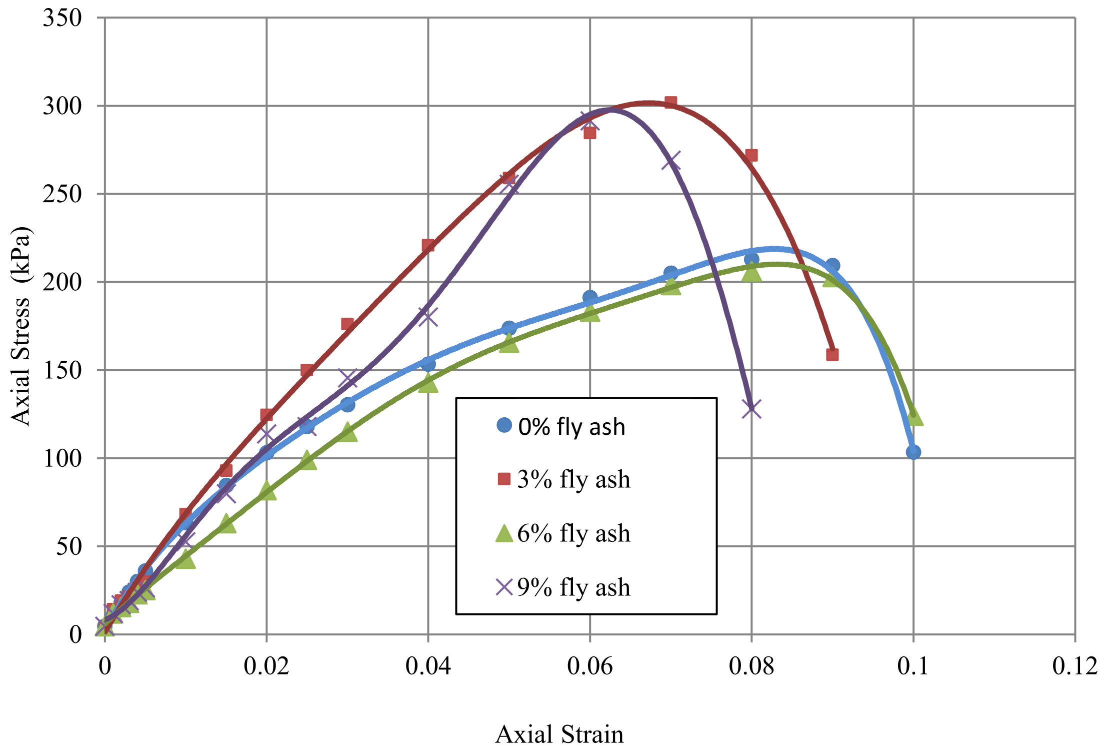


Figure 4.18: Axial stress vs axial strain for the samples cured for 14 days

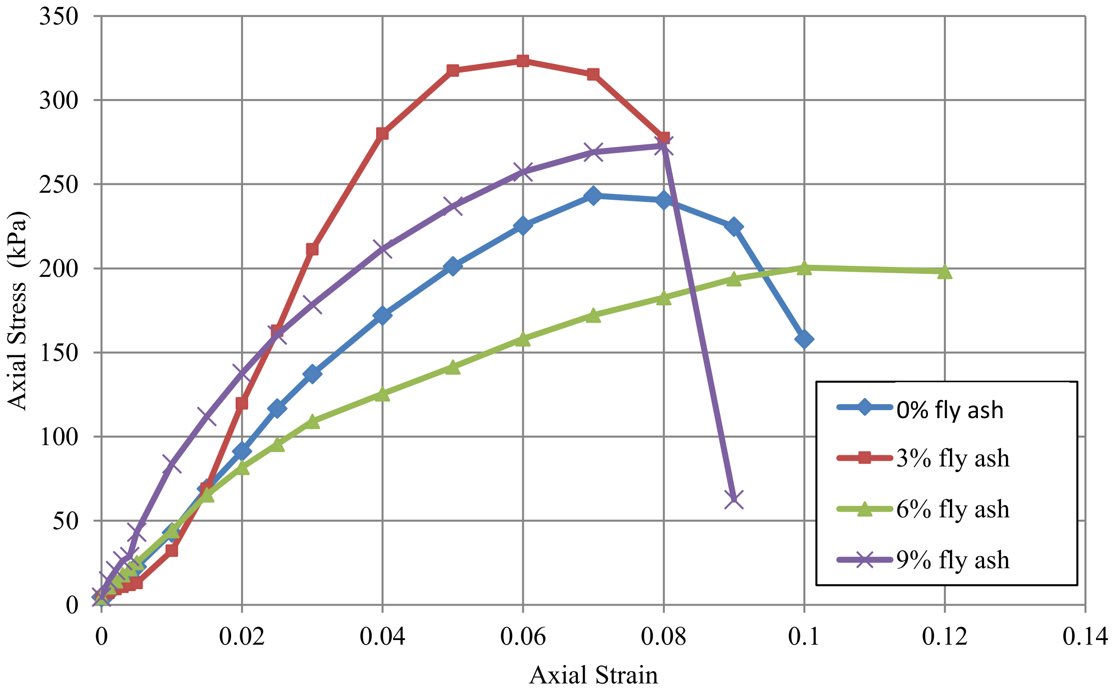


Figure 4.19: Axial stress vs axial strain for the samples cured for 21 days

Table 4.14: Variations of Failure Strain with Fly Ash Content and Curing Age

Sample	Failure Strain (%)			
	0 Day	7 Days	14 Days	21 Days
0% Fly Ash	9	8.5	8.5	7
3% Fly Ash	10	9	7	6
6% Fly Ash	9	7.8	8.5	10
9% Fly Ash	7.5	5	6.3	8

The variation of axial stress with respect to curing time for treated and untreated soil samples with various fly ash (0%, 3%, 6% and 9%) contents are shown in Figures 4.20, 4.21 and 4.22. The outcomes are as follows:

(1) The UC test results revealed that compressive strength increases with the curing time, and significant strength improvement is achieved at 21 days.

(2) The main strength gaining process of fly as h is the time dependent pozzolanic reaction wherein highly alkaline pore solution the dissolution of aluminium and silicon take place from the clay structure.

(3) Aluminium and silicon react with calcium ions present in the pore solution and form calcium silicate hydrate (C-S-H) and calcium aluminium hydrate (C-A-H), which are crystallised and develop strength with time. However, 21 days curing sample with 3% fly ash exhibited maximum strength than the sample with 9% fly ash.

(4) Figure 4.20 shows that the unconfined compressive strength obtained is 325 kPa in 21 days of curing for 3% fly ash mixed sample. Although, without curing, the value is about 130 kPa, the increase of compressive strength is about 2.5 times the initial strength.

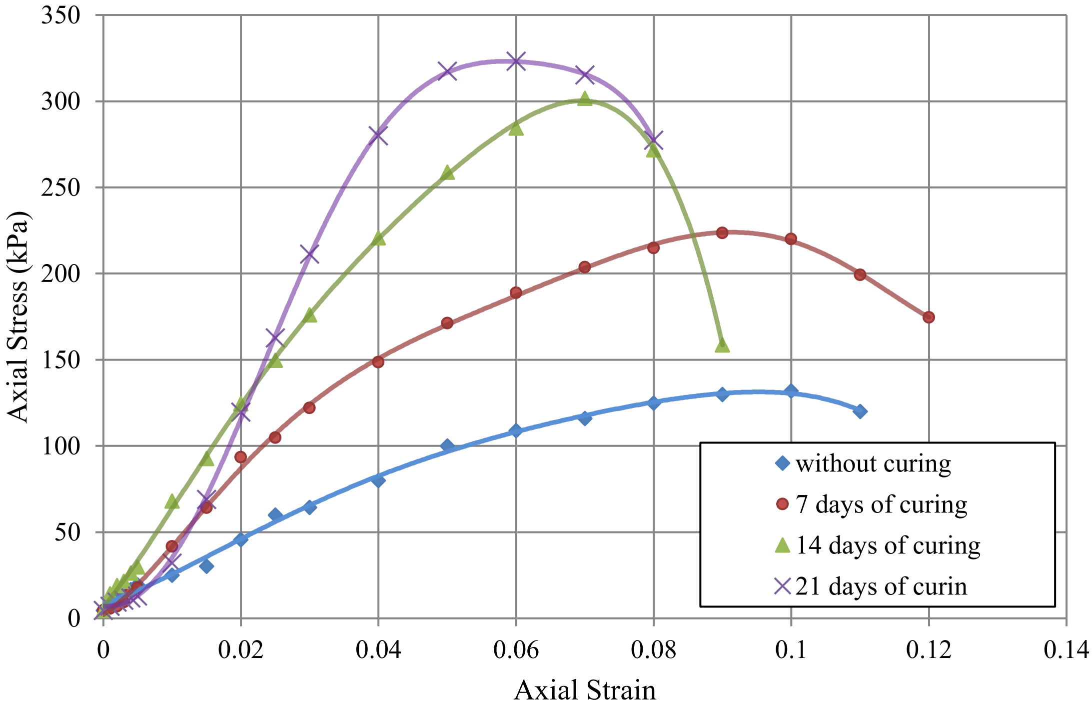


Figure 4.20: UC test result for 3% fly ash mixed soil with various curing time

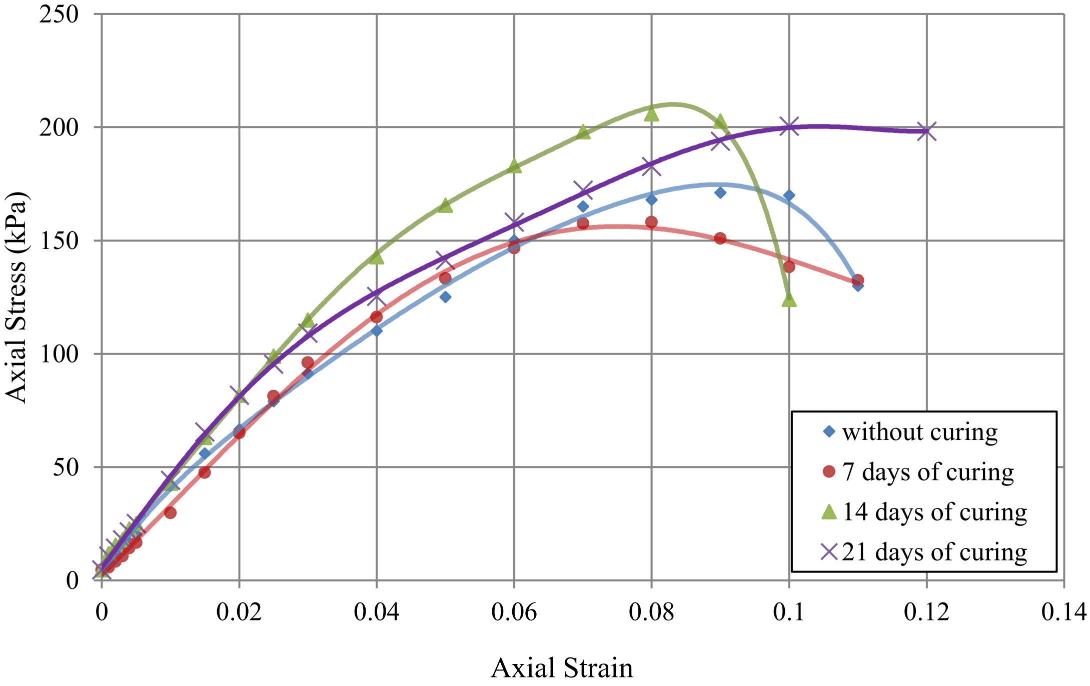


Figure 4.21: UC test results for 6% fly ash mixed soil with various curing time

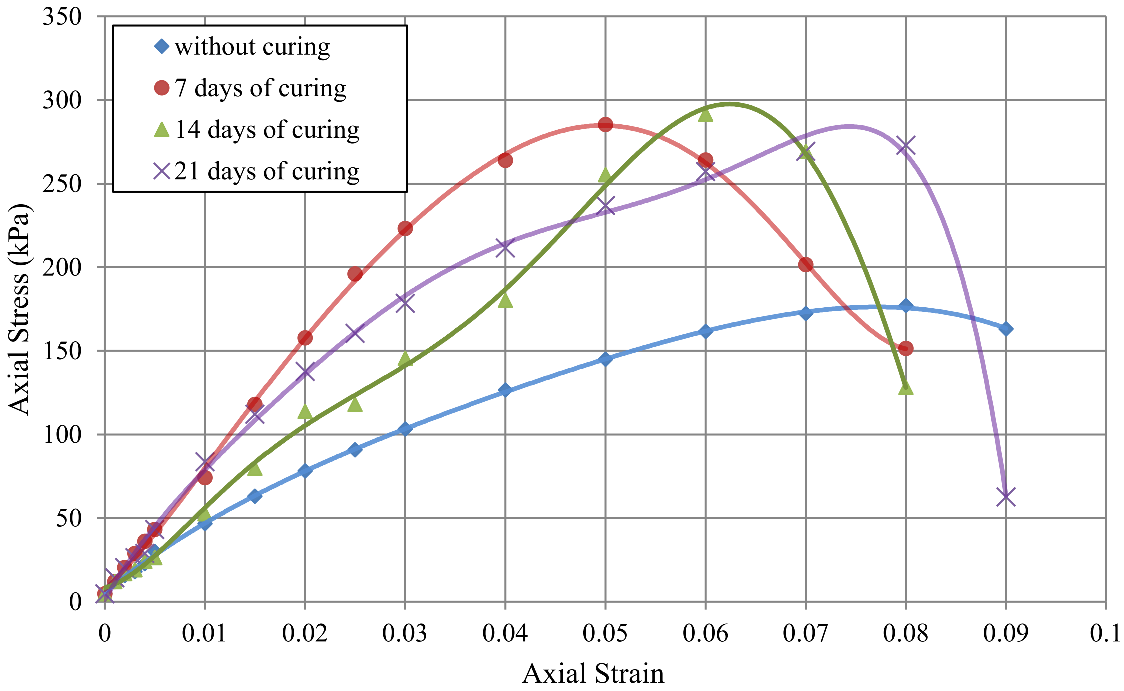


Figure 4.22: UC test results for 9% fly ash mixed soil for various curing time

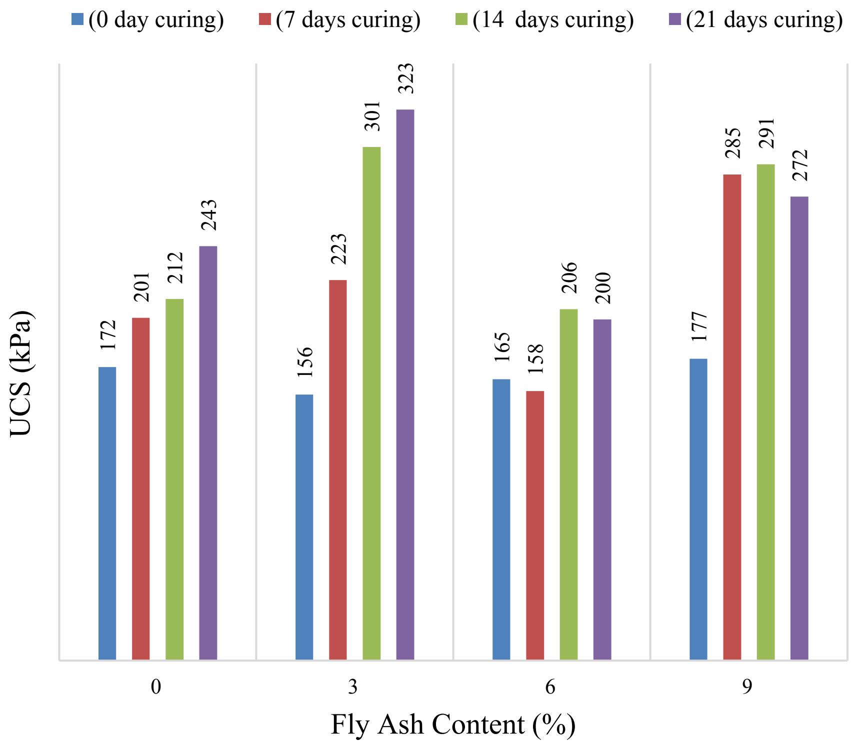


Figure 4.23: Variation of compressive strength with curing time and fly ash content

Figure 4.23 shows that the UC increases with fly ash content and drops for cured samples for higher fly ash content. Soil samples with 9% fly ash content at 21 days of curing and soil sample with 3% fly ash at 21 days and 14 days of curing demonstrated a higher peak value. The exception is that the strength decreases for cured soil samples with 6% fly ash. It may be happened due to the inconsistency in the preparation of soil samples.

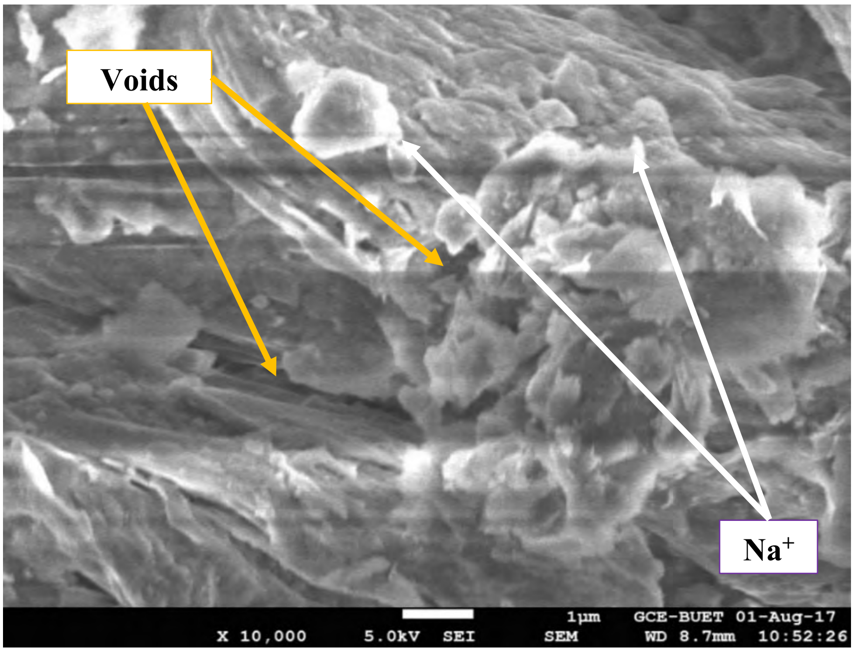
4.8 Scanning Electron Microscopy (SEM)

Figures 4.24 represent SEM test images of prepared soil samples with 0%, 3%, 6%, and 9% fly ash. The interpretations from the SEM tests are as follows:

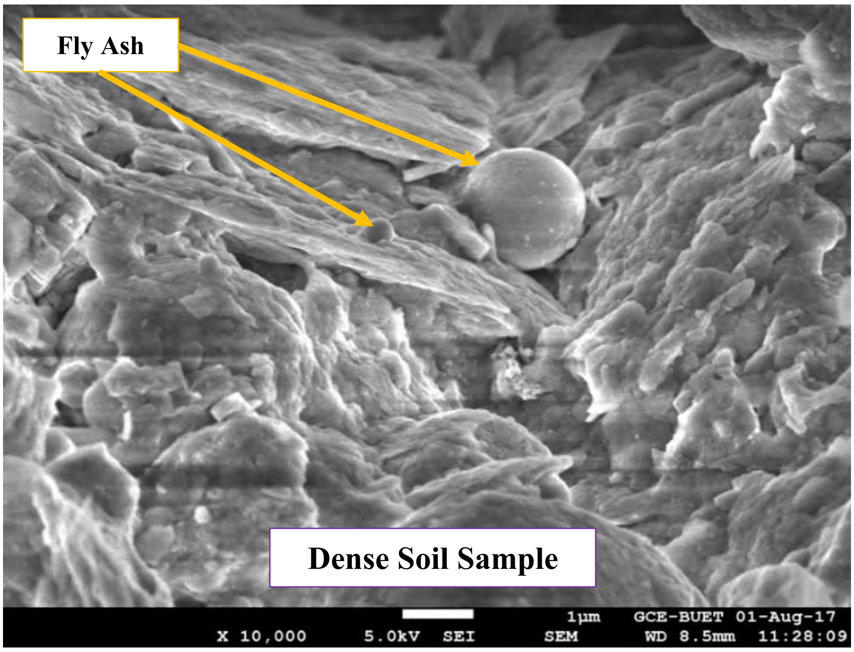
(1) In Figure 4.24a, the SEM image shows the presence of voids in the untreated soil sample. In addition, the presence of sodium ions (Na^+) is also observed. The microstructure of soil particles is loose enough to be dispersed easily. Hence, due to the presence of water (H_2O), sodium ions react with water and produce sodium hydroxide {$Na(OH)_2$}. These phenomena cause the deflocculation of soil particles and are termed soil dispersivity.

(2) SEM image in Figure 4.24b is prepared soil samples with 3% fly ash content showing few unreacted fly ash particles on the microfabric of soil. The microstructure of the prepared soil sample reveals that soil particles are bonded together and flocculated due to the addition of fly ash content. A similar pattern is observed in the SEM images of Figures 4.24c and 4.24d.

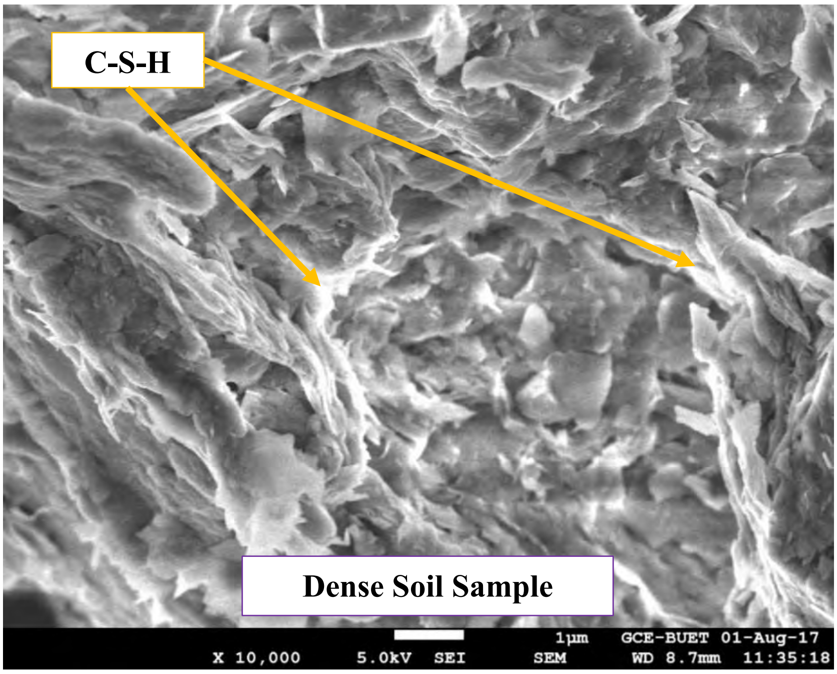
(3) SEM images in Figures 4.24c and 4.24d, the pores of the prepared soil particles are filled up with fly ash content, C-S-H and C-A-H crystals. It means that the strength of the prepared soil increased with the increase of fly ash content. The crystallisation of C-S-H gels is visible, which means the cementation process improved the intermolecular bondage of soil particles and reduced soil dispersivity to the desired extent. In the SEM image of Figure 4.24d, C-S-H and C-A-H gels are visible with some fly ash particles. It means the strength of the sample is increased due to the hydration process.


Voids
Na$^+$
1µm GCE-BUET 01-Aug-17
X 10,000 5.0kV SEI SEM WD 8.7mm 10:52:26

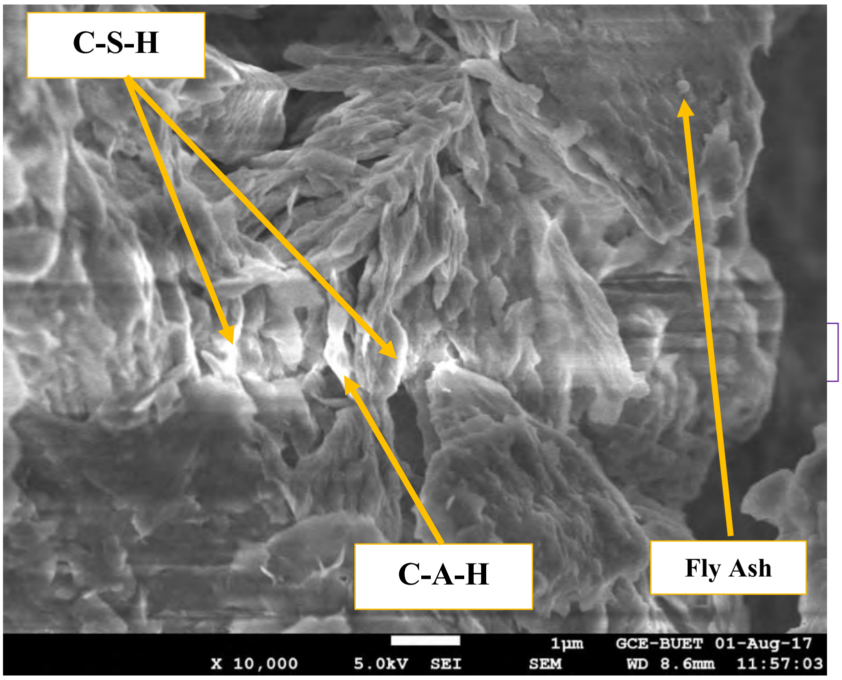
(a)


Fly Ash
Dense Soil Sample
1µm GCE-BUET 01-Aug-17
X 10,000 5.0kV SEI SEM WD 8.5mm 11:28:09

(b)



(c)



(d)

Figure 4.24: SEM images of soil samples: (a) untreated soil sample, (b) treated soil sample with 3% fly ash, (c) treated soil sample with 6% fly ash, (d) treated soil sample with 9% fly ash

Finally, the microstructure of the prepared soil sample with 9% fly ash signifies a well-coordinated connection among the soil particles. As a result, the microstructure of soil particles becomes more compact and resistant to dispersive. Therefore, it represents that 9% fly ash content is the optimum dose to reduce soil dispersivity significantly.

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Dispersive soils are clay soil that erodes in the presence of floodwater, rainfall, and even stagnant water. It happens due to higher percentages of sodium ions (Na^+) among the soil particles. A visual inspection cannot distinguish the dispersive soil from other ordinary clay soils. Also, visual classification, i.e., Atterberg's Limit and particle size analysis, do not provide adequate evidence to differentiate between dispersive soil and ordinary clayey soil. Hence, it is a significant threat to megastructures like railway embankments, roads, dams, hydroelectric projects, etc.

The main objective of this study was to determine the geotechnical and chemical properties of dispersive soil and thereby stabilize the dispersive soil with fly ash. The results obtained from different experiments are accumulated and interpreted. Finally, conclusions are drawn from the findings and recommendations are given in the subsequent paragraphs.

5.2 Conclusions

The conclusions drawn from the comprehensive study and experimental investigations are as follows:

(1) Index properties revealed that the sample soil is kaolinite clay, moderate to highly compressible, plastic in nature with medium to high dry strength, a low percentage of colloidal clay containing the mineral kaolinite, and low swelling potential. In fact, dispersive soil has a high swelling potential due to the presence of excess sodium ions. So, index properties are not significant enough to determine soil dispersivity.

(2) The soil dispersivity is identified through four tests, i.e. crumb test, double hydrometer test, pinhole test and chemical test. Due to different experimental processes, the results of the degree of dispersion are variable. Nevertheless, it is confirmed that the soil sample is dispersive and should be treated before any construction works.

(3) To reduce soil dispersivity, type F fly ash is used to prepare soil samples with 0%, 3%, 6%, and 9% fly ash content. The crumb test revealed that soil dispersivity is reduced with the increases in fly ash content. The double hydrometer test indicated that the addition of 3%, 6%, and 9 % fly ash reduces the dispersion value by 25%, 29%, and 33%, respectively, from untreated soil.

(4) The pinhole test is the most reliable test procedure to determine soil dispersivity. The water flow reduces significantly with 6% and 9% fly ash contents. The samples containing 9% fly ash exhibited completely nondispersive characteristics and were termed ND1. After all the test procedures, 9% fly ash is optimum to modify the soil from dispersive to nondispersive.

(5) UC test results show that the addition of fly ash increases the strength and the addition of a higher percentage of fly ash (9%) causes a reduction in failure strain because the addition of a higher percentage of fly ash makes the soil sample brittle. It is also observed that with the increase of curing age, the failure strain of soil sample reduces and with the increase of fly ash content, the failure strain of soil sample decreases. With the increase of curing age, the water content of the treated soil samples reduces, making the samples brittle. Increased fly ash requires higher water content for proper hydration and pozzolanic reaction. Hence the samples need to be prepared more than the higher percentage of initial water content, i.e. OMC, for proper hydration of fly ash content.

(6) SEM images reveal the presence of voids and excessive sodium in an untreated soil sample. The soil particles are loose enough to be dispersed easily due to the deflocculation process caused by water and sodium ions. Due to adding fly ash, the microstructure of soil particles becomes more compact and resistive to dispersive. With the increase of fly ash contents, the rate of pozzolanic reactions also increased, producing C-A-H and C-S-H crystals around the molecular level of soil particles. The crystallization of C-A-H and C-S-H gels improves the cementation process of soil particles and reduces soil dispersivity to the desired extent. SEM images also represent that 9% fly ash content is the optimum dose to reduce soil dispersivity significantly.

5.3 Recommendations for Further Studies

The main objective of this study is to know the behavior of dispersive soil and the reasons for the dispersivity of soil. In addition, the aim was to stabilize the dispersive soil with fly ash. For further clarification following studies may be conducted in the future:

(1) In this study, index properties are only considered for untreated soil samples. Therefore, the effect of the addition of fly ash content on index properties of dispersive soil can be studied.

(2) In this study, the initial water content was the OMC of the dispersive soil for an increase in fly ash contents. Therefore, the amount of water required for the hydration process of fly ash on dispersive soil needs to be studied.

(3) In this study, only the effect of fly ash on UC strength has been studied. Further research to investigate the effect of fly ash on California Bearing Ratio (CBR), shear stress parameters, and compressibility parameters on dispersive soil needs to be carried out.

(4) A comprehensive study is required to investigate the microstructure of fly ash stabilized dispersive soil.

REFERENCES

Abbaslou, H., Hadifard, H. and Poorgohardi, A., "Characterization of Dispersive Problematic Soils and Engineering Improvements: *A Review", Computations and Materials in Civil Engineering in Spiral Publishing*, Vol. 1(2), pp. 65-83, 2016.

Abbaslou, H., Hadifard, H., Ghanizadeh, A., and Kharazmi, S., "Biological Stabilizers for Different Dispersive Clayey Soils", *AUT Journal of Civil Engineering,* Vol. 4(1), pp. 17-26, 2020.

Anon, R. (1999), "Effects of sodicity and salinity on soil structure", *SOILpak for dryland farmers on the red soil of Central Western NSW, NSW Dept. Primary Industry.*

Arfien, A., Saha, M.S., Sultana, S., Ahmed, A.N. and Das, R.C., "Coal Fly Ash of Barapukuria Thermal Power Plant, Bangladesh: Physico Chemical Properties Assessment and Utilization", *International Journal of Scientific & Engineering Research*, Vol. 4, 2013.

Ashraf, M., and Islam, M.S., "Experimental Studies on The Characteristic Behaviour of Dispersive Soil and Stabilization with Fly Ash", *4th International Conference on Advances in Civil Engineering 2018 (ICACE 2018)*, CUET, Chittagong, Bangladesh, 19 –21 December 2018.

ASTM D4221-99, "Standard test method for dispersive characteristics of clay soil by double hydrometer", *American Society for Testing and Materials,* Pennsylvania, 2007.

ASTM D422-63, "Standard Test Method for Particle-Size Analysis of Soils", *Annual Book of ASTM Standards*, Vol. 4(8), 2002.

ASTM D4542-95, "Standard Test Method for Pore Water Extraction and Determination of the Soluble Salt Content of Soils by Refractometer", *American Society for Testing and Materials,* Pennsylvania, 2000.

ASTM D4647-93, "Standard Test Method for Identification and Classification of Dispersive Clay Soils by the Pinhole Test", *American Society for Testing and Materials,* Pennsylvania, 2000.

ASTM D1557-12, "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lb/ft^3 (2,700 kN-m/m^3))", *American Society for Testing and Materials,* Pennsylvania, 2021.

ASTM D2166-06, "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil", *American Society for Testing and Materials,* Pennsylvania, 2010.

ASTM D4254-00, "Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density", *American Society for Testing and Materials*, Pennsylvania, 2007.

ASTM D4318-17, “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils”, *American Society for Testing and Materials*, Pennsylvania, 2018.

ASTM D6572-21, “Standard Test Methods for Determining Dispersive Characteristics of Clayey Soils by the Crumb Test”, *American Society for Testing and Materials*, Pennsylvania, 2021.

ASTM D698-12, “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft^3 (600 kN-m/m^3))”, *American Society for Testing and Materials*, Pennsylvania, 2021.

ASTM D854-14, “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer”, *American Society for Testing and Materials*, Pennsylvania, 2016.

ASTM E2809-13, “Standard Guide for Using Scanning Electron Microscopy/X-Ray Spectrometry in Forensic Paint Examinations”, *American Society for Testing and Materials*, Pennsylvania, 2018.

Batool, S., Malik, A.A., Akbar, A. and Sultan, T., “Improvement of CBR and Compaction Characteristics of Bauxite Rich Dispersive Soils Available in Pakistan: A Case Study of Khushab Soil”, Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan, Vol. 20 (IV), pp.19-27, 2015.

Beetham, P., Dijkstra, T., Dixon, N., Fleming, P., Hutchison, R., and Bateman, J., “Lime stabilisation for earthworks: a UK perspective”, *Proceedings of the Institution of Civil Engineers-Ground Improvement,* Vol. 168(2), pp. 81-95, 2015.

Belarbi, A., Zadjaoui, A. and Bekkouche, A., “Dispersive clay: Influence of Physical and Chemical Properties on Dispersion Degree”, *The Electronic Journal of Geotechnical Engineering,* Vol. 18, pp. 1727-1738, 2013.

Belarbi, A., Zadjaoui, A., and Bekkouche, A., “Use of milk of lime for dispersive soil treatment in the region of Tlemcen in Algeria”, International Journal of Emerging Technology and Advanced Engineering, Vol. 2(2), pp. 281-286, 2012.

Bhuvaneshwari, S., Soundra, B., Robinson, R.G., and Gandhi, S.R. “Stabilization and microstructural modification of dispersive clayey soils”, *Proc. of Sri Lankan Geotechnical Society’s 1st Int. Conf. on Soil & Rock Engineering,* Colombo, Sri Lanka, pp. 1-7, 2007.

Davies, S., and Lacey, A., (2009), *“Identifying dispersive soils”*, Western Australia, Department of Agriculture and Food.

Elahi, T.E., Shahriar, A.R. and Islam, M.S., “Engineering characteristics of compressed earth blocks stabilized with cement and fly ash", *Construction and Building Materials,* Vol. 277, 2021, doi:10.1016/j.conbuildmat.2021.122367.

Elahi, T.E., Shahriar, A.R., Islam, M.S., Mehzabin, F., and Mumtaz, N., "Suitability of fly ash and cement for fabrication of compressed stabilized earth blocks", *Construction and Building Materials,* Vol. 263, 2020.

FAO/UNESCO (1976), *"Soil map of the world. Southeast Asia"*, Sheet IX. Edition 1/1976.

Faruk, M.O., Islam, M.S., Hoque, M.Z., and Shorno, M.A., "Stabilization of dispersive soil by using fly ash", *Proceedings, International Conference on Disaster Risk Management,* Dhaka, Bangladesh, January 12-14, 2019.

Fattah, M.Y., Omran, H.A., and Abdul Latif, T.M., "Modification of pinhole apparatus for identification and classification of dispersive clay soils", *Journal of Engineering and Development, University of Al-Mustansiriya,* Vol. 18(6), pp.181-201, 2014.

Faulkner, H., (2006), *"Piping hazard on collapsible and dispersive soils in Europe"*, Soil erosion in Europe, pp. 537-562.

Fell, R., Mac, Gregor, P., and Stapledon, D. "Geotechnical Engineering of Embankment Dams", *A. A. Balkema Publishers.* p 675, 1992.

Forrest, T.G., (1980), *"Engineering and Design - Laboratory soils testing, Appendix XIII: Pinhole erosion test for identification of dispersive clays"* Department of tee army, Washington, U.S.A.

Foster, M., Fell, R., and Spannagle, M., "The statistics of embankment dam failures and accidents." Can. Geotech. J., Vol. 37(5), pp. 1000–1024, 2000.

Frenkel, H., Levy, G.J., and Fey, M.V., "Clay dispersion and hydraulic conductivity of clay-sand mixtures as affected by the addition of various anions", Clays and Clay Minerals, Vol. 40(5), pp. 515-521, 1992.

Goodarzi, A.R., and Salimi, M., "Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag", *Applied Clay Science 108,* pp. 61-69, 2015.

Hardie, M., (2009), *"Dispersive soils and their management",* Technical Reference Manual, Sustainable Land Use, Department of Primary Industries and Water (DPIW), State of Tasmania, ISBN 978-0-7246-774-1.

Hardie, M.A., Cotching, W. E., and Zund, P. R. "Rehabilitation of field tunnel erosion using techniques developed for construction with dispersive soils", *Soil Research,* Vol. 45(4), pp. 280-287, 2007.

Heinz, W.F., (2012), *"Dams founded on dispersive soils and rocks drilling and grouting under difficult conditions",* In Grouting and Deep Mixing 2012, pp. 1134-1146.

Heinzen, R.T., and Arulanandan, K., "Factors Influencing Dispersive Clays and Methods of Identification", *ASTM Special Technical Publication,* Vol. 623, pp. 202-217, 1977.

Huq, S.M.I. and Shoaib, J.U.M., (2013), *"The Soils of Bangladesh",* Springer Dordrecht Heidelberg New York London, DOI 10.1007/978-94-007-1128-0

Indraratna, B., Nutalaya, P., and Kuganenthira, N., "Stabilization of a dispersive soil by blending with fly ash", *Quarterly Journal of Engineering Geology,* Vol. 24, pp. 275-290, 2015.

Islam, M.S., Elahi, T.E., Shahriar, A.R., and Mumtaz, N., "Effectiveness of fly ash and cement for compressed stabilized earth block construction", *Construction and Building Materials,* Vol. 255, 2020.

Islam, M.S., Islam, T. and Khatun, N., "Permeability alteration of low plastic clay and poorly graded sand", *Indian Geotechnical Journal,* 2021, doi:10.1007/s40098-020-00493-5.

Ismael, R.H., Fattah, M.Y., Aswad, M.F., "Consistency Characteristics of Dispersive Clays", *Engineering and Technology Journal 39,* Vol. 12, pp. 1753-1759, 2021.

Karthik, S., Kumar, E.A., Gowtham, P., Elango, G., Gokul, D., and Thangaraj, S. "Soil Stabilization by Using Fly Ash", *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE),* Vol. 10, pp. 20-26, 2014.

Khan, M.A.A., Saha, M.S., Sultana, S., Ahmed, A.N., and Das, R.C., "Coal fly ash of Barapukuria Thermal Power Plant, Bangladesh: physicochemical properties assessment and utilization", *International Journal of Scientific and Engineering Research,* Vol. 4(11), pp. 1456-1460, 2013.

Maharaj, A., Van Rooy, L., and Paige-Green, P., "Revised test protocols for the identification of dispersive soils", *Journal of the South African Institution of Civil Engineering,* Vol. 57(1), pp. 31-37, 2015.

Marchuk, A., and Rengasamy, P., "Threshold electrolyte concentration and dispersive potential in relation to CROSS in dispersive soils", *Soil Research,* Vol. 50(6), pp. 473-481, 2012.

Masud, M.H., Shakib, M.N., and Rokonuzzaman, M., (2014). "Study of environmental impacts of the Barapukuria Thermal Power Plant of Bangladesh", *Global Journal of Research in Engineering,* Vol. 14(1), pp. 47-52, 2014.

McElroy, C.H., "Using Hydrated Lime to Control Erosion of Dispersive Clays" *Lime for Environmental Uses. Gutschich K G. ASTM STP,* Vol. 931, pp 100-114, 1987.

Mojiri, A., Aziz, H.A., Zaman, N.Q., Aziz, S.Q., and Zahed, M.A., "Powdered ZELIAC augmented sequencing batch reactors (SBR) process for co-treatment of landfill leachate and domestic wastewater", *J. Environ. Manag.* Vol. 139, pp. 1–14, 2014a.

Nadal-Romero, E., Verachtert, E., and Poesen, J., "Pinhole test for identifying susceptibility of soils to piping erosion: effect of water quality and hydraulic head", *Advances in studies on desertification,* pp. 351-354, 2009.

Nadal-Romero, M.E., Verachtert, E., and Poesen, J., "Pinhole test for identifying susceptibility of different horizons in less-derived soils to piping erosion", *Landform Analysis,* Vol. 17, pp. 131-134, 2011.

Nagy, G., Nagy, L., and Kopecskó, K., "Examination of the physico-chemical composition of dispersive soils", *Periodica Polytechnica Civil Engineering,* Vol. 60(2), 269-279, 2016.

Nelson, D.J., and Miller, J.D., (1992), *"Expansive Soils: Problems and Practice in Foundation and Pavement Engineering"*, Wiley, New York.

Ouhadi, V.R. and Goodarzi, A.R., "Assessment of the stability of a dispersive soil treated by alum", *Journal of Engineering Geology,* Vol. 85, pp. 91–101, 2006.

Premkumar, S., Piratheepan, J., Rajeev, P. and Arulrajah, A., "Stabilizing Dispersive Soil Using Brown Coal Fly Ash and Hydrated Lime", *Journal of Geotechnical Engineering Division, ASCE, Geo-Chicago,* Vol. 271, pp. 874-884, 2016.

Puppala, A.J., Manosuthkij, T., and Hoyos, L.R., "Better characterization of expansive soils for the design of pavement infrastructure", *Infrastructure Development on Expansive Soils, INDEX 2009 Proceedings, August 27–29, 2009,* pp. 74–89, 2009.

Puppala, A.J., Pedarla, A., & Bheemasetti, T., (2015), *"Soil modification by admixtures: concepts and field applications",* Chemical, Electrokinetic, Thermal, and Bioengineering Methods, pp. 291-309, doi:10.1016/B978-0-08-100191-2.00010-1.

Puppala, A.J., Pokala, S., Intharasombat, N., and Williammee, R., "Effects of organic matter on physical strength and volume change properties of compost amended expansive clay", *J. Geotech. Geoenviron. Eng.* Vol. 133 (11), pp.1449–1461, 2007.

Qadir, M., Oster, J.D., Schubert, S., Noble, A.D., and Sahrawat, K.L., "Phytoremediation of sodic and saline-sodic soils", Advanced in Agronomy, Vol. 96, pp. 197–247, 2007.

Rani V., Aloysious, A., Ajayakumar A. and Russel, B.S., (2017), *"Remediation of dispersive soil",* International Conference on Geotechniques for Infrastructure Projects, 27th and 28th February 2017, Thiruvananthapuram, India.

Sherard, J.L., Dunnigan, L.P. and Decker, R.S., "Identification and Nature of Dispersive Soils", *ASCE Geotechnical Division,* Vol. 102(4), pp. 69-87, 1976.

Suresh, A., Ajith K.P., Ajith K.P. and Joy, A., "An Experimental study on Dispersive Nature of Soil", *International Journal of Innovative Research in Science, Engineering and Technology,* Vol. 2, 2013.

Tamim, M.M., Dhar, A., and Hossain, M.S., "Fly ash in Bangladesh-an overview", International Journal of Scientific & Engineering Research, Vol. 4(4), pp. 809-812, 2013.

Umesh, T.S., Dinesh, S.V., and Sivapullaiah, P.V., "Characterization of Dispersive Soils", *Department of Civil Engineering, Siddaganga Institute of Technology, Tumkur, India,* pp. 629-633, 2011.

US Department of Agriculture (USDA), (1992), *"Dispersive Clay Soils",* Natural Resources Conservation Service, Engineering Field Handbook (EFH), Notice 210-WI-62.

US Department of Agriculture (USDA), (1999), *"Dispersive Clays",* Soil Conservation Service, Engineering Division, 210-VI-SMN-13, pp. 1-24.

Vakili, A.H., Selamat, M.R.B., and Aziz, H.B.A., "Filtration of broadly graded cohesive dispersive base soils", *Journal of Geotechnical and Geoenvironmental Engineering, January 2015,* Vol. 141(5), pp. 1-12, 2015.

Vakili, A.H., Selamat, M.R.B., Aziz, H.B.A., Mojiri, A., Ahmad, Z., and Safarzadeh, M., "Treatment of dispersive clay soil by ZELIAC", *Geoderma,* Vol. 285, pp. 270-279, 2017.

Vakili, A.H., Selamat, M.R.B., Moayedi, H., and Amani, H., "Stabilization of Dispersive Soils by Pozzolan", *Forensic Engineering 2012@ ASCE 2013,* pp. 726-735, 2012.

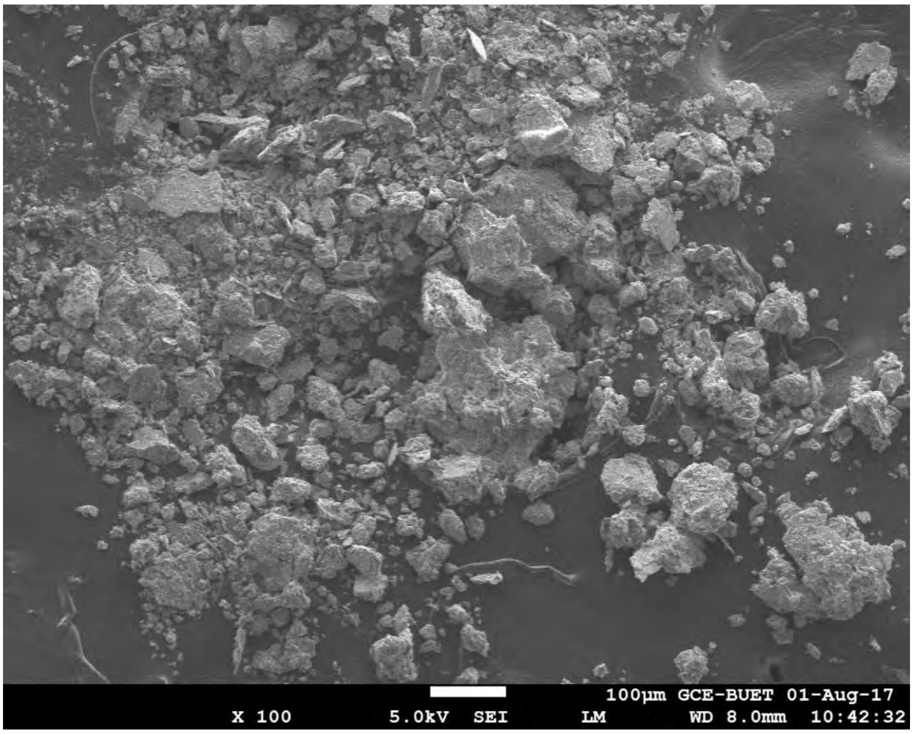
Vyas, S., Phougat, N., Sharma, P., and Ratnam, M., "Stabilization of dispersive soil by blending polymers*", International Journal of Earth Sciences and Engineering,* Vol. 4(6), pp. 42-54, 2011.

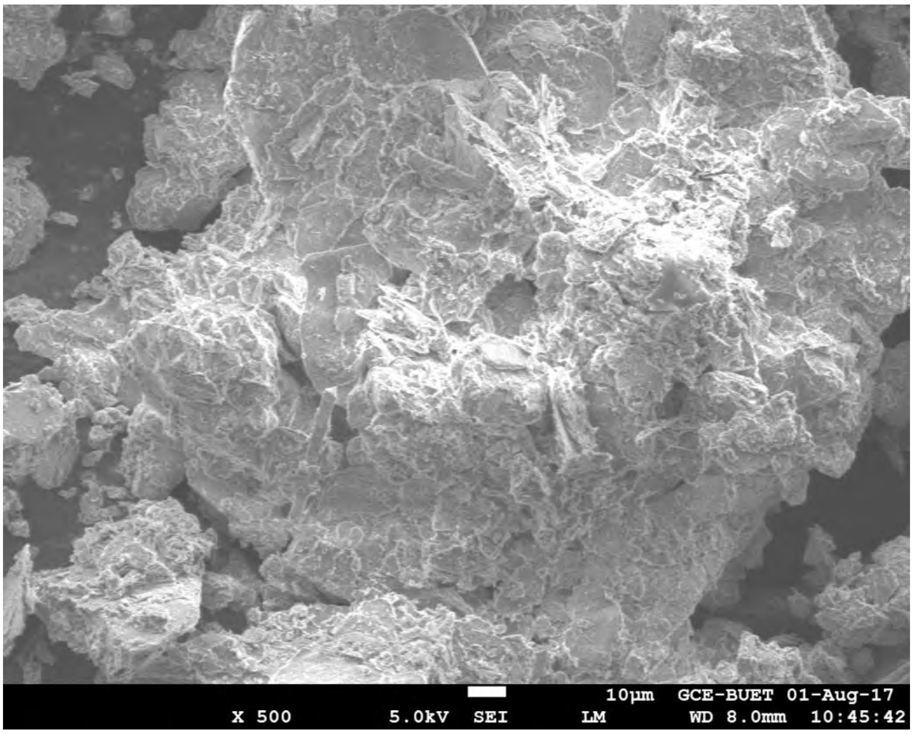
Wang, X., Sale, P., Hayden, H., Tang, C., Clark, G., and Armstrong, R., "Plant roots and deep-banded nutrient-rich amendments influence aggregation and dispersion in a dispersive clay subsoil", *Soil Biology and Biochemistry,* Vol. 141, pp. 1-12, 2020.

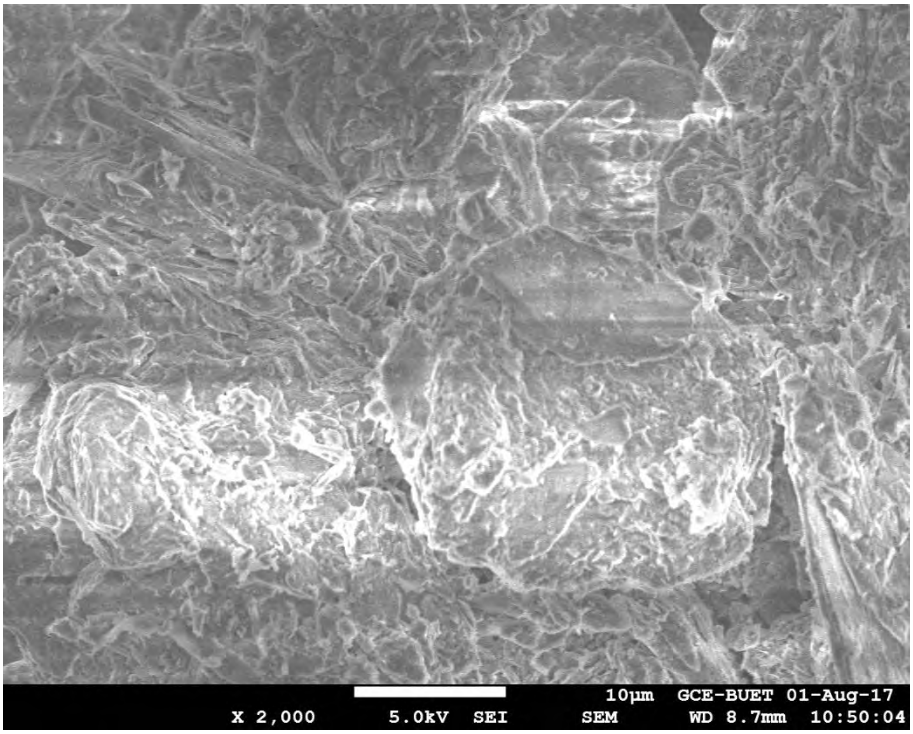
APPENDIX A

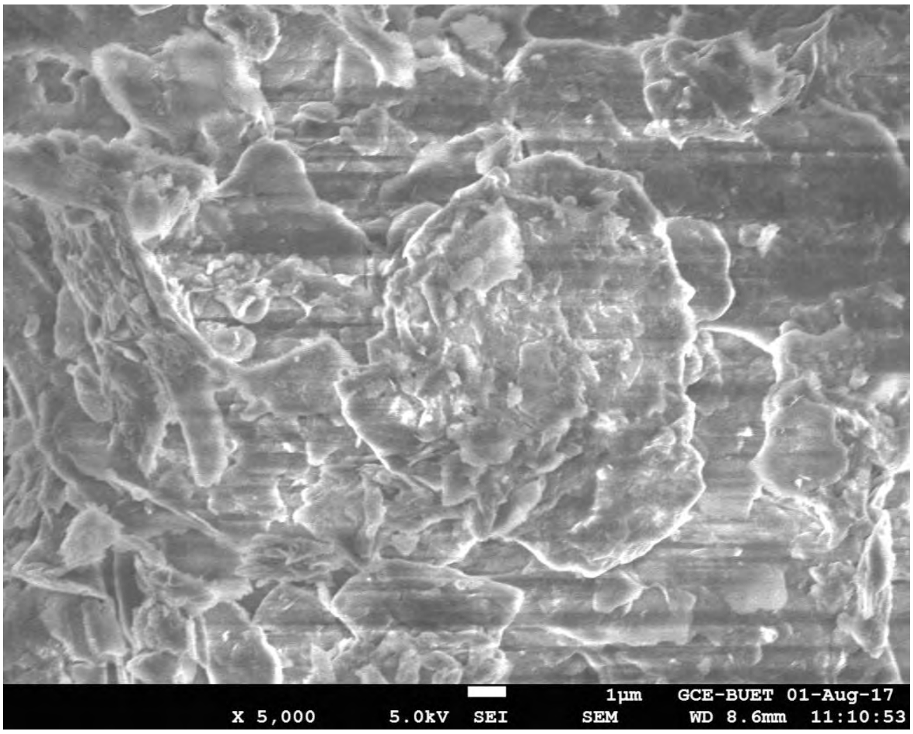
SEM IMAGES OF TREATED AND UNTREATED DISPERSIVE SOILS

1. SEM Images of Dispersive Soil Samples

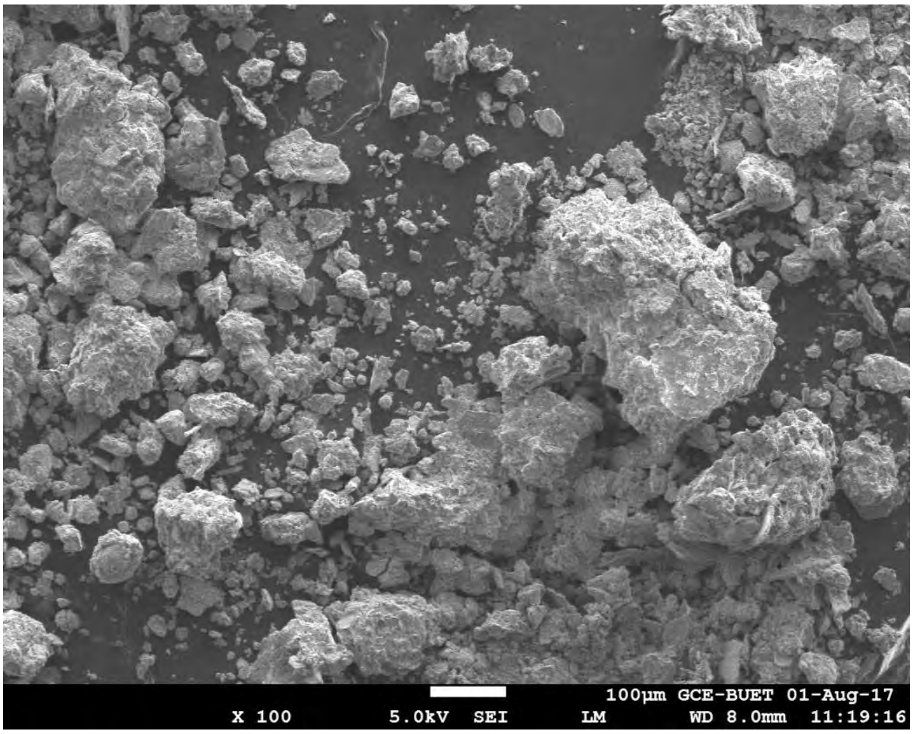


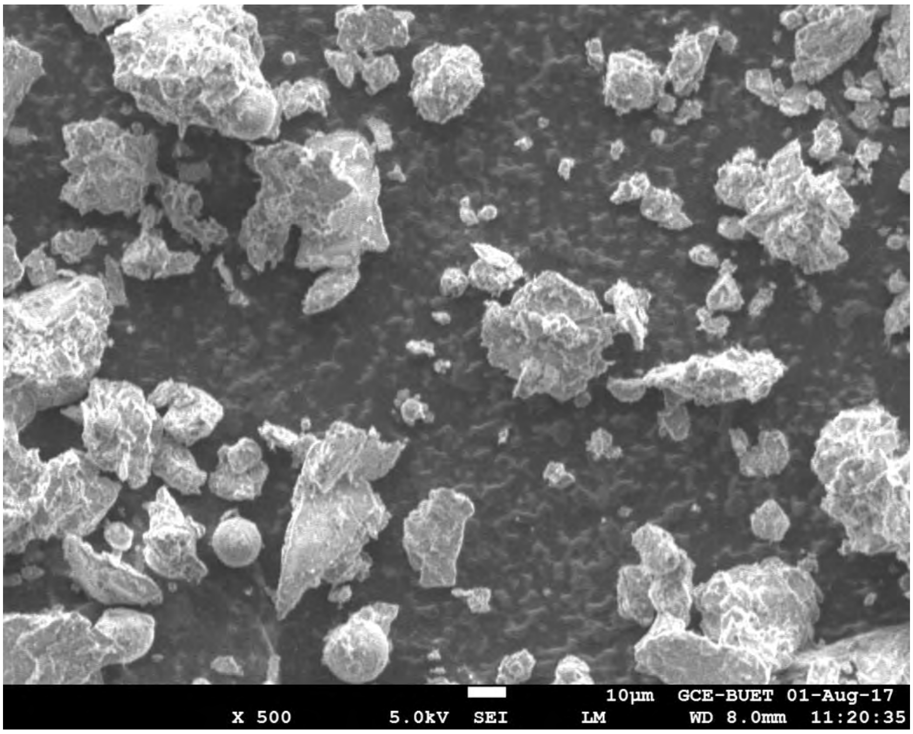


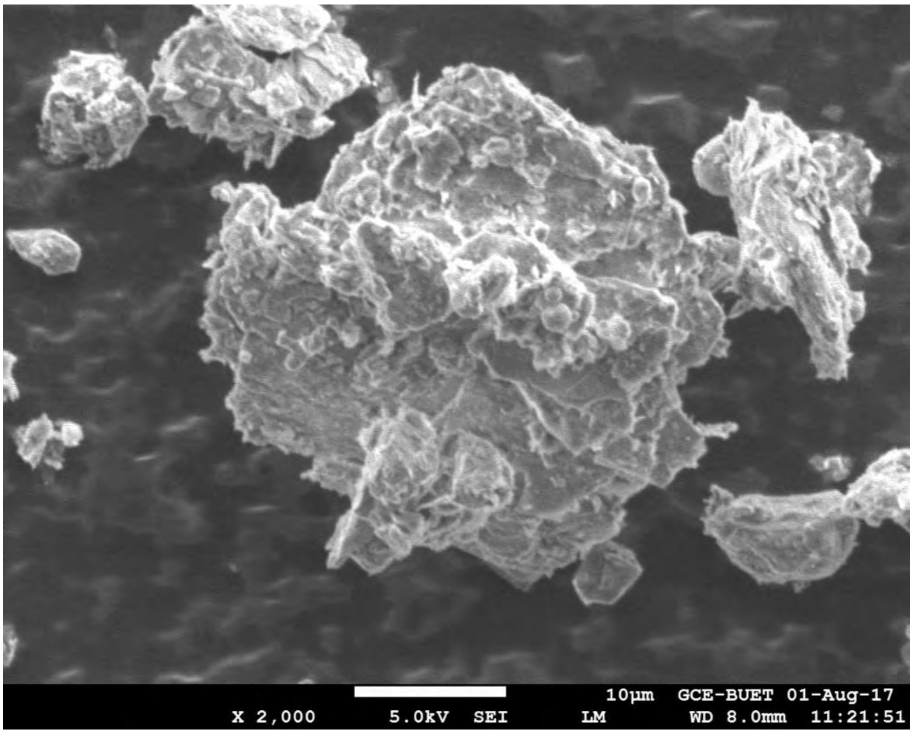

10µm GCE-BUET 01-Aug-17
X 2,000 5.0kV SEI SEM WD 8.7mm 10:50:04

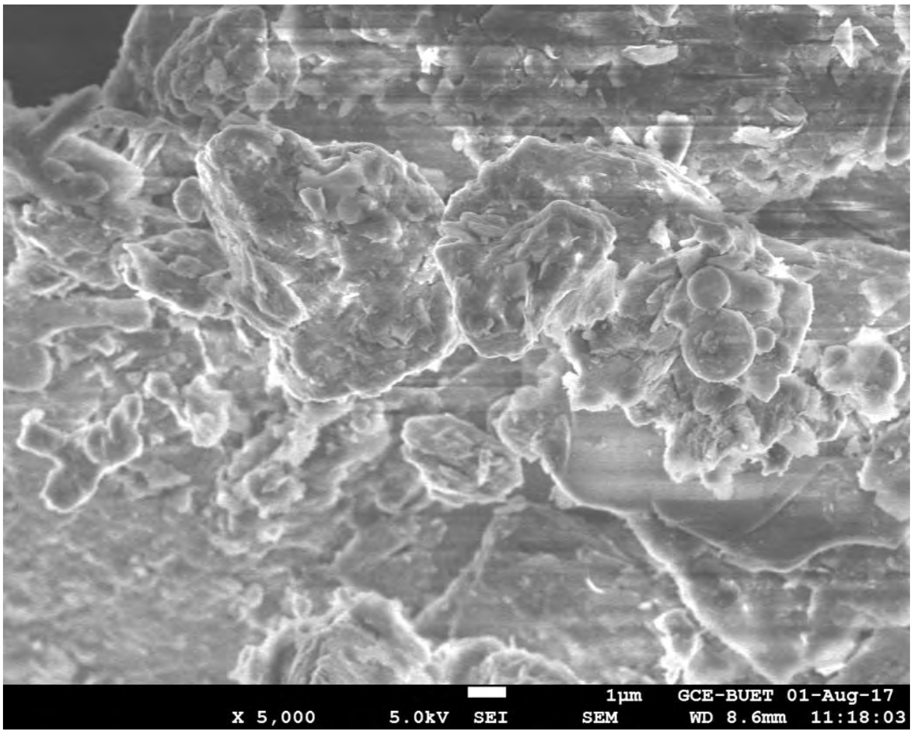

1µm GCE-BUET 01-Aug-17
X 5,000 5.0kV SEI SEM WD 8.6mm 11:10:53

2. SEM Images of Soil Sample Treated with 3% Fly Ash

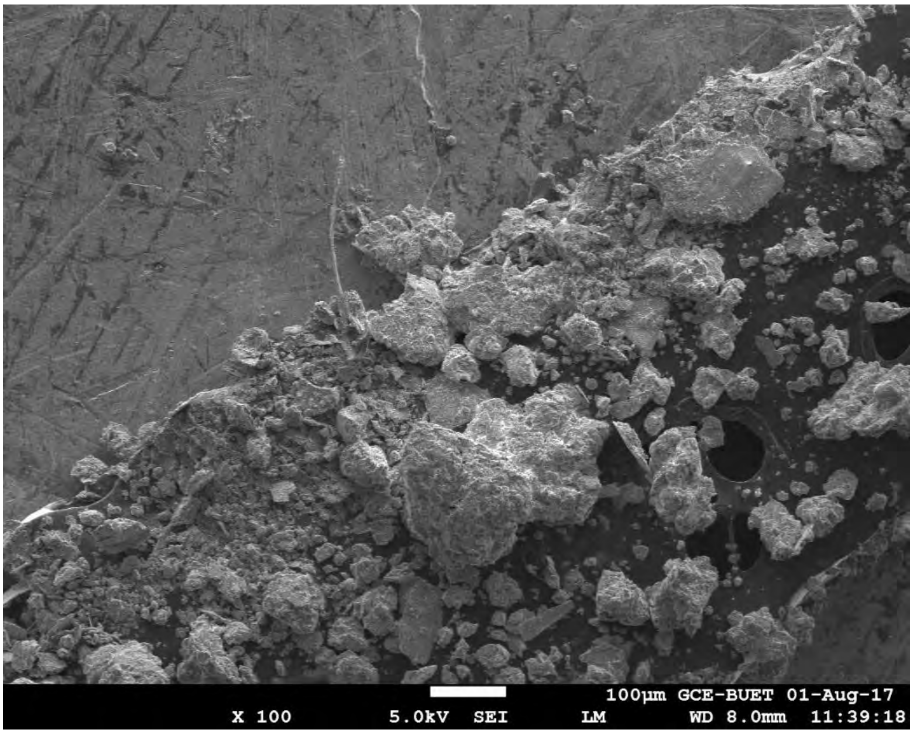


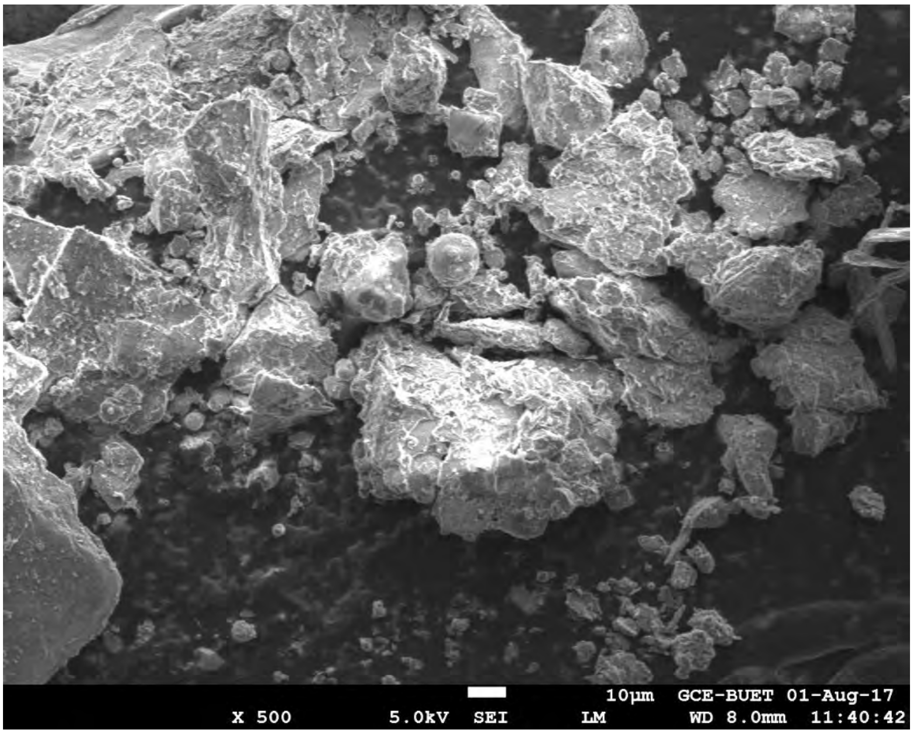


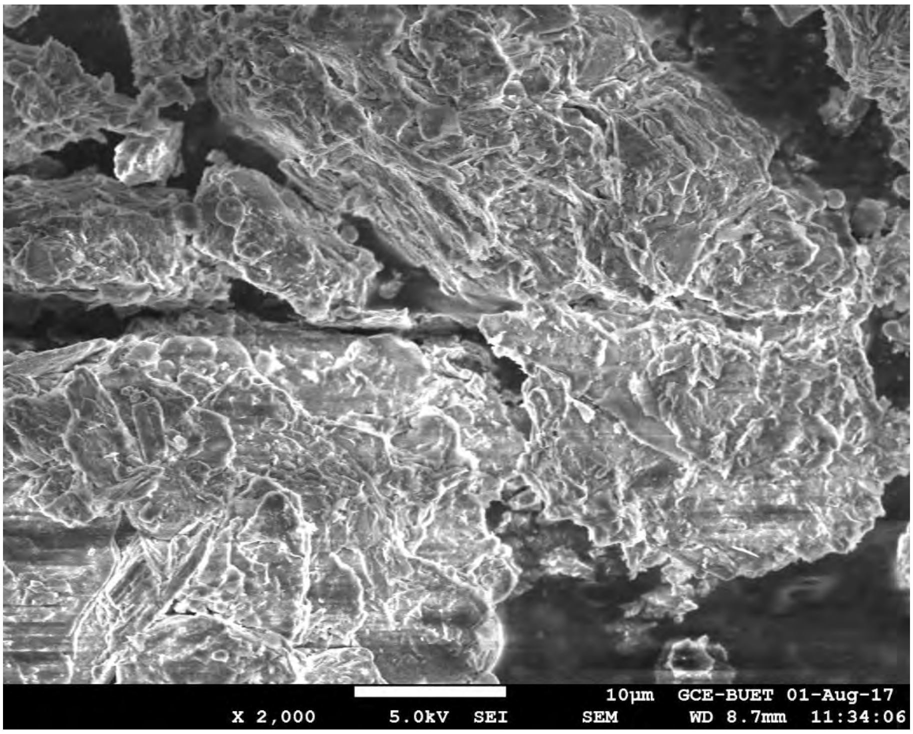

10µm GCE-BUET 01-Aug-17
X 2,000 5.0kV SEI LM WD 8.0mm 11:21:51

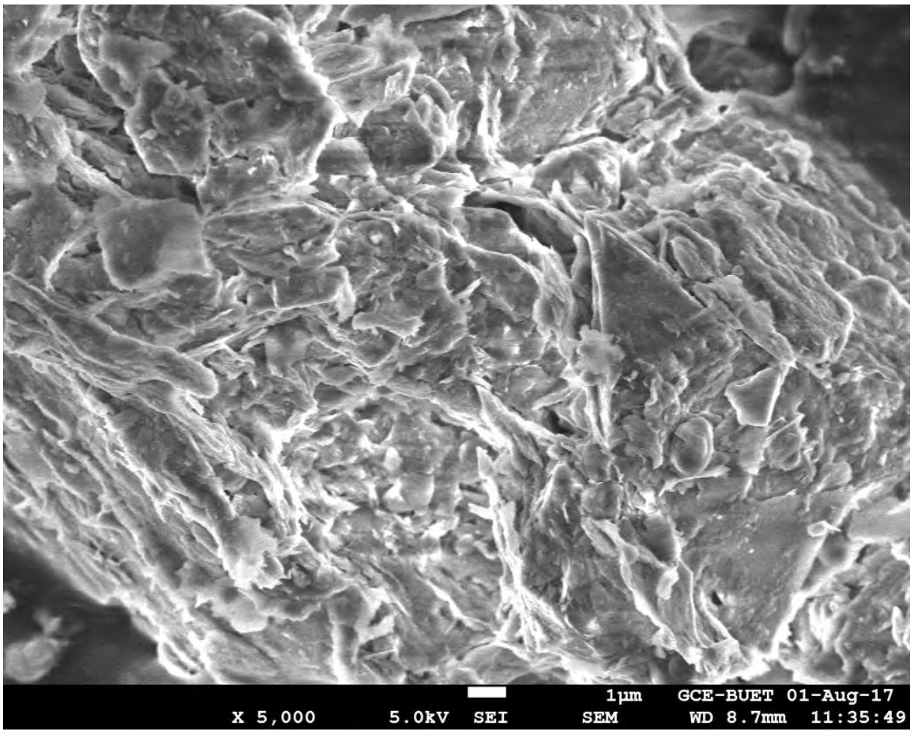

1µm GCE-BUET 01-Aug-17
X 5,000 5.0kV SEI SEM WD 8.6mm 11:18:03

3. SEM Images of Soil Sample Treated with 6% Fly Ash

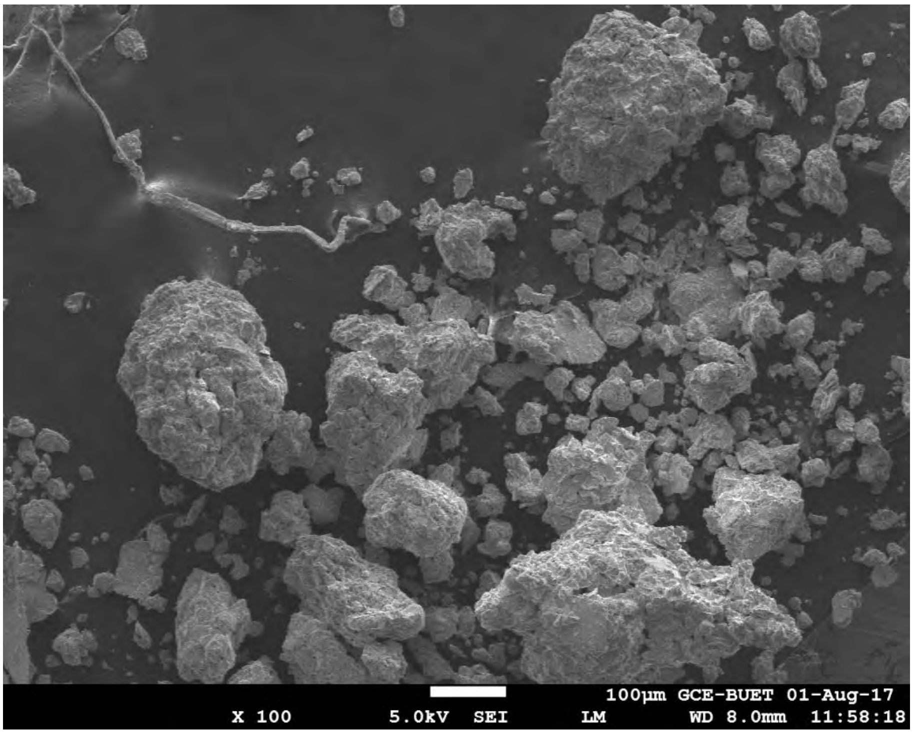


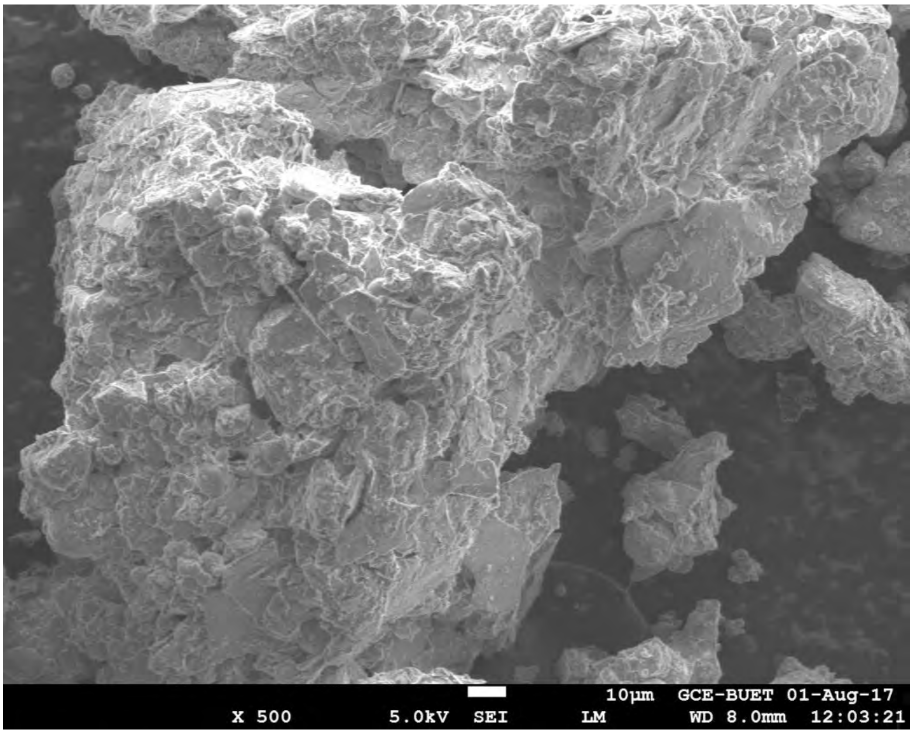


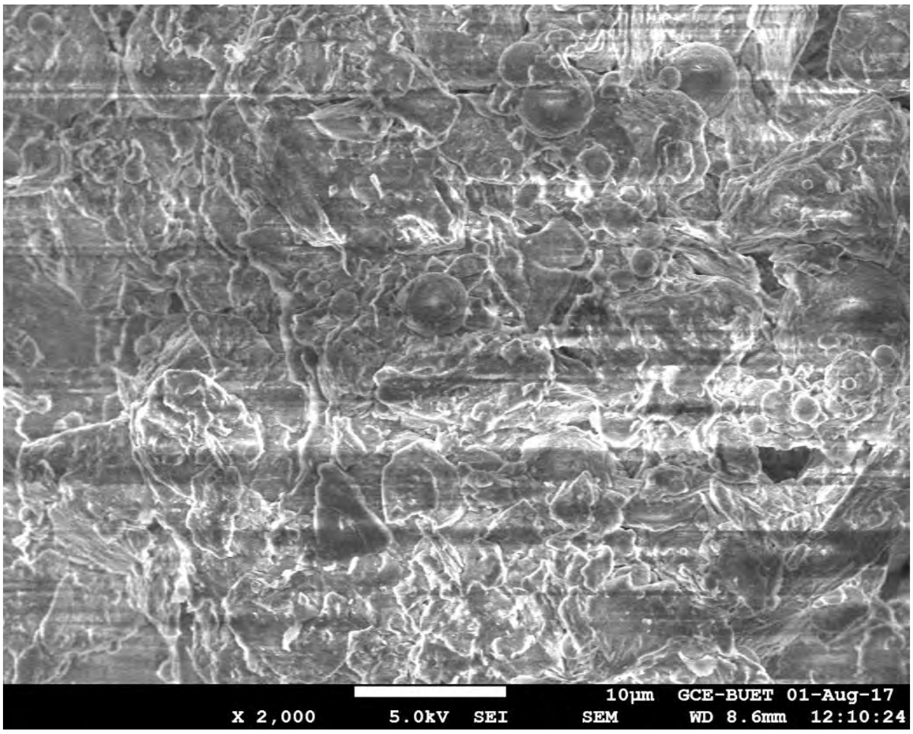

10µm GCE-BUET 01-Aug-17
X 2,000 5.0kV SEI SEM WD 8.7mm 11:34:06

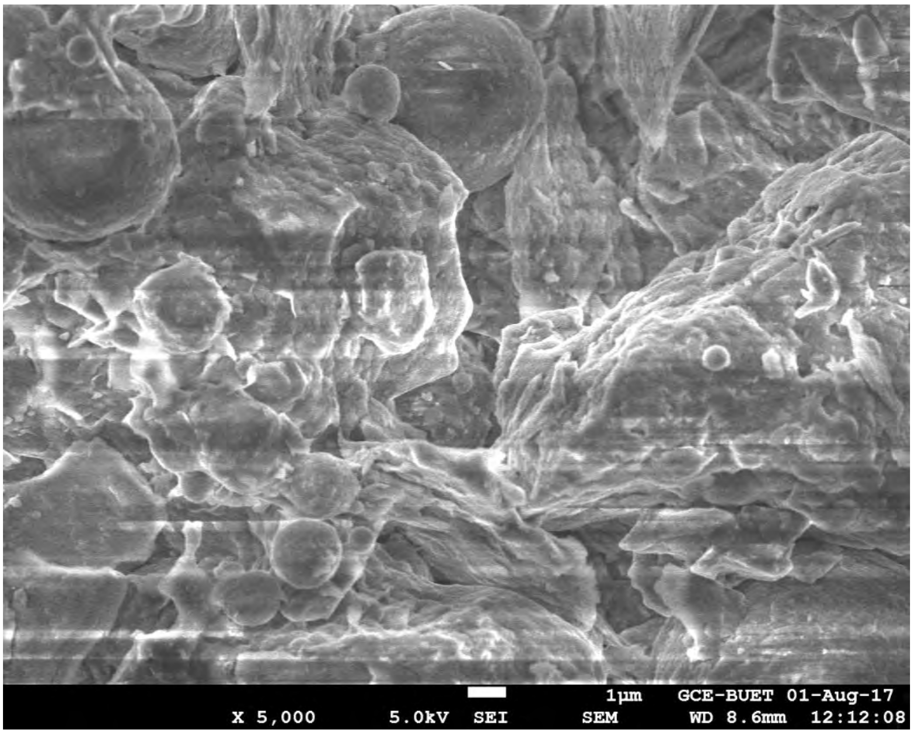

1µm GCE-BUET 01-Aug-17
X 5,000 5.0kV SEI SEM WD 8.7mm 11:35:49

4. SEM Images of Soil Sample Treated with 9% Fly Ash

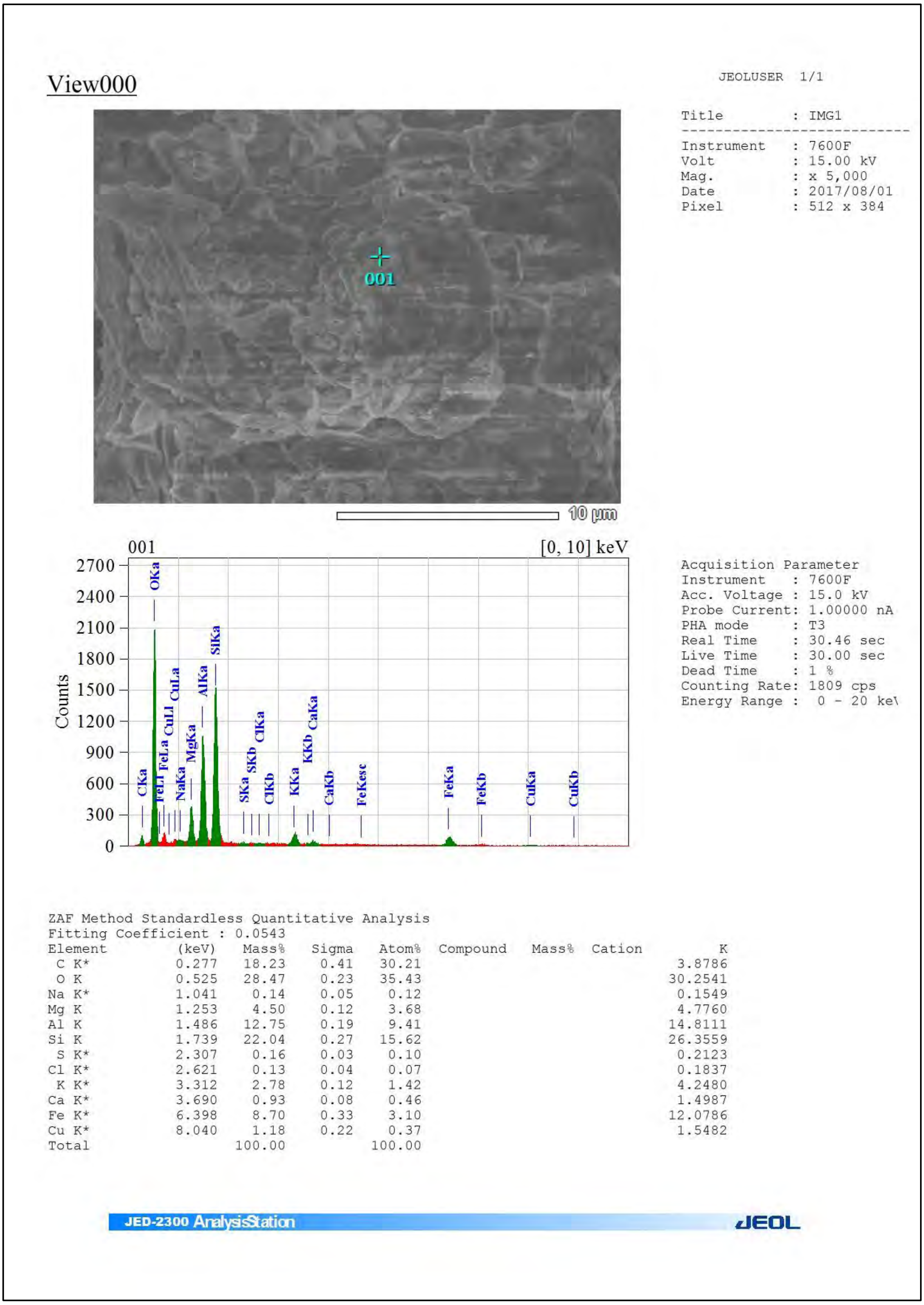





10µm GCE-BUET 01-Aug-17
X 2,000 5.0kV SEI SEM WD 8.6mm 12:10:24


1µm GCE-BUET 01-Aug-17
X 5,000 5.0kV SEI SEM WD 8.6mm 12:12:08

5. SEM Images and Data of Dispersive Soil



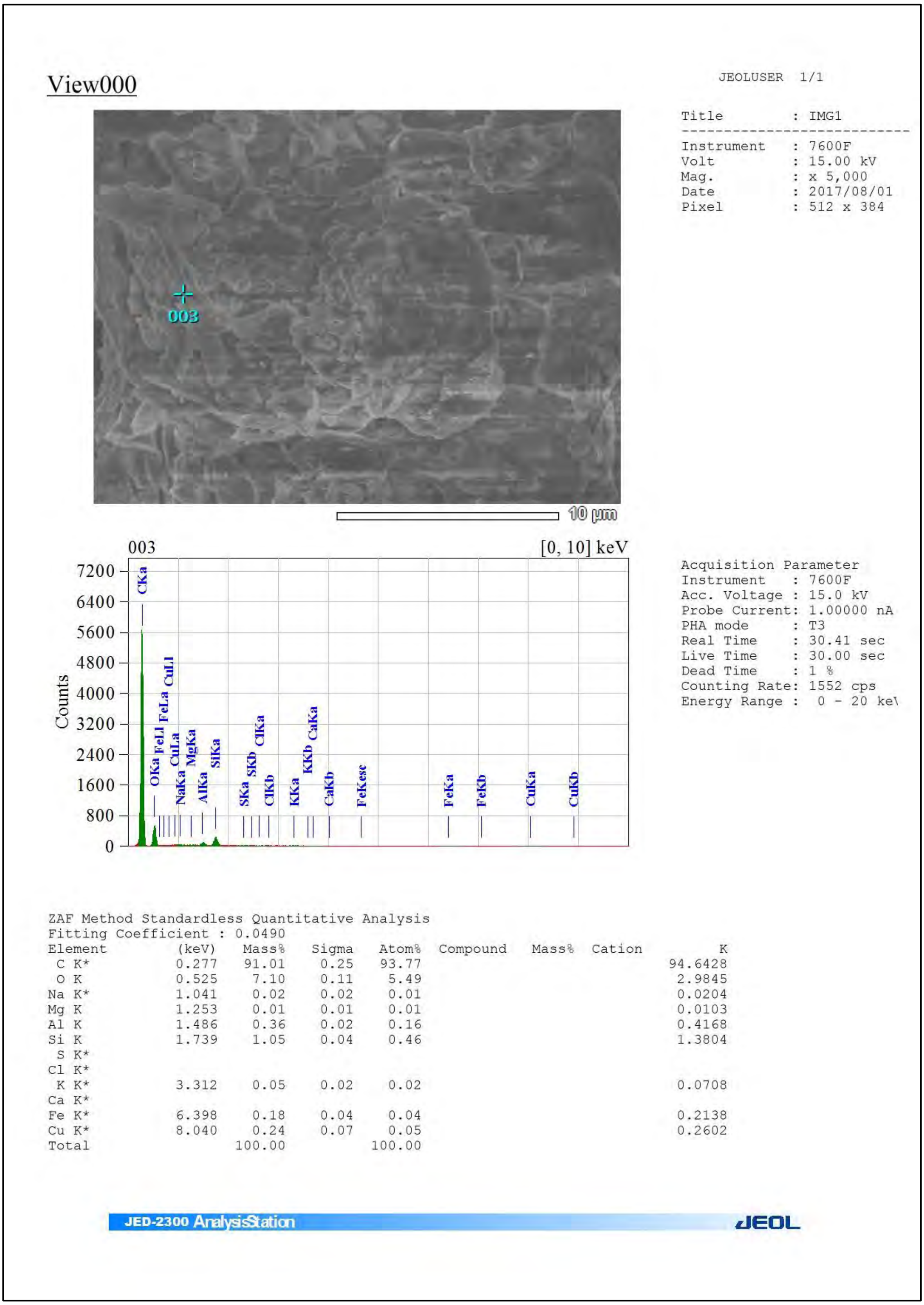
View000

```
JEOLUSER  1/1

Title          : IMG1
----------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.46 sec
Live Time      : 30.00 sec
Dead Time      : 1 %
Counting Rate: 1809 cps
Energy Range :  0 - 20 keV
```

```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0543
Element         (keV)   Mass%   Sigma   Atom%  Compound    Mass%  Cation        K
 C K*           0.277   18.23    0.41   30.21                                3.8786
 O K            0.525   28.47    0.23   35.43                               30.2541
Na K*           1.041    0.14    0.05    0.12                                0.1549
Mg K            1.253    4.50    0.12    3.68                                4.7760
Al K            1.486   12.75    0.19    9.41                               14.8111
Si K            1.739   22.04    0.27   15.62                               26.3559
 S K*           2.307    0.16    0.03    0.10                                0.2123
Cl K*           2.621    0.13    0.04    0.07                                0.1837
 K K*           3.312    2.78    0.12    1.42                                4.2480
Ca K*           3.690    0.93    0.08    0.46                                1.4987
Fe K*           6.398    8.70    0.33    3.10                               12.0786
Cu K*           8.040    1.18    0.22    0.37                                1.5482
Total                  100.00          100.00
```



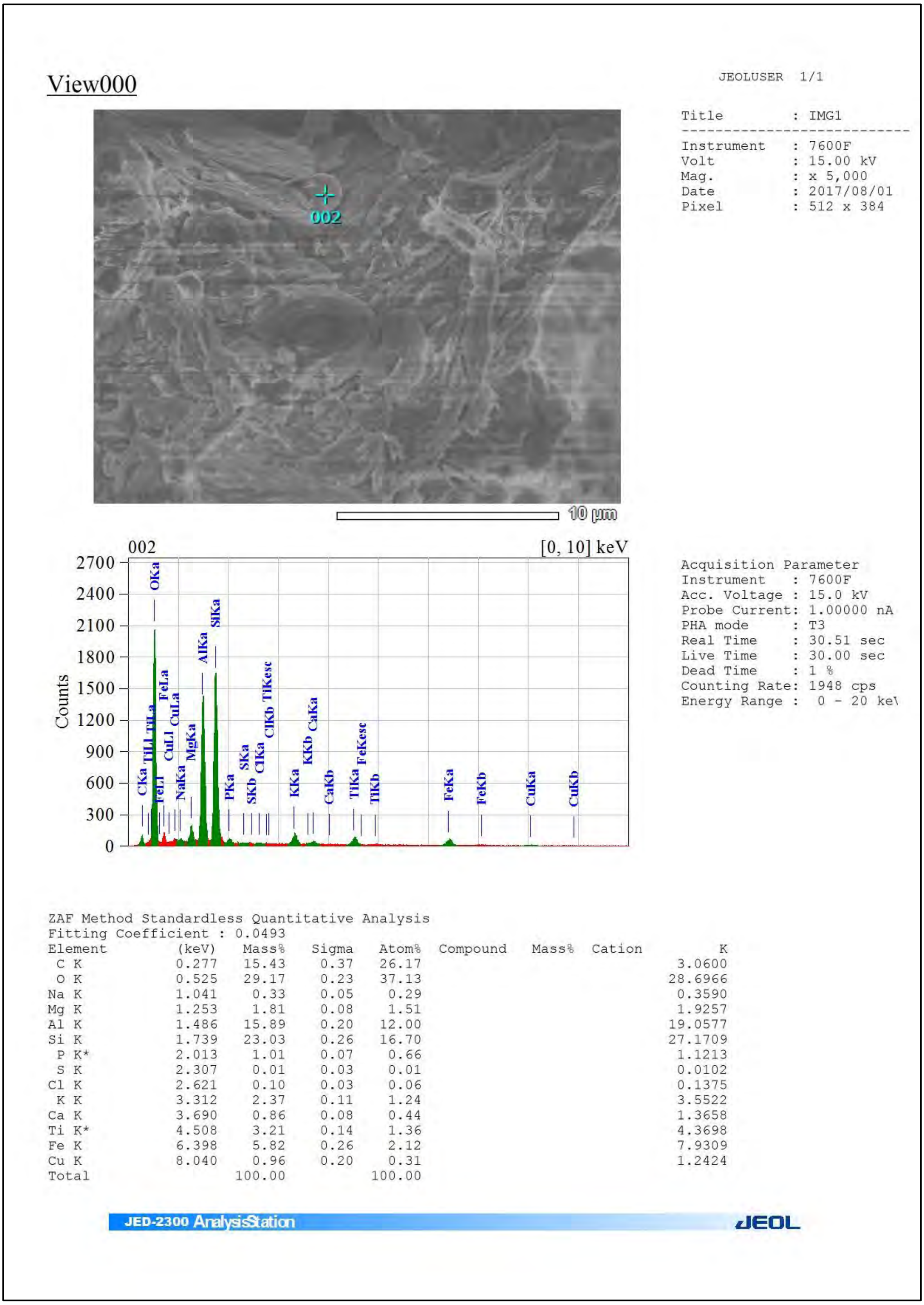
```
JEOLUSER  1/1

Title          : IMG1
---------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.41 sec
Live Time      : 30.00 sec
Dead Time      : 1 %
Counting Rate: 1552 cps
Energy Range :  0 - 20 ke\
```

```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0490
Element          (keV)   Mass%   Sigma   Atom%  Compound    Mass%  Cation           K
 C K*            0.277   91.01    0.25   93.77                              94.6428
 O K             0.525    7.10    0.11    5.49                               2.9845
Na K*            1.041    0.02    0.02    0.01                               0.0204
Mg K             1.253    0.01    0.01    0.01                               0.0103
Al K             1.486    0.36    0.02    0.16                               0.4168
Si K             1.739    1.05    0.04    0.46                               1.3804
 S K*
Cl K*
 K K*            3.312    0.05    0.02    0.02                               0.0708
Ca K*
Fe K*            6.398    0.18    0.04    0.04                               0.2138
Cu K*            8.040    0.24    0.07    0.05                               0.2602
Total                   100.00          100.00
```

6. SEM Images and Data of Treated Soil with 3% Fly Ash



View000

```
JEOLUSER  1/1

Title          : IMG1
----------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

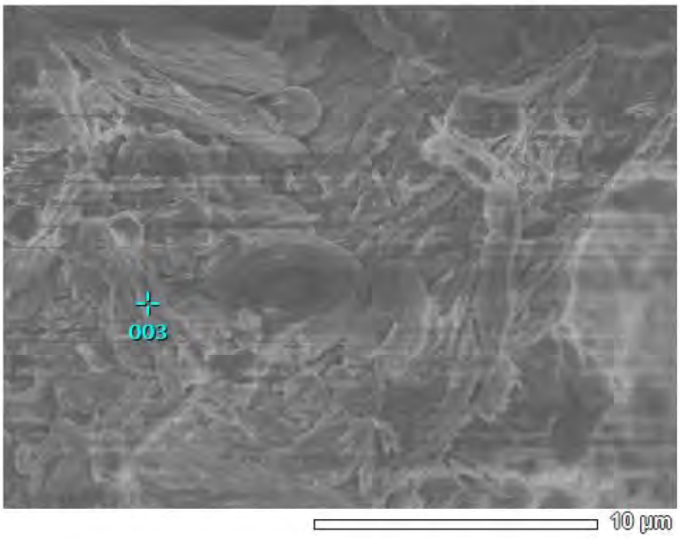
```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.51 sec
Live Time      : 30.00 sec
Dead Time      : 1 %
Counting Rate: 1948 cps
Energy Range :  0 - 20 ke\
```

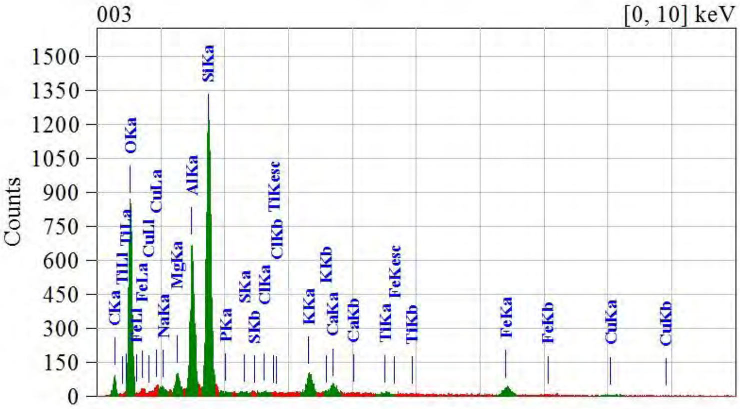
```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0493
Element          (keV)    Mass%    Sigma    Atom%  Compound    Mass%  Cation          K
 C K             0.277    15.43     0.37    26.17                                3.0600
 O K             0.525    29.17     0.23    37.13                               28.6966
Na K             1.041     0.33     0.05     0.29                                0.3590
Mg K             1.253     1.81     0.08     1.51                                1.9257
Al K             1.486    15.89     0.20    12.00                               19.0577
Si K             1.739    23.03     0.26    16.70                               27.1709
 P K*            2.013     1.01     0.07     0.66                                1.1213
 S K             2.307     0.01     0.03     0.01                                0.0102
Cl K             2.621     0.10     0.03     0.06                                0.1375
 K K             3.312     2.37     0.11     1.24                                3.5522
Ca K             3.690     0.86     0.08     0.44                                1.3658
Ti K*            4.508     3.21     0.14     1.36                                4.3698
Fe K             6.398     5.82     0.26     2.12                                7.9309
Cu K             8.040     0.96     0.20     0.31                                1.2424
Total                    100.00            100.00
```

View000

```
JEOLUSER  1/1

Title          : IMG1
-----------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

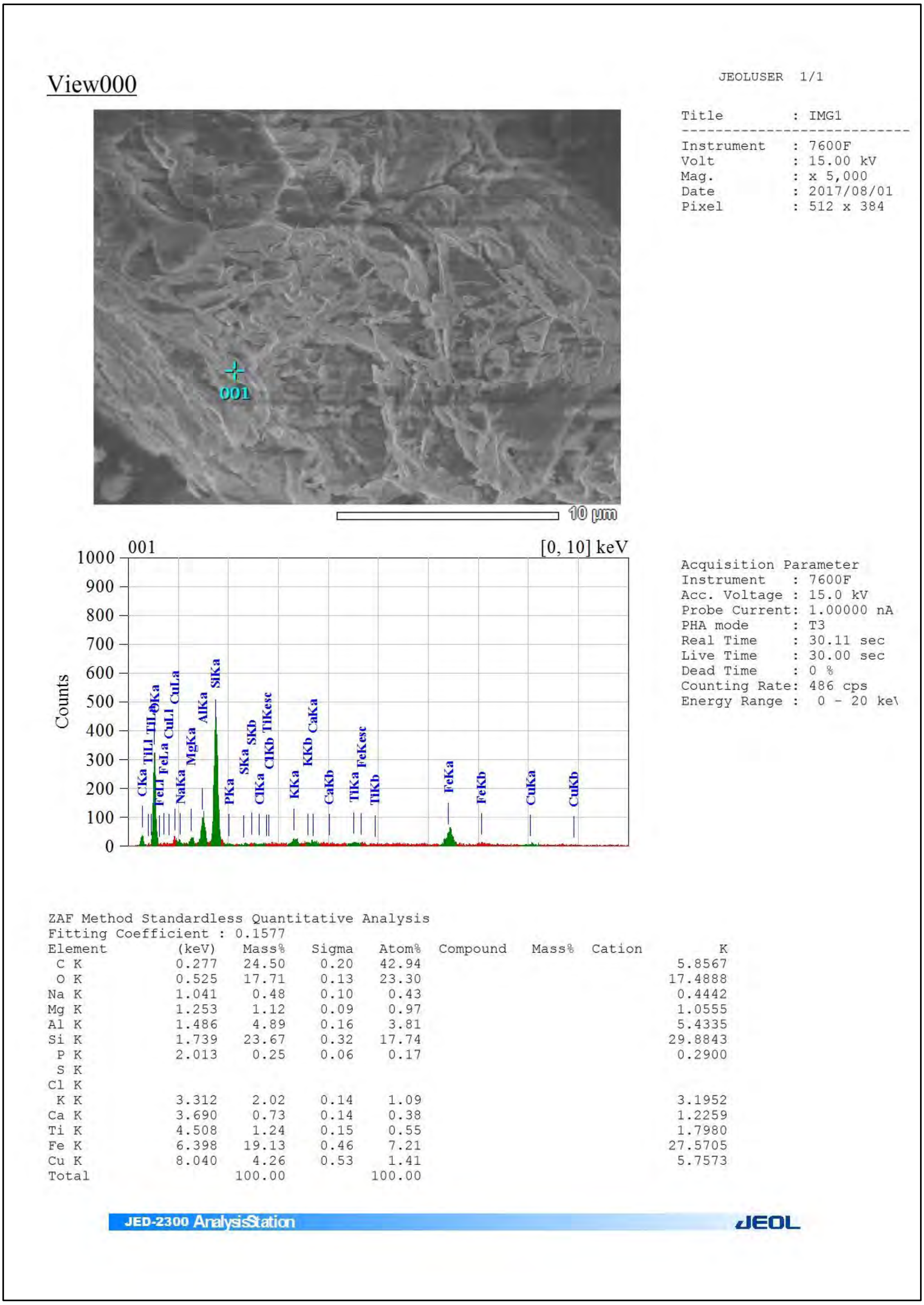




```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.28 sec
Live Time      : 30.00 sec
Dead Time      : 0 %
Counting Rate: 1145 cps
Energy Range :  0 - 20 ke\
```

```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0667
Element         (keV)   Mass%   Sigma   Atom%  Compound    Mass%  Cation          K
 C K            0.277   24.79    0.59   39.81                                5.5321
 O K            0.525   22.55    0.28   27.19                               21.1437
Na K            1.041    0.26    0.06    0.22                                0.3218
Mg K            1.253    1.33    0.09    1.06                                1.5746
Al K            1.486   11.23    0.22    8.03                               14.9552
Si K            1.739   26.75    0.35   18.37                               36.2917
 P K*           2.013    0.00    0.05    0.00                                0.0040
 S K            2.307    0.07    0.04    0.04                                0.0929
Cl K            2.621    0.16    0.05    0.09                                0.2442
 K K            3.312    3.56    0.16    1.76                                5.8051
Ca K            3.690    1.78    0.13    0.85                                3.0427
Ti K*           4.508    0.55    0.10    0.22                                0.8062
Fe K            6.398    6.01    0.34    2.07                                8.8570
Cu K            8.040    0.95    0.28    0.29                                1.3288
Total                  100.00          100.00
```

7. SEM Images and Data of Treated Soil with 6% Fly Ash



View000

```
JEOLUSER  1/1

Title          : IMG1
----------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

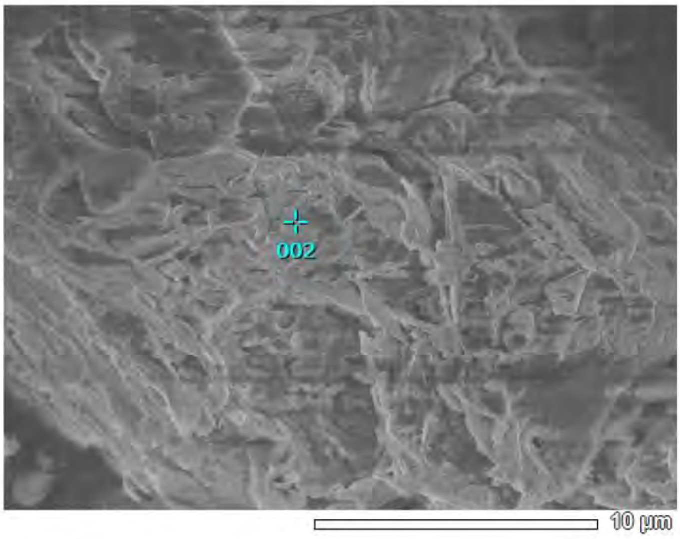
```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.11 sec
Live Time      : 30.00 sec
Dead Time      : 0 %
Counting Rate: 486 cps
Energy Range :  0 - 20 ke\
```

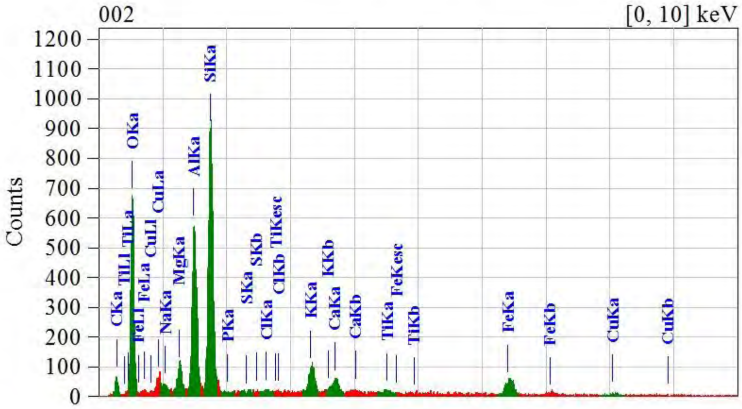
```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.1577
Element        (keV)   Mass%   Sigma   Atom%  Compound     Mass%  Cation          K
 C K           0.277   24.50    0.20   42.94                                 5.8567
 O K           0.525   17.71    0.13   23.30                                17.4888
Na K           1.041    0.48    0.10    0.43                                 0.4442
Mg K           1.253    1.12    0.09    0.97                                 1.0555
Al K           1.486    4.89    0.16    3.81                                 5.4335
Si K           1.739   23.67    0.32   17.74                                29.8843
 P K           2.013    0.25    0.06    0.17                                 0.2900
 S K
Cl K
 K K           3.312    2.02    0.14    1.09                                 3.1952
Ca K           3.690    0.73    0.14    0.38                                 1.2259
Ti K           4.508    1.24    0.15    0.55                                 1.7980
Fe K           6.398   19.13    0.46    7.21                                27.5705
Cu K           8.040    4.26    0.53    1.41                                 5.7573
Total                 100.00          100.00
```

View000

```
JEOLUSER  1/1

Title          : IMG1
-----------------------------
Instrument     : 7600F
Volt           : 15.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```



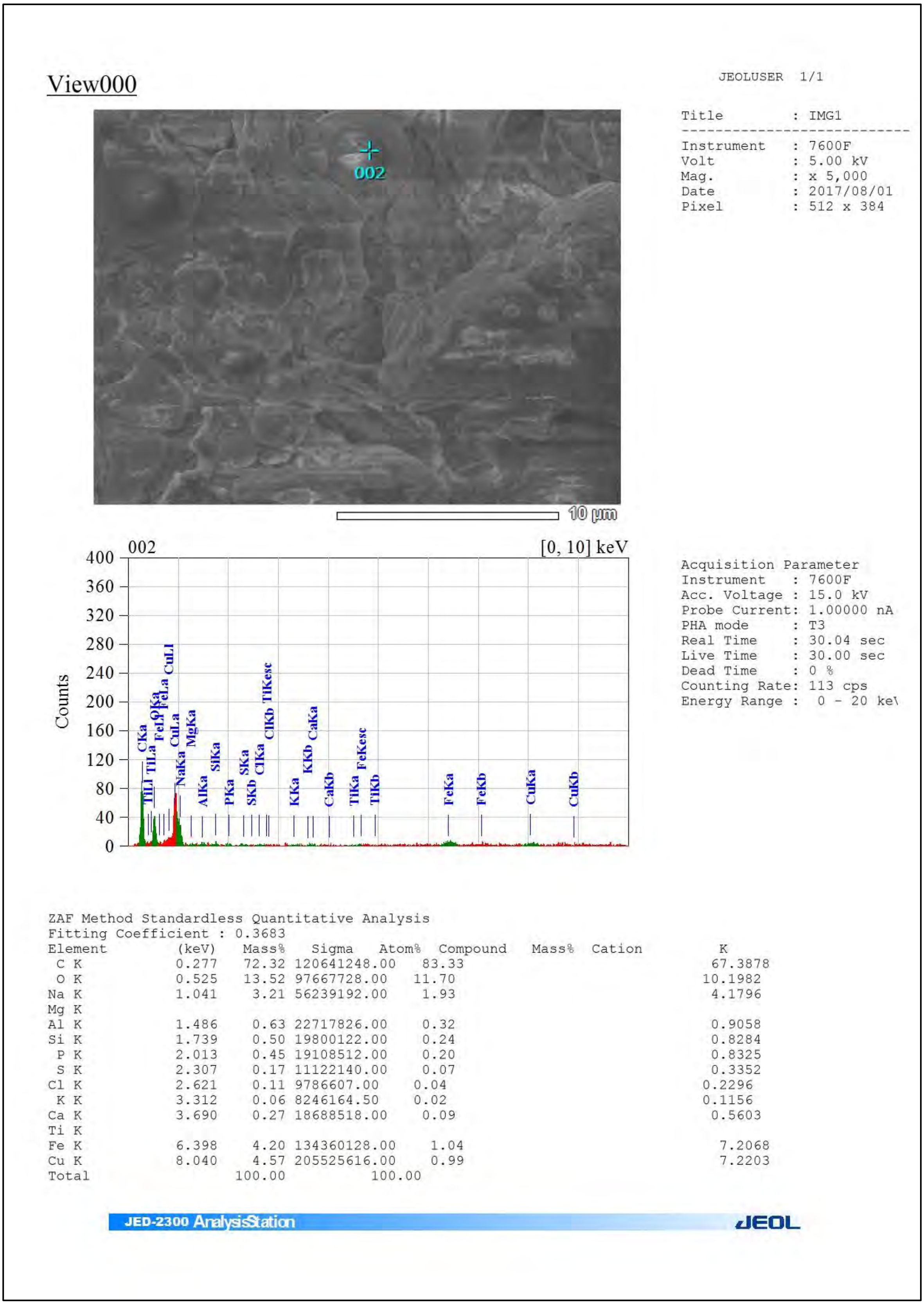


```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.28 sec
Live Time      : 30.00 sec
Dead Time      : 0 %
Counting Rate: 1027 cps
Energy Range :   0 - 20 ke\
```

```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0891
Element          (keV)    Mass%    Sigma    Atom%  Compound     Mass%  Cation            K
 C K             0.277    22.01     0.58    37.64                                   4.9096
 O K             0.525    19.61     0.27    25.18                                  17.8441
Na K             1.041     0.47     0.08     0.42                                   0.5238
Mg K             1.253     2.32     0.12     1.96                                   2.5032
Al K             1.486    12.14     0.25     9.25                                  14.8084
Si K             1.739    23.21     0.36    16.98                                  29.1933
 P K
 S K
Cl K             2.621     0.35     0.06     0.20                                   0.5103
 K K             3.312     4.57     0.19     2.40                                   7.2474
Ca K             3.690     2.66     0.17     1.36                                   4.4281
Ti K             4.508     0.75     0.12     0.32                                   1.0688
Fe K             6.398     9.75     0.47     3.59                                  14.0193
Cu K             8.040     2.16     0.40     0.70                                   2.9437
Total                    100.00           100.00
```

JED-2300 AnalysisStation JEOL

8. SEM Images and Data of Treated Soil with 9% Fly Ash



```
JEOLUSER  1/1

Title          : IMG1
----------------------------
Instrument     : 7600F
Volt           : 5.00 kV
Mag.           : x 5,000
Date           : 2017/08/01
Pixel          : 512 x 384
```

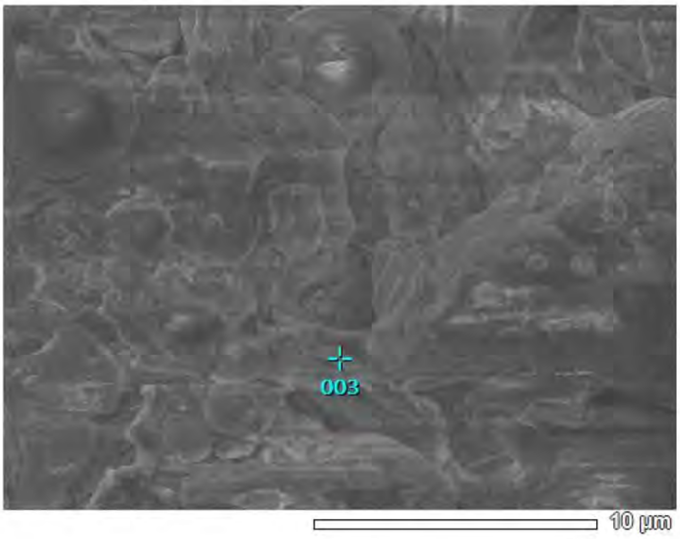
```
Acquisition Parameter
Instrument     : 7600F
Acc. Voltage   : 15.0 kV
Probe Current: 1.00000 nA
PHA mode       : T3
Real Time      : 30.04 sec
Live Time      : 30.00 sec
Dead Time      : 0 %
Counting Rate: 113 cps
Energy Range :  0 - 20 keV
```

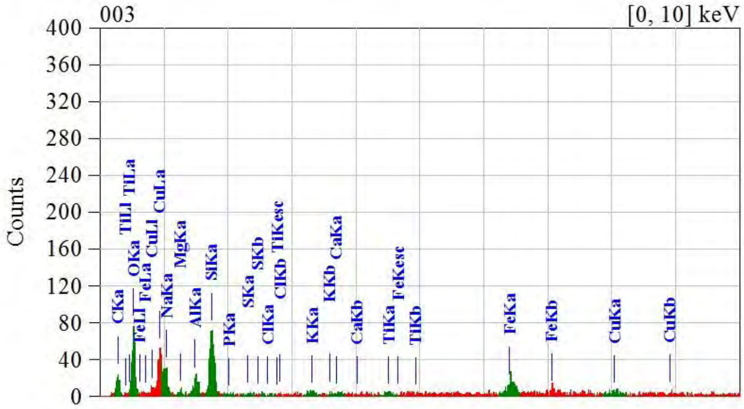
```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.3683
Element         (keV)   Mass%   Sigma    Atom%  Compound    Mass%  Cation          K
 C K            0.277   72.32 120641248.00   83.33                                 67.3878
 O K            0.525   13.52 97667728.00   11.70                                 10.1982
Na K            1.041    3.21 56239192.00    1.93                                  4.1796
Mg K
Al K            1.486    0.63 22717826.00    0.32                                  0.9058
Si K            1.739    0.50 19800122.00    0.24                                  0.8284
 P K            2.013    0.45 19108512.00    0.20                                  0.8325
 S K            2.307    0.17 11122140.00    0.07                                  0.3352
Cl K            2.621    0.11 9786607.00    0.04                                  0.2296
 K K            3.312    0.06 8246164.50    0.02                                  0.1156
Ca K            3.690    0.27 18688518.00    0.09                                  0.5603
Ti K
Fe K            6.398    4.20 134360128.00    1.04                                  7.2068
Cu K            8.040    4.57 205525616.00    0.99                                  7.2203
Total                 100.00             100.00
```

View000

JEOLUSER 1/1

```
Title         : IMG1
----------------------------
Instrument    : 7600F
Volt          : 5.00 kV
Mag.          : x 5,000
Date          : 2017/08/01
Pixel         : 512 x 384
```





```
Acquisition Parameter
Instrument    : 7600F
Acc. Voltage : 15.0 kV
Probe Current: 1.00000 nA
PHA mode      : T3
Real Time     : 30.06 sec
Live Time     : 30.00 sec
Dead Time     : 0 %
Counting Rate: 169 cps
Energy Range :  0 - 20 ke\
```

```
ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.3570
Element        (keV)    Mass%    Sigma    Atom%  Compound    Mass%  Cation          K
 C K           0.277    37.05     1.64    58.45                              13.7854
 O K           0.525    14.79     0.63    17.51                              14.9937
Na K           1.041     3.63     0.49     2.99                               3.7222
Mg K           1.253     1.21     0.24     0.94                               1.2016
Al K           1.486     2.76     0.36     1.94                               3.3026
Si K           1.739    12.89     0.71     8.70                              18.1232
 P K
 S K
Cl K
 K K           3.312     1.05     0.28     0.51                               1.9319
Ca K           3.690     0.10     0.23     0.05                               0.1929
Ti K           4.508     2.12     0.42     0.84                               3.5110
Fe K           6.398    19.36     1.74     6.57                              31.5702
Cu K           8.040     5.04     1.86     1.50                               7.6653
Total                  100.00           100.00
```