

**GEPOLYMER STABILIZED CEMENT DEEP  
MIXING PILES FOR ROAD EMBANKMENT ON  
RECONSTITUTED SOFT SOILS**

**SHARIF ALI HOSSAIN**

**M.Sc. ENGINEERING THESIS**



**DEPARTMENT OF CIVIL ENGINEERING  
MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY  
DHAKA, BANGLADESH**

**MARCH 2023**

# GEOPOLYMER STABILIZED CEMENT DEEP MIXING PILES FOR ROAD EMBANKMENT ON RECONSTITUTED SOFT SOILS

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of  
Science in Civil Engineering



DEPARTMENT OF CIVIL ENGINEERING  
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I hereby declare that the study reported in this thesis entitled as above is my own original work and has not been submitted before anywhere for any degree or other purposes. Further I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged and cited in the reference section.

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M.Sc. Engineering Thesis

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## ACKNOWLEDGEMENTS

All praise to Almighty ALLAH for His favor for allowing the researcher to complete the research work. The author articulates his sincerest appreciation to his supervisor, Lieutenant Colonel Mohammed Russedul Islam, PhD, Instructor Class A, Department of Civil Engineering, MIST, for his incessant attention, continuous encouragement, and thoughtful direction throughout this study. His inquisitiveness, valuable suggestions, and productive supervision at every step made this study efficacious.

The author acknowledges the inspiration and unremitting guidance of Dr. Md. Aftabur Rahman, Professor, Department of Civil Engineering, CUET. The author greatly acknowledges his external examination committee member, Professor Dr Md Hadiuzzaman, Department of Civil Engineering, Bangladesh University of Engineering and Technology, for his constructive explanations and assessments. The overall guidance of the respected Professor Dr. Md. Zoynul Abedin was unfathomable.

The author also expresses his profound gratitude to Brigadier General Md. Wahidul Islam, Head of the Department, Department of Civil Engineering, MIST, for his encouragement and cooperation. All responsible personnel of the Transportation and Geotechnical Engineering Laboratory, MIST are duly acknowledged by the author.

The author is in debt to all those who he, formally or informally, talked to, interviewed, and consulted in connection with the research, without which this research work would not be possible. Finally, the author would like to thank his spouse and sons for their limitless support and encouragement in completing the work.

## ABSTRACT

### **Geopolymer Stabilized Cement Deep Mixing Piles for Road Embankment on Reconstituted Soft Soils**

This study was carried out to utilize fly ash and industrial slag based for constructing deep mixing piles. A total of six combinations with slag and fly ash based geopolymer along with cement were used to improve the strength characteristics of soil samples collected from a catchment area of Padma River at Mawa in the laboratory based experiments. Cylindrical samples prepared with different combinations were cured in four different curing conditions and tested for unconfined compressive strength and split tensile strength. Meanwhile, laboratory scale miniature Deep Mixing Pile (DMP) machine was designed and constructed. Reconstituted soil bed was prepared by consolidation process with one liquid limit of water. Laboratory scale deep mixing piles were constructed in the reconstituted soil bed by the miniature deep mixing pile machine using selected three combinations from the laboratory based experiment results. After curing, the extruded pile samples were tested for unconfined compressive strength and split tensile strength. Moreover, microstructure analysis of the pile samples was conducted by Scanning electronic microscope (SEM) and Energy-dispersive x-ray spectroscopy (EDS). It was found that samples cured in humid condition followed by 24 hours heat before test manifested higher strength among the samples of four curing condition, which was five to ten times of the samples cured only in humid condition. Moreover, with the addition of the geopolymer, compressive strength of the cylindrical samples was found to increase up to 25% of geopolymer content. However, further increment of geopolymer resulted in reduction of strength. The laboratory scale machine worked well and could successfully executed deep mixing piles. Among the three combinations used for deep mixing pile, five percent cement with fifteen percent binder showed highest strength value of 527 kPa.

**Geopolymer Stabilized Cement Deep Mixing Piles for Road Embankment on Reconstituted Soft Soils**

এই গবেষণায় ডিপ মিক্সিং পাইল (Deep Mixing Pile) তৈরীতে সিমেন্টের বিকল্প হিসেবে ফ্লাই এ্যাশ ও স্ল্যাগ ভিত্তিক জিওপলিমার এর ব্যবহার নিয়ে কাজ করা হয়েছে। গবেষণার প্রথম অংশে সিমেন্টের পাশাপাশি ফ্লাই এ্যাশ ও স্ল্যাগ ভিত্তিক ছয়টি জিওপলিমার মিশ্রন দ্বারা পদ্মা অববাহিকার মাওয়া অংশের মাটির শক্তির উন্নতিতে ল্যাবরেটরীতে পরীক্ষামূলক কাজ করা হয়েছে। বিভিন্ন মিশ্রনের নমুনাগুলোকে ভিন্ন চারটি কিউরিং প্রক্রিয়ায় রেখে ইউসিএস ও স্প্লিট টেনসাইল স্ট্রেস পরীক্ষা করা হয়েছে। ইতোমধ্যে ল্যাবরেটরীতে ব্যবহারযোগ্য ক্ষুদ্রাকৃতির ডিপ মিক্সিং পাইল মেশিন ডিজাইন ও প্রস্তুত করা হয়েছে। কনসোলিডেশন পদ্ধতিতে মাটির রিকম্প্রিউট বেড তৈরী করা হয়েছে, যেখানে পানির পরিমাণ ছিল এক লিকুইড লিমিট। অতঃপর নির্বাচিত তিনটি মিশ্রন দিয়ে উদ্ভাবিত উপায়ে ল্যাব স্কেলে তৈরীকৃত ডিপ মিক্সিং পাইল যন্ত্রের মাধ্যমে রিকম্প্রিউট বেড এর মধ্যে ডিপ মিক্সিং পাইল বানানো হয়। এর পরে ২৮ দিন কিউরিং করার পরে পাইলগুলোকে তুলে ইউসিএস এবং স্প্লিট টেনসাইল স্ট্রেস পরীক্ষা করা হয়। এছাড়া এসইএম এবং ইডিএম এ্যানালাইসিসের মাধ্যমে নমুনাগুলোর মাইক্রো স্ট্রাকচার বিশ্লেষণ করা হয়। ল্যাবরেটরীতে পরীক্ষার পূর্বে তাপ প্রদানকৃত নমুনাগুলো সবগুলো মিশ্রনের মধ্যে সর্বোচ্চ শক্তি প্রদর্শন করে আর্দ্র অবস্থায় কিউরিংকৃত নমুনা অপেক্ষা পাঁচ থেকে দশগুন বেশি। এছাড়াও জিওপলিমার এর পরিমাণ বাড়ার সাথে সাথে নমুনাগুলোর শক্তি ২৫% পর্যন্ত বাড়তে দেখা যায়। কিন্তু এর পরে ক্রমান্বয়ে বাড়ানো জিওপলিমারের জন্য শক্তি ধীরে ধীরে কমে যেতে দেখা যায়। গবেষণার দ্বিতীয় অংশে দেখা যায়, পাঁচ শতাংশ সিমেন্ট ও পনের শতাংশ জিওপলিমারের মিশ্রন শুধুমাত্র সিমেন্ট এবং শুধুমাত্র জিওপলিমার মিশ্রনের তুলনায় বেশি শক্তি প্রদর্শন করে, যেটি হচ্ছে ৫২৭ কেপিএ।

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## LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BET	Brunauer-Emmett-Teller
CBR	California Bearing ratio
CSH	Calcium Silicate Hydrate
C5B0	5% Cement
C5B15	5% Cement with 15% Binder
C0B20	20% Binder
C0B25	25% Binder
C0B30	30% Binder
C0B	30% Binder
CO <sub>2</sub>	Carbon di-oxide
DMP	Deep Mixing Pile
FA	Fly ash
FE-SEM	Field Emission Scanning Electron Microscope
FSI	Free Swell Index
GGBS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Contents
GP	Geopolymer
LRF	Ladle Furnace Slag
LL	Liquid Limit
L/S	Liquid/Solid Ratios
NaOH	Sodium Hydroxide

Na <sub>2</sub> SiO <sub>3</sub>	Sodium Silicate
OPC	Ordinary Portland Cement
POFA	Palm Oil Fuel Ash
PL	Plastic Limit
PI	Plasticity Index
PBRLP	Padma Bridge Rail Link Project
RHD	Roads and Highways Department
SEM	Scanning Electronic Microscope
TXDOT	Texas Department of Transportation
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
VA	Volcanic Ash

# CHAPTER 1

## INTRODUCTION

### 1.1 General

Unwanted and differential settlement, crack, frequent maintenance, less longevity etc. are being considered as major issues on pavement and railway engineering. Even severe collapse may also happen due to low bearing capacity of soil. Soil improvement is found to be one of the effective solutions to this issue. Soil improvement has been an economic and environment friendly process advancing day by day engaging many materials around us without compromising the basic bearing capacity. Among the various deep-mixing methods, Cement Deep Mixing Pile (DMP) has a relatively long history for its practical application to many instances (Yi et al., 2019). Different types of investigation to improve deep mixing piles have been carried out through years like Stiffened Deep Cement Mixing (SDCM) pile (Farouk and Shahien, 2013). However, the emission of a considerable amount of CO<sub>2</sub> during cement production pointed out the feasibility of using it in ground improvement techniques. At this point, the potential use of waste products draws significant attraction among the researchers working in ground improvement methods. Slag, the by-product of steel re-rolling factories and fly ash, the by-product of coal-based power plant are produced with huge quantities every year. Though the material composition of slag and fly ash shows sufficient bonding characteristics, a positive catalyst may further increase the bonding characteristics (Davidovits, 2015). Highlighting this issue, the concept of geopolymers is applied in ground improvement methods. The term geopolymer refers to the inorganic polymer formed by the alkaline activation. That is, an activator when added to an aluminosilicate rich by-product is defined as geopolymer (Duxson et al., 2007).

### 1.2 Background Study of the Research

Chemical stabilization of soft soils is a standard method by which binders, such as Ordinary Portland Cement (OPC) and lime, are incorporated into the soil to improve interfacial particle bonds (Yi, Gue and Liu, 2015). The OPC became the most favored material in geotechnical engineering projects because of its sufficient mechanical properties, availability and cost. However, the overdependence on cement has given rise to several environmental concerns, including large CO<sub>2</sub> emissions, natural resource depletion, and

dust generation (Fatehi et al., 2018). Apart from the environmental drawbacks, OPC often shows a high plastic shrinkage and reduced mechanical strength due to the loss of water and incomplete hydration at early ages (Bushlaibi and Alshamsi, 2002).

A distinct category of alumino-silicate-polymers known as Geopolymers has attracted much interest in recent years as an environmentally sustainable alternative to OPC (Davidovits, 1991). The solid compressive strength and minimal shrinkage qualities of geopolymers were well-known. Geopolymers had a lower carbon footprint than lime and OPC, making them more environmentally benign than other traditional soil stabilization additives (Radovic and Puppala, 2019). The geopolymer was already heralded as the next-generation "green" alternative to OPC. However, this claim has yet to be proven. In general, most geopolymer studies and some environmental evaluations of geopolymers back up the assertion with considerable reductions in CO<sub>2</sub> emissions (Devidovits, 2020).

In order to reduce the environmental impacts and enhance the mechanical performance, OPC was replaced with pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), where the partially replaced OPC examples exhibited enhanced mechanical properties, and durability in terms of moisture resistance, water absorption, and shrinkage (Pourakbar et al. 2015). However, the pozzolanic replacement is often limited to low quantities, and the environmental impact of OPC is still a concern (Ghadir and Ranjbar 2018).

### **1.3 Research Objectives and Possible Outcome**

The objectives of the study are as follows:

- (i) To examine effectiveness of geopolymer stabilized deep mixing piles on strength improvement.
- (ii) To determine the optimum dosages of geopolymer in deep mixing piles.

The findings of the research may lead to an alternative solution for soft ground improvement. The study may provide a guideline for engineers relating to soil stabilization using geopolymeric agents.

## **1.4 Organization of the Thesis**

This thesis comprises of five chapters. Chapter 1 starts with the background study. Subsequently, research objectives and conceptual framework, etc. are covered. A literature review is briefly described in Chapter 2. Chapter 3 outlines the detailing of adopted experimental techniques and the methodology. The outcomes of laboratory experiments are described in Chapter 4 at length. Furthermore, this chapter also includes a critical evaluation of each test result. The conclusion and essential recommendations based on the research is presented in Chapter 5.

## **CHAPTER 2 LITERATURE REVIEW**

### **2.1 General**

To overcome the distress on pavement and railway track, different methods of improving the subgrade is being adopted since many years. The cement deep mixing (CDM) pile technique is one of the most efficient and cost-effective methods among them. Conventional deep mixing pile technique with cement provides very good output but it causes high emission of Carbon-di-Oxide (CO<sub>2</sub>) which has negative impact on environment. So, researchers are trying to improvise the technique over the years and are trying to find an environment friendly solution. The deep mixing piles with partially replaced cement and without cement introducing binder material available as waste can be a better alternative. Cement replaced with Fly ash and slag with alkali activator can be an environment friendly solution as it is found in the industries in abundant quantity.

### **2.2 Soft Soil Behavior and Associated Problems in Pavement**

In the process of shrinking and drying due to rainy season followed by dry season, soil exhibits volumetric changes. This results in substantial damage into the pavement and rail track bed. And the alluvial soil of Bangladesh behaves like this. Swell potential is affected by several parameters such as, thickness of the soil layer, moisture availability, climatic and geologic conditions, clay mineralogy etc. (Puppala et al., 2008)

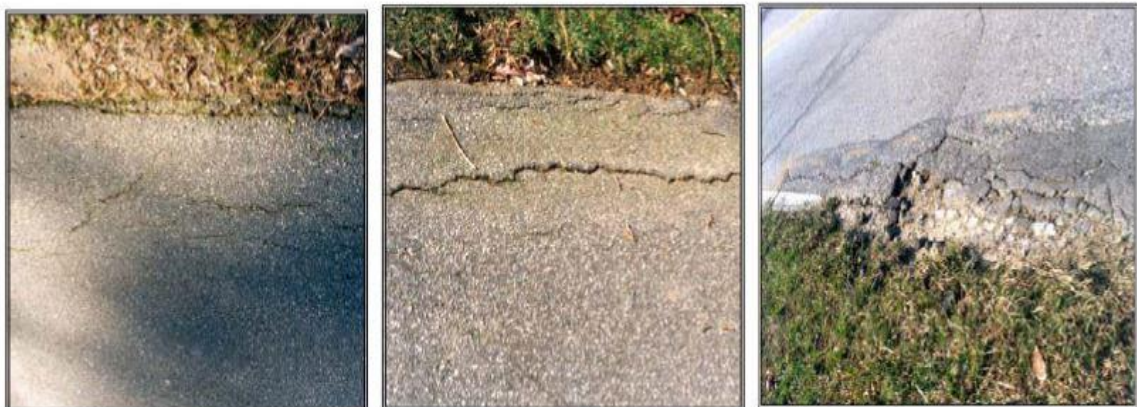


Fig. 2.1: Different types of pavement cracks.

Figure 2.1 shows failure in road pavement due to soil expansive behavior. The most common types of distress modes noticed in pavements built over soft subgrades are surface deformation, cracks along longitudinal direction and warping near trees and pipe culverts. For rail track constructed over soft subgrades may confront cracks on sleeper, differential settlement and deformation of rail track.

Different soil parameters affecting soil subgrade behavior play a vital role on designing pavement and rail embankments. So, soil parameters affecting subgrade behavior should be considered when designing, rehabilitation and analyzing pavement. (Velasco and Lytton, 1981). Researchers investigated pavement roughness which is related to expansive soil subgrade. They forecasted several roughness prediction models in the process, and which take into account to treatment type (cement, lime stabilization), traffic circumstances, subgrade features, pavement type and meteorological circumstances. They expressed multiple indices through different tools and methods (Puppala et al., 2008).

### **2.3 Soil Stabilization Techniques**

Several soil stabilization techniques have been practiced since many years. Most common among them are chemical stabilization and mechanical stabilization. In chemical stabilization, lime mixing with the soil bed is one of the common techniques and in mechanical stabilization using roller to stabilize the soil is also a traditional technique to stabilize soil. The deep soil mixing (DSM) method is an in-situ treatment of soil which involves native soil mixed with binder materials like cement, lime, etc. (Bruce et al., 2013). It is considered as most economic and environment friendly method compared to other methods especially for low to medium loaded structure. The deep soil mixing method consist of auger that mixes soil with lime, cement or other cementitious chemicals. This method strengthens the soil bearing capacity by fixing the poor bearing capacity soil. The deep soil mixing techniques increase strength of loose and contaminated soil; thus makes the soil strong enough to bear the load. Figure 2.2 represents a typical deep soil mixing column in the field.



Fig. 2.2: Deep soil mixing columns.

Cement hydration, pozzolanic reactions and other binding properties provide high strength within very short time. Both dry mixing and wet mixing are used as deep soil mixing technique. For higher level of water table, dry mixing is used and wet mixing is for low water table zone. Grouting with and without jets are used in building projects to strengthen ground soil, support excavation etc. The deep soil mixing pile with various column orientation of size, shape and grid is used in Fig 2.3 on the basis of different soil parameters, load transferring system, grid and other characteristics. These deep soil mixing column configurations are widely used (Puppala, 2008).

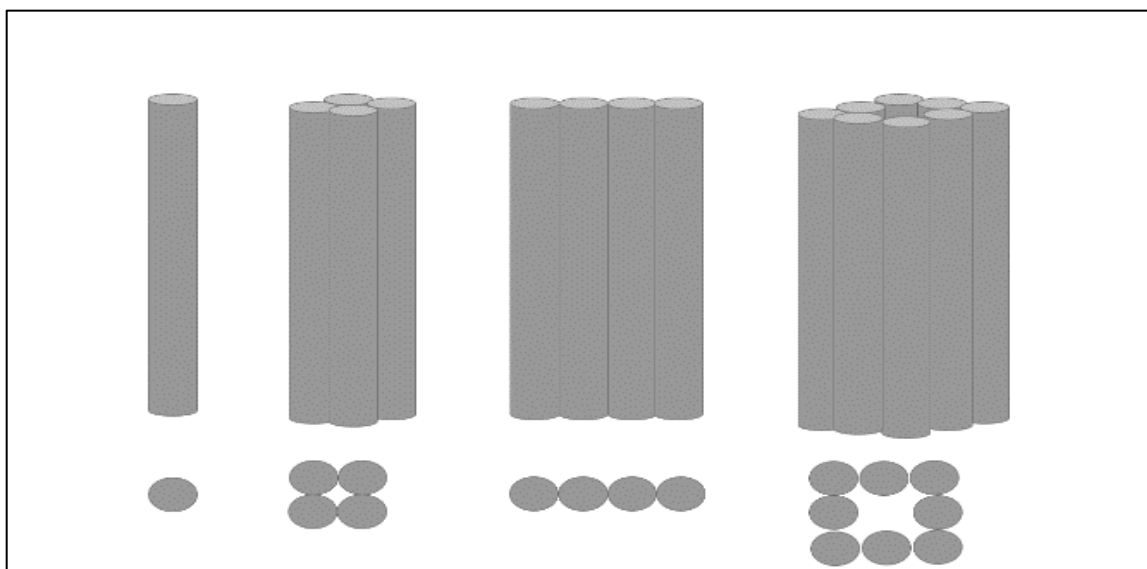


Fig. 2.3: Different deep soil mixing column stacks.

To form a soil-binder column, different cementitious materials such as lime, slag, fly ash, bentonite, glass powder, silica fume, marble dust, metakaolin etc. are used. Thus, the required design strength is achieved and expensive soil stabilization methods i.e., removal and replacement, jet grouting, traditional drilled pile, etc. are avoided. Minimum effort, fast strengthening, minimal vibration is few of the benefits of this method. Moreover, this method is suitable for different soil types including sand, clay, clayey silt, silty clay, sandy silt, organic, black and peat soil, etc. (Canakci, Güllü and Alhashemy, 2019). Quality assurance is one of the most challenging difficulties in deep soil mixing technology. Much difference is expected between ground treatment and laboratory prepared samples due to various reason. So, homogenization, probabilistic and synthetic judgement methods are adopted to investigate the stiffness and strength of the soil treated. (Porbaha, 2002). The prospects of using cement with high calcium fly ash to strengthen plastic soil with higher clay content is described in the study of (Kolias, Kasselouri-Rigopoulou and Karahalios, 2005). These stabilized materials may be used in strengthening subgrades, sub-base, capping layer as well as airport pavements where different mechanical parameters such as tensile strength, flexural strength, modulus elasticity, CBR and compressive strength are significantly improved.

Japan first used deep soil mixing piles until late 1980s and later it became popular in Europe and United States of America; and then to the other parts of the world. Figure 2.4 depicts some projects where deep soil mixing piles are used (Kitajume and Terashi, 2001).



(a)



(b)

Fig. 2.4: Deep soil mixing pile used in different places of Japan (a) Kansai Airport-Japan, (b) Haneda Airport-Japan (Kitajume and Terashi, 2001).

## 2.4 Deep Soil Mixing Pile in Bangladesh

In Bangladesh, DSM pile named as Cement Mixing Pile (CMP) was first introduced in the fast-track project of the Government of Bangladesh which is 172km long Padma Bridge Rail Link Project (PBRLP) (Fig. 2.5). Having much alluvial soil, which has low bearing capacity; rail track becomes vulnerable to this phenomenon especially between bridges, culverts and underpass approaches. So, strengthening of the soil with cement mixing pile was introduced to avoid the settlement which results in track collapse. Total 14.5 lac running meter of cement mixing pile is planned for the project.

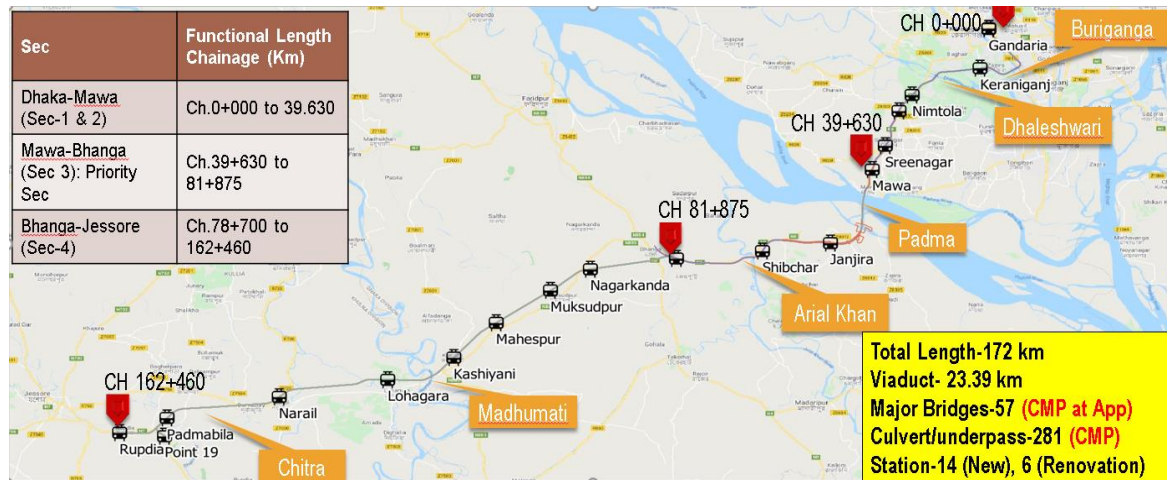


Fig 2.5: PBRLP alignment map.

One of the biggest projects in Bangladesh which is Rooppur NPP has also used deep soil mixing with cement of around  $275\text{kg/m}^3$  (Rooppurnpp, 2018). This treatment was done below main and ancillary buildings. Around 4.5 Million cubic meter low bearing soil was treated with 1.2 Million cubic meters of cement. Thus, many projects are encouraging to use this method though it is not yet much popular in Bangladesh.

## 2.5 Geopolymer

Geopolymer is made up with aluminosilicate rich materials i.e. fly ash and industrial slag along with alkali activators to make it more reactive. The raw materials are described in subsequent paragraphs.

### 2.5.1 Fly Ash

Residue coming from burned grinded or powdered coal that occurs at the combustion

zone treatment system can be defined as Fly Ash as per American Concrete Institute (ACI). Before the combustion gases are released to the atmosphere, the dust collecting system removes fly ash from the combustion gases, either mechanically or by electrostatic precipitators. (Hardjito, 2005). Figure 2.6 shows the generation process of fly ash at Boropukuria thermal power plant (BTTP).

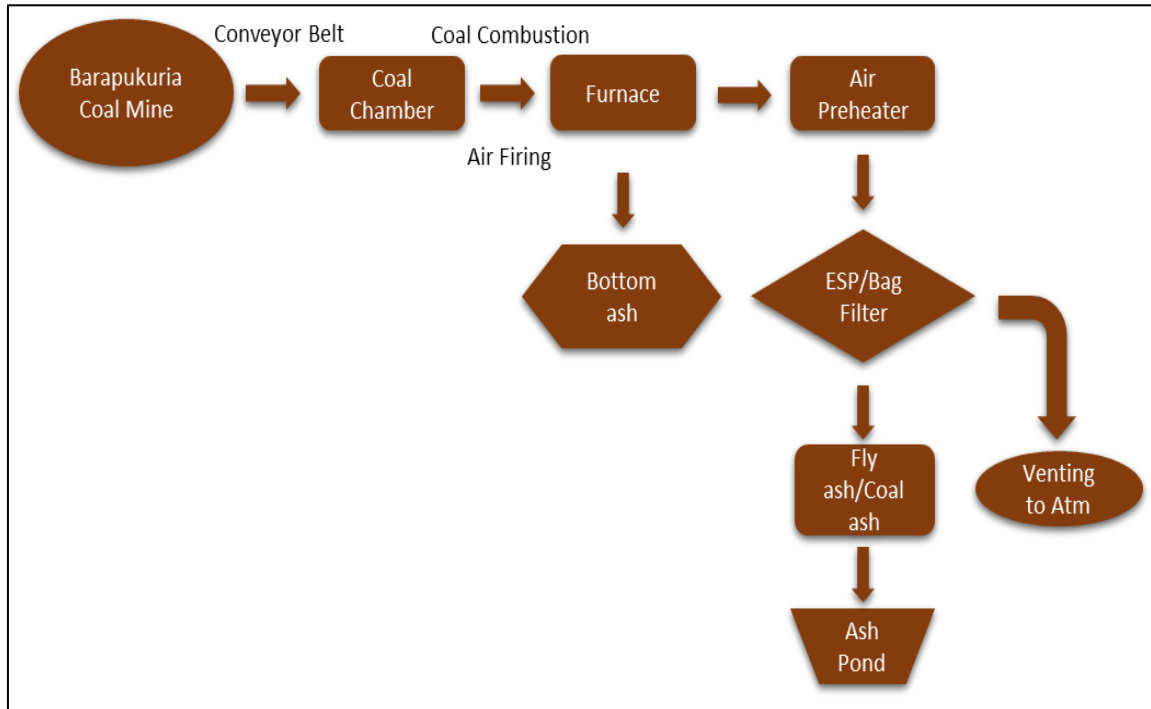


Fig. 2.6: Generation of fly ash in the BTTP, Parbatipur, Bangladesh (Howladar and Islam, 2016).

Fly ash (FA) has economic benefits over metakaolinite. Over 349 million tons of fly ash were produced in the world in the year of 2000 (Howladar and Islam, 2016). Two primary groups are defined for fly ash by ASTM C618 (2003) based on the source of coal mineral. Fly ash is defined by class F and C in terms of physical properties. A thorough chemical composition study is needed for to differentiate these two categories. These two classes are based on the determination of the amount of silica, alumina and iron oxide in fly ash. Class F is classified when silica, iron oxide and alumina percentage is at least 70% and calcium oxide percentage limited to 10%. And class C is classified when silica, iron oxide and alumina is at least 50% where calcium oxide is 10% to 30% with high reactivity of all elements (Bouaissi et al., 2018). Boropukuria Thermal Power Plant is categorized as F type Fly Ash producer as per ASTM C-618 (2003).

As there is pozzolanic nature in fly ash, this can be used in the cement industry, concrete

and alternate material to these. Type F Fly Ash's active ingredient is Alumina silicate or siliceous glass. (Anwar et al., 2013). Due to the lack of cementitious feature, only 1.165 million tons of type F fly ash is used in the production of cement out of 12 million tons in Australia. So, the abundant amount of type F fly ash can be a raw material to produce geopolymer. (Song, 2007). About 52 thousand tons of solid by-products which are called fly ash are generated in Boropukuria Thermal Power Plant. (Islam et al., 2019). And about 0.08 million metric tons of fly ash are being deposited on designated pond. But this disposal is making issues to the environment. Figure 2.7 shows the disposal of fly ash in pond.



Fig. 2.7: Discharge of fly ash to the pond causing threat to environment (Howladar and Islam, 2016).

When mixed with sand and cement, fly ash improves the mixture quality, compressive strength, bearing capacity, consistency and on the other hand reduces hydraulic conductivity of soil and concrete (Howladar and Islam, 2016). Possessing pozzolanic properties, this fly ash can replace OPC mass by 60%-65% (Hardjito, 2005).

### 2.5.2 Slag

Slag is produced at the steel and iron factories as by product. It is produced in granular shape and is made up of aluminates and calcium silicates with other bases. Its chemical composition is similar to cement clinker. The fineness and chemical composition determine its performance. (Sugapriya et al., 2017). Investigations have been focused on reducing the amount of slag produced, recovering valuable materials from it, and finding

viable applications for the slag. Slag reuse can help to reduce CO<sub>2</sub> emissions. The sustainable use of slag can help saving natural resources, reduce energy usage, and reduce CO<sub>2</sub> emissions, especially in highly populated nations like Bangladesh. This will contribute to the steel industry's long-term viability. Bangladesh consumes almost 4 million tons of steel each year, with a per capita usage of about 25 kg (Islam, 2022). In Bangladesh, some 400 steel mills of various types and sizes now produce steel. Bangladesh's present steel manufacturing capacity, which includes both governmental and private companies, is around 9 million tons per year (Islam, 2022). In Bangladesh, the average per capita steel consumption is around 45 kg. Bangladesh produces about 250,000 tons of steelmaking slag (Islam, 2022). Bangladesh is lagging behind in utilizing the slag whereas countries like USA, Germany, France, Japan etc. are utilizing almost 100%, mostly on road construction and rest are recycled within factory. For long term sustainability, it is a must to utilize this slag to a proper way. Slag has larger surface area, rough surface, more friction and shear strength than aggregates; this property contributes to a strong bond with Portland cement. Thus durability, long lasting property, strong interlocking ability, and great impact resistance makes slag a proper material to replace typical aggregates (Chakma, Parvez and Barua, 2022). Table 2.1 shows the physical properties of slag as per Taj et al. (2022).

Table 2.1: Physical Properties of Slag (Taj et al.,2022)

Properties	Values
Specific Gravity	> 3.2 - 3.6
Approximate Dry rodded Unit Weight, kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	1600 – 1920, (100-120)
Water Absorption	up to 3%

### 2.5.3 Alkaline Activators

The alkaline activators are made of sodium hydroxide and sodium silicate solution which activates the silicon and aluminum in fly ash to make the binder. This reaction becomes faster when soluble silicate and potassium or sodium silicate is available. Moreover, Sodium hydroxide solution produces better mineral dissolution over potassium hydroxide solution (Hardjito, 2005). Both potassium and sodium hydroxide are soluble to tap water.

Sodium hydroxide is used more often and widely. Concentrated NaOH (14M) is required to get stronger geopolymer concrete. There is some ideal ratio of NaOH to Na<sub>2</sub>SiO<sub>3</sub> (Sodium silicate). (Song, 2007). Table 2.2 shows the activator composition effect on strength as per the mentioned paper.

Table 2.2: Activator composition effect on strength (Song, 2007)

Mixture	NaOH Solution(M)	Na <sub>2</sub> SiO <sub>3</sub> /NaOH by mass	Strength after 60°C 24h (MPa)	Note
A-1	8	0.4	17.3	Activator: NaOH+Na <sub>2</sub> SiO <sub>3</sub> NaOH: 98% purity, diluting to 8M or 14M
A-2	8	2.5	56.8	
A-3	14	0.4	47.9	
A-4	14	2.5	67.6	

## 2.6 Effect of Na<sub>2</sub>SiO<sub>3</sub> to NaOH Ratio

Flow value, compressive strength, setting time of geopolymer mortar are connected and effected by Sodium silicate and sodium hydroxide ratio. When the ratio between Na<sub>2</sub>SiO<sub>3</sub> and NaOH is 2.5, the compressive strength is found to be around 5.12MPa after 7 days of curing (Hamzah et al., 2016). 30% NaOH and 70% Na<sub>2</sub>SiO<sub>3</sub> combination of activator produces best results in terms of unconfined compression strength after 3, 7, 14 and 28 days curing (Yaghoubi et al., 2018).

## 2.7 Effect of Water-Binder Ratio

In chemical stabilization, water is a vital component in soil stabilization interaction. To achieve effective mixing and getting proper hydration, water is indispensable. In the conventional deep soil mixing column design, stabilizer element is utilized as vital part at a specified curing period and also strength is impacted by this factor. (Lorenzo, Burgado and Solarrump, 2006). The cement concentration can be modified based on the water content to reach the necessary strength because this ratio is constant for a certain target strength. (Yaghoubi et al., 2018). After analyzing, many researches showed that strength development is a function of water content in the treated soil (Puppala et al.,

2008). Clay water content to binder content ratio controls the engineering behavior of soil treated (Arikado, 2002).

## 2.8 Effect of Curing Conditions

In the process of geopolymerization, optimal temperature and curing time play a vital role on gaining better strength. There undergoes a polymerization reaction between concrete and geopolymer mortar which gains more strength in higher temperature than room temperature. Around 70% strength is gained within 3-4 hours of heat curing. (Adam, 2014). Table 2.3 shows how different studies vary from each other in terms of describing optimum temperature and time required.

Table 2.3: Different study on optimum curing temperature

No	Range	Optimum	Researcher
1	30, 60, 91°C for 24 hours	60°C 24h	Hardjito
2	30, 75°C for 24 hours	60°C 24h	Sindhunata
3	75, 95°C for 6 and 24 hours	60°C 24h	Bakharev
4	45, 65, 85°C for 24 hours	60°C 24h	Fernandez-Jimenez and Palomo

It is claimed that, there is little effect on physical properties of geopolymer caused by relative humidity during curing. (Sindhunata et al. 2004). Wet samples are usually sealed before being heated on higher temperature. Synthesizing at room temperature is less effective as geopolymers do not set at 23° Celsius. (Song, 2007).

Figure 2.8 shows the strength difference among heat and air cured geopolymer and OPC mortar. It shows heat cured geopolymer demonstrates better result than OPC mortar. On the other hand, air cured geopolymer shows poor strength (Adam, 2014).

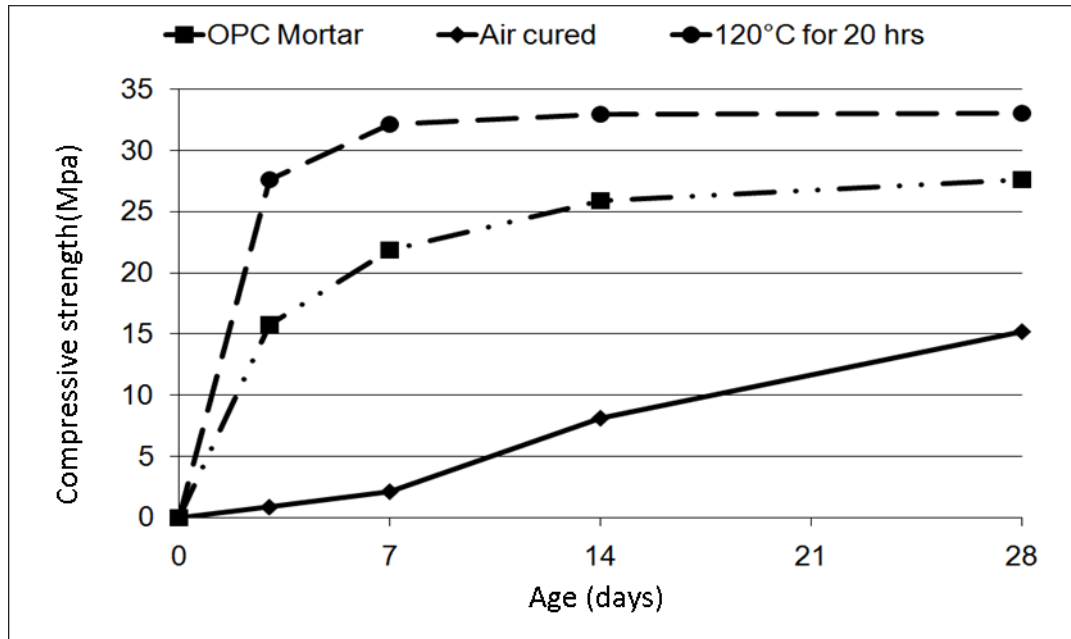


Fig. 2.8: Strength comparison among air, heat cured geopolymer and OPC (Adam, 2014).

## 2.9 Reconstituted Bed

Reconstituted bed can be prepared mainly with two methods; by compaction and by consolidation. In consolidation process, seepage induction, dead load, self-weight consolidation are some methods where bed is prepared from slurry to get required characteristic. (Imai, 1979), (Been and Sills, 1981), (Bowin et al., 1999), (Blewett et al., 2002), (Robinson et al., 2003), (Ghosh and Yasuhara, 2004). And in compaction process, beds are prepared with temping wet clay having the required moisture. (Malarvizhi and Ilamparuthi, 2004), (Ambily and Gandhi, 2007), (Ammar et al., 2009), (Liu et al., 2009), (Shivshankar et al., 2010), (Deb, Samadhiya and Namdeo, 2011), and (El-Garhy et al., 2011) prepared bed with compaction method but the issue is there would be trapped air void that will decline the uniformity. In natural condition, clay beds are deposited through consolidation, not by compaction. So, performance can much differ from natural consolidation clay to air dried clay bed (Pandian, Nagraj and Babu, 1991). Imai (1979) adopted a special method of consolidation utilizing seepage from different water heads. But this method will not satisfy high stress application. Bowin et al. (1999) studied deformation behavior of highly moist soil which subjected to external weight with larger consolidation setup.

## 2.10 Deep Soil Mixing Device

Figure 2.9 below shows the mixing device indicating its components. Usually, the device contains auger shaft, auger rotation motor, auger blades, control point etc. Moving plate is responsible to control the shaft vertically. Speed of the auger is kept 58 rpm where the pressure is 0.5 bar which will prevent mortar blocking issue. The auger can rotate both in clockwise and anticlockwise manner. The blades will rotate and injection of slurry will begin mixing the surrounded soil uniformly and thus making deep mixed column (Esmaeili, Astaraki and Khajehei, 2017).

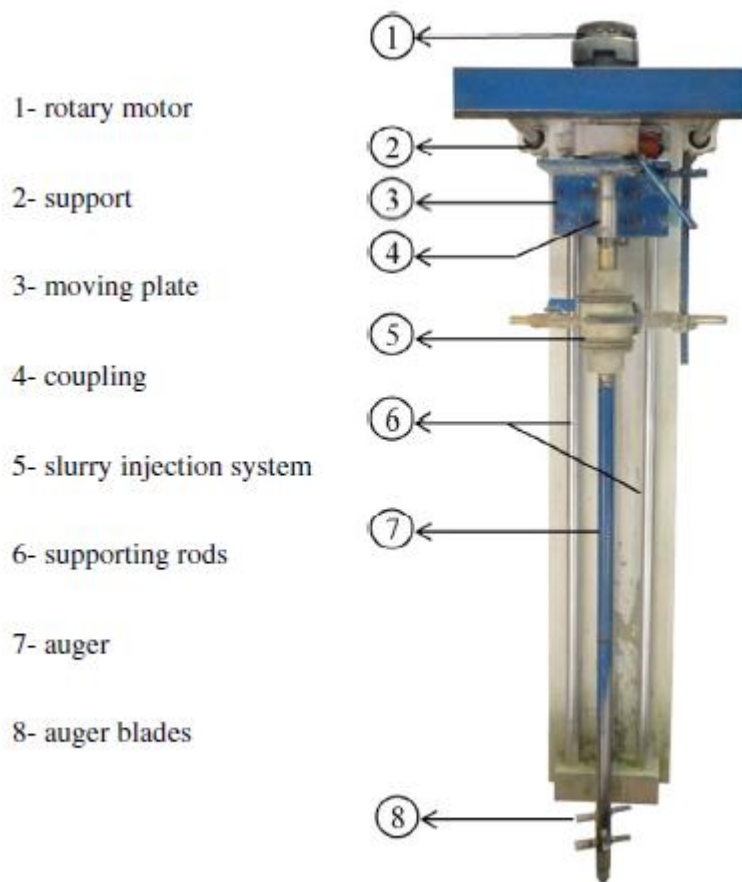


Fig. 2.9: Deep soil mixing device designed at Iran University of Science and Technology (Esmaeili, Astaraki and Khajehei,2017).

## **CHAPTER 3**

### **TEST PROGRAM AND PROCEDURE**

#### **3.1 General**

A laboratory scale miniature deep mixing machine was constructed and placed in the laboratory to execute deep mixing piles on reconstituted bed where cement was fully replaced and partially replaced with geopolymer made with slag and fly ash. Initially in laboratory-based experiment, a total of six combinations i.e. 5% cement, 5% cement with 15% binder, 20% binder, 25% binder, 30% binder, 35% binder were used to make mold specimens. Afterwards, three suitable combinations were picked and set for the execution of deep mixing piles on reconstituted bed by the laboratory scale deep mixing machine. The selected combinations were 5% cement, 5% cement with 15% binder and 25% binder. This chapter designates overall testing methods, key instruments, materials and design process to reach to the aimed objectives.

#### **3.2 Test program**

The test program was designed in two different steps i.e. the laboratory based experiment and laboratory scale deep mixing pile based experiment. The raw materials were collected from various sources which includes soil, LRF slag, fly ash and activators. Investigation of basic properties of soil, slag and fly ash were carried out in the laboratory. Then geopolymer was prepared in the laboratory by mixing slag and fly ash with alkaline activators in varying ratio. Afterwards, molds were prepared with six different combinations i.e. 5% cement, 5% cement with 15% binder, 20% binder, 25% binder, 30% binder and 35% binder along with alkali activator. These molds were cured in four different curing conditions i.e. immediate heat followed by ambient condition, ambient condition, humid condition and humid curing followed by heat before test condition. Finally, most favorable combinations were selected to execute the deep mixing pile in laboratory condition through unconfined compression strength test and split tensile test. Figure 3.1 shows the laboratory based experimental overview.

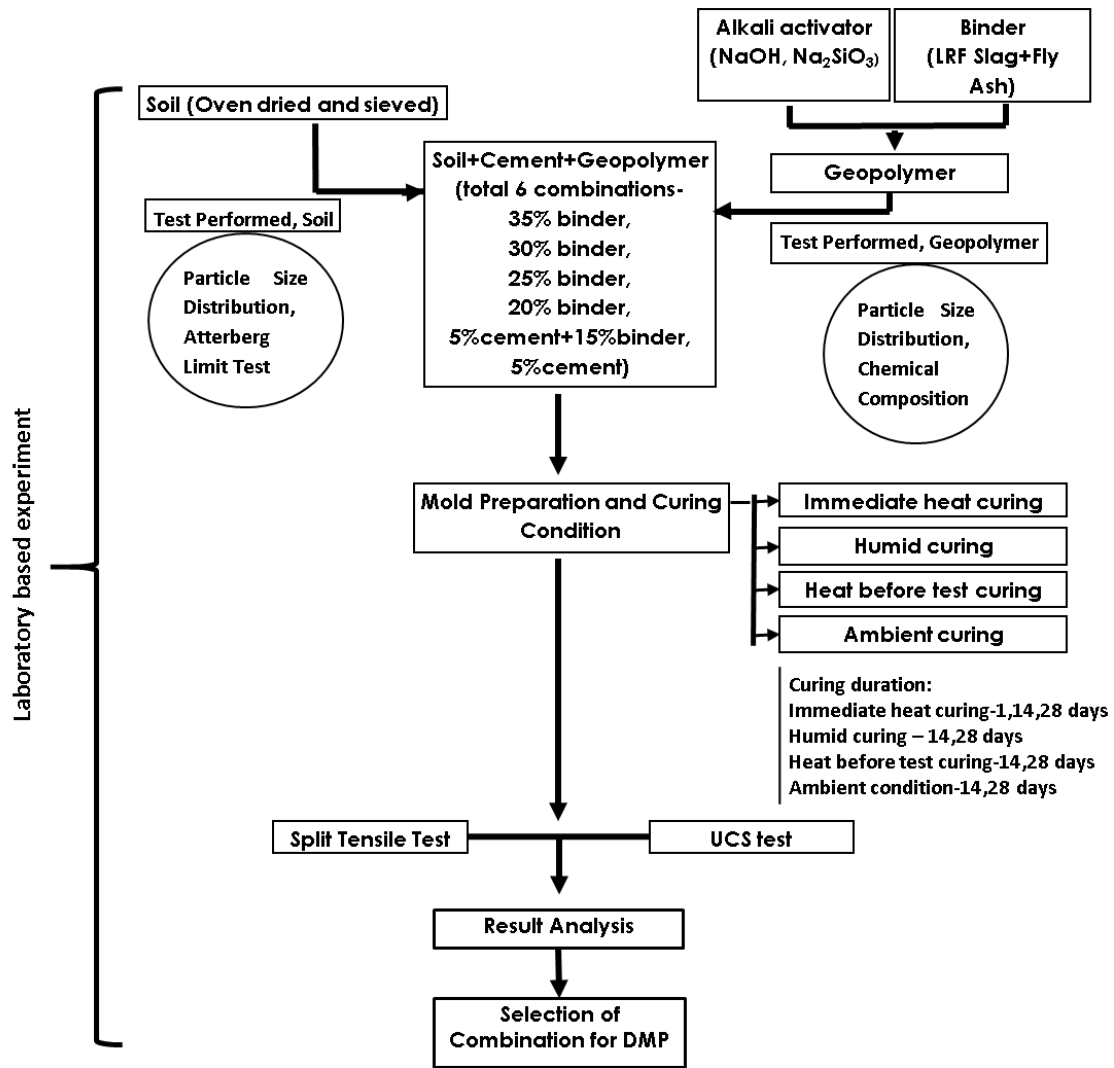


Fig. 3.1 Flow chart of laboratory based experiment.

A laboratory scale Auger Mixer Deep Soil Mixing Machine was designed and constructed with a capability of injecting slurry in the soil. Reconstituted soil bed was prepared to accommodate the geopolymer- soil mixing pile in the laboratory. Deep mixing pile was prepared in the reconstituted soil bed with selected combinations through the laboratory scale deep soil mixing machine. After curing of the piles, unconfined compressive strength, tensile strength and microstructure analysis was conducted to come to the conclusion of the study. Figure 3.2 shows the laboratory scale deep mixing machine based experiment flow chart.

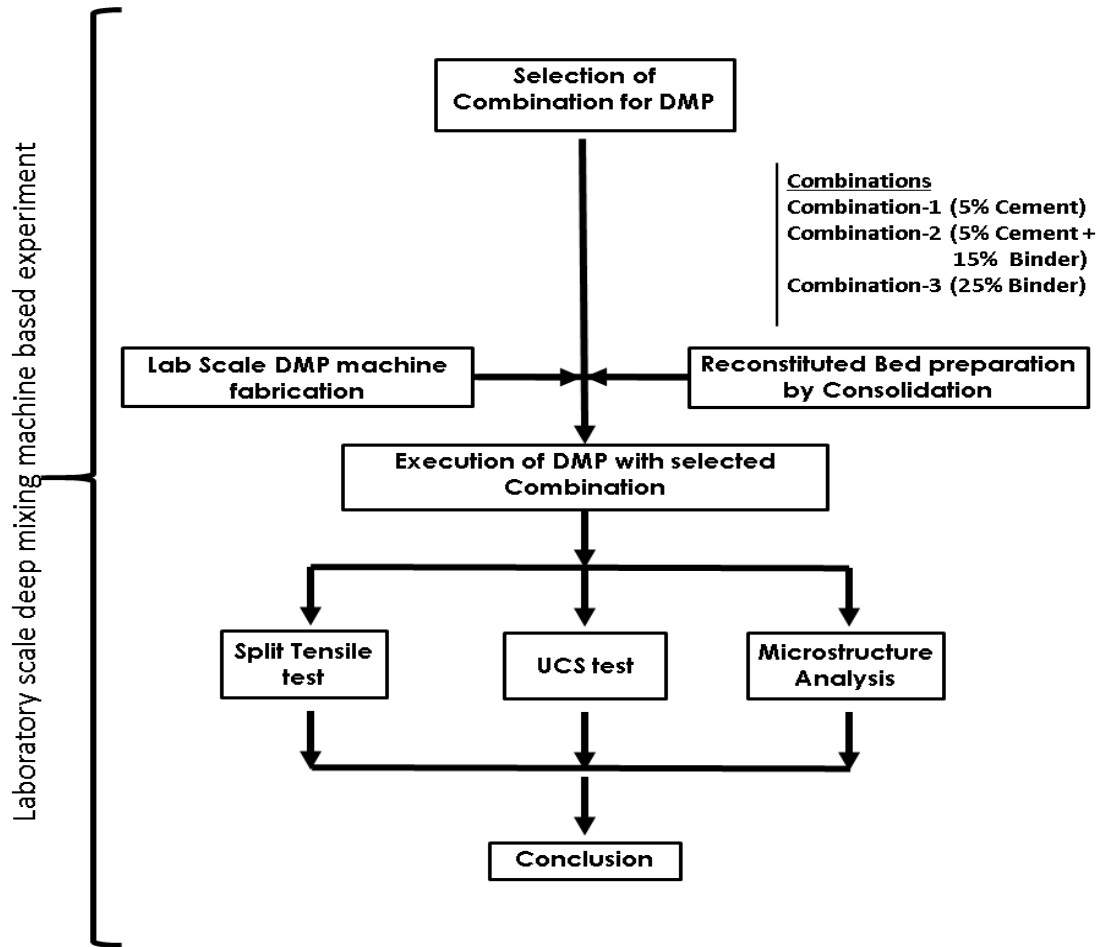


Fig. 3.2: Laboratory scale deep mixing machine based experiment flow chart.

### 3.3 Collection of Raw Materials and Preliminary Investigation

Materials used in this study were soil, slag, fly ash, cement, sodium hydroxide and sodium silicate. Preliminary tests were performed to discover the basic properties of these materials.

#### 3.3.1 Soil

Soil sample was collected from the catchment area of Padma river at Mawa. The soil was stored carefully in polyethene bag. Soil lump stored was broken into small pieces with hammer and grinding machine was used to produce finer particles. Finally, soil was sieved to get the desired sized particle (Fig 3.3). Then again soil was stored in polythene bag for further experiment.



Fig. 3.3: Collected Soil before grinding and after grinding

As per ASTM D4318 (2017), Atterberg limit test was done. Plasticity Chart of Aurther Casagrande was used to classify the soil from liquid Limit (LL) and Plasticity Index (PI). Test results are presented in chapter 4. Figure 3.3 shows the atterberg limit test samples.



Fig. 3.4: Atterberg Limit Test

According to ASTM D 6913(2017), sieve analysis of soil was performed. For particles passing no 200, hydrometer analysis was performed. Figure 3.5 shows the hydrometer test arrangement.



Fig. 3.5: Hydrometer Test

### 3.3.2 Fly Ash

Fly ash was collected from Barapukuria Power plant location at Dinajpur. Fly ash was sieved to separate unwanted size and particles. Then, fly ash was kept inside couple of thick and airtight polyethene to make sure fly ash is protected from moisture. The sample is shown in Fig 3.5. Fly ash was used as a component of geopolymer. Grain size distribution is presented in Chapter 4.



Fig. 3.6: Sample of fly ash after oven dried.

### 3.3.3 Slag

Slag was collected from a steel rerolling mill of Chattogram. It was collected as grinded condition and kept in airtight bags after oven dry to ensure no contact with moisture can occur. Slag was sieved to separate unwanted size and particles. Grain size distribution is presented in Chapter 4.

### 3.3.4 Cement

Ordinary Portland Cement (OPC) from Akij Cement Brand was collected from commercially available source and preserved in polybags to ensure prevention of contact with moisture.

### 3.3.5 Activators

Sodium Hydroxide (NaOH) and Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) were collected from commercially available source (Brand-EMSURE). Sodium hydroxide was collected as pallet form with purity of 98% and sodium silicate was collected as crystal form (as sodium metasilicate). Table 3.1 shows the chemical properties of activators.

Table 3.1: Chemical properties of activators

Properties	Sodium Hydroxide	Sodium Metasilicate
Molar Mass (gm/mol)	40	266
Density (gm/cc)	2.13	2.4

## 3.4 Laboratory Based Experiment

In the laboratory based experimental scheme, six combinations were selected to prepare the mold with soil. Specimens were prepared and cured in different curing conditions. Specimens were then tested for gained strength. In the preparation of mold, for the strength gaining process, water to binder ratio plays a vital role. It gives enough liquidity but decreases the compressive strength with the increment of the ratio (Matsuo, 2002). To make the mix workable, a minimum ratio of 0.4 is needed. Soil, slag and fly ash were sieved with no. 50 sieve, as finer materials are better for proper mixture. Slag was used three times more than fly ash, as slag has more CaO in it; which is a major component in binding. Binder

and alkali ratio are recommended to keep constant by Cristelo, Glendinning and Pinto (2011). 70%  $\text{Na}_2\text{SiO}_3$  with 30% NaOH was used as activators. Cement was kept 5% as per the study of Teerawattanasuk and Voottipruex (2019). Preliminary combination counted on are given in Table 3.2.

Table 3.2: Precursors combination in laboratory-based experiment

Sample ID	Mixing Combination	Mix Proportion Percentage							
		Soil	Binder				Activator		
			Total binder	Slag	Fly Ash	Cement	Total Activator	NaOH	$\text{Na}_2\text{SiO}_3$
C5B0	5%cement	95	5	-	-	5	-	-	-
C5B15	5%cement, 15%binder	65	20	11.25	3.75	5	15	4.29	10.71
C0B20	20%binder	60	20	15	5	-	20	5.71	14.29
C0B25	25%binder	50	25	18.75	6.25	-	25	7.14	17.86
C0B30	30%binder	40	30	22.5	7.5	-	30	8.57	21.43
C0B35	35%binder	30	35	26.25	8.75	-	35	10	25

Note: In this table, binder (B) represents slag and fly ash, and cement (C) represents OPC.

Preliminary unconfined compressive strength tests were performed after curing the molds in four different curing condition. In addition, split tensile tests were conducted. Comparing among the results obtained, three combinations were selected for the final execution of deep mixing piles in reconstitute bed.

### 3.4.1 Specimen Preparation

Figure 3.7 shows the flow chart of mixture procedure. Before mixing the materials, they were oven dried. Materials were mixed uniformly. As per predetermined ratio, sodium hydroxide and sodium silicate were mixed with water and rested for 30 minutes to cool it down and to ensure proper reaction. Then the previously mixed dry materials were mixed with the solution made for about 6-10 minutes to ensure mixing uniformity. Afterwards, the mixture was laid in the mold (50 mm x 100 mm) with 3 layers and each of them were given 25 blows to free up entrapped air. Figure 3.8 depicts the mixing procedure of all combinations.

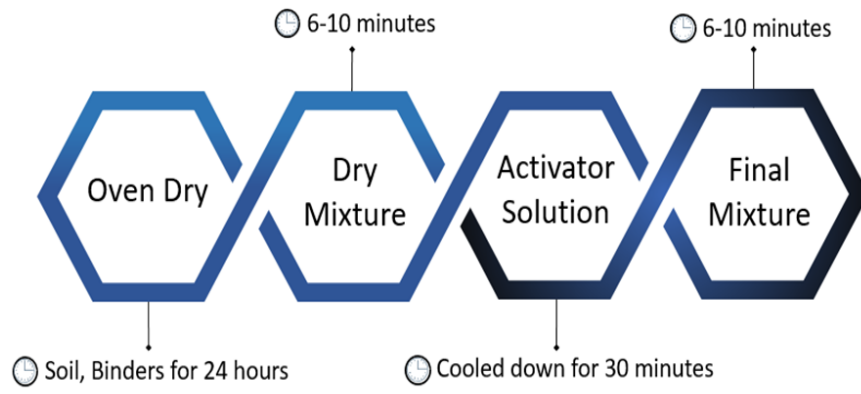


Fig. 3.7: Flow chart of mixture procedure

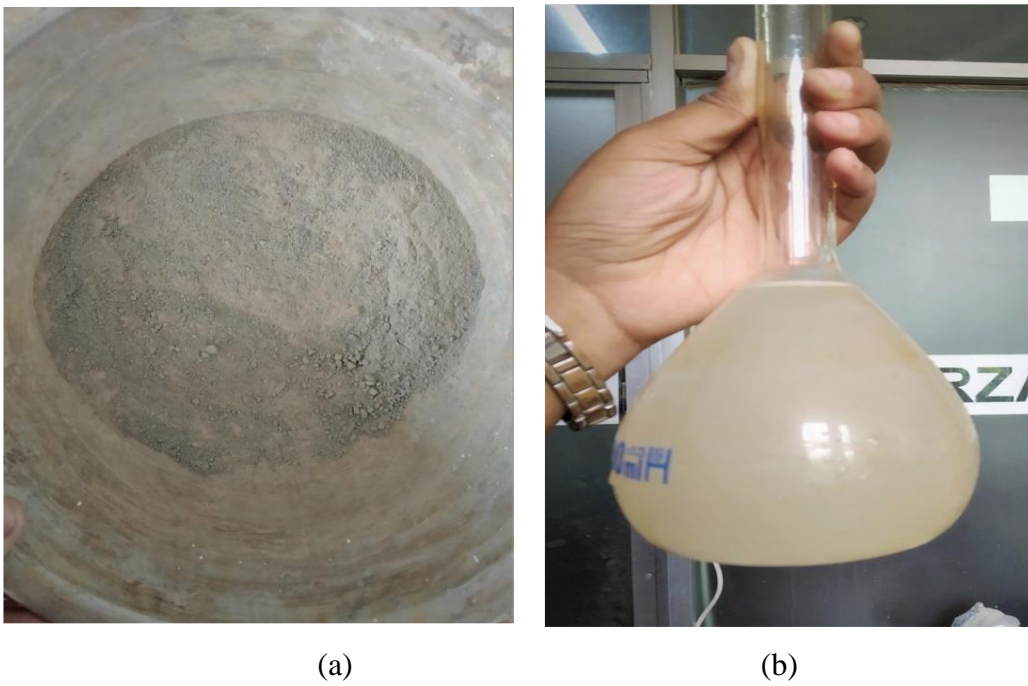


Fig. 3.8: Mixing procedure (a) dry mixing (b) activator solution



(c)



(d)

Fig. 3.8: Mixing procedure (c) final mixing (d) prepared samples

### 3.4.2 Curing Condition

A total of four types of curing condition were used to investigate the strength comparison. These are curing in Humid Condition, Humid condition curing followed by Heat Curing before Test, Immediate Heat followed by curing in Ambient Condition and curing in Ambient Condition. Details about these curing conditions are described in subsequent sub sections.

#### 3.4.2.1 Curing in Humid Condition

Specimens were wrapped in tight polythene and placed into the humid chamber. The humid chamber was controlled to 99% relative humidity and the temperature was put to 24 degrees Celsius ( $\pm 2^{\circ}\text{C}$ ). After 14 and 28 days, unconfined compressive strength tests were performed. Figure 3.9 manifests this curing condition.



(a)



(b)

Fig. 3.9: Curing in Humid Condition (a) specimens in humid chamber, (b) humid chamber condition

### 3.4.2.2 Humid Curing followed by Heat Curing before Test

In this curing condition specimens were wrapped and put into the humid chamber for 14 and 28 days. Subsequently specimens were oven dried for 24 hours at a temperature of 100 degrees Celsius ( $\pm 2^\circ\text{C}$ ). And then UCS tests were performed. Figure 3.10 illustrates this curing condition.



(a)



(b)

Fig. 3.10: Heat cured specimens before testing (a) with mold, (b) without mold

### 3.4.2.3 Immediate Heat followed by Ambient Curing Condition

Specimens were wrapped up with polythene and left at room temperature for about 3 hours. Then subjected to oven dry condition of 100<sup>0</sup> C for about 24 hours. Later UCS tests were executed after 1, 14 and 28 days of ambient curing. Figure 3.11 demonstrates the described curing condition.

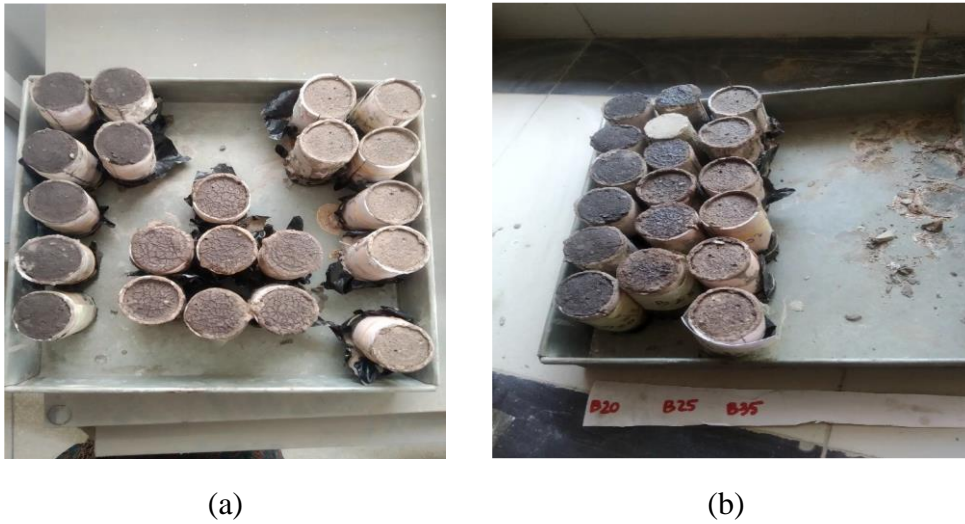


Fig. 3.11: Immediate heat curing samples (a) 5% cement with 15% binder, 5% cement and 30% binder (b) 20% binder, 25% binder and 35% binder

### 3.4.2.4 Ambient Curing Condition

Specimens were wrapped with polythene and put into room temperature (24<sup>0</sup>C ±2<sup>0</sup>C) for 14 days and 28 days. Figure 3.12 below illustrates the specimens in ambient curing condition.



Fig. 3.12: Specimens in ambient condition (a) before and (b) after curing period

### 3.5 Strength Properties of Treated Sample

Both unconfined compression strength and split tensile tests were performed to compare the strengths among the variably mixed specimens cured in different curing conditions.

#### 3.5.1 Unconfined Compressive Strength Test

The UCS tests were performed according to ASTM D1633 (2017). The diameter of the specimens was fixed to 38mm and the length was fixed to 76mm. Figure 3.13 below shows the UCS machine and test.



Fig. 3.13: Unconfined compression test

#### 3.5.2 Split Tensile Test

Split tensile tests were performed according to ASTM C496 (2017). Figure 3.14 shows split tensile machine and failure of samples in split tensile test.



Fig. 3.14: Split tensile test in compression machine.

### 3.6 Combinations Selected for Laboratory Scale Deep Mixing Pile Machine Experiment

Comparing the preliminary combinations on the basis of strength, three optimum combinations were selected. And these combinations were used in the execution of deep mixing piles on the reconstituted soil bed. Precursor combinations in this experiment is given in Table 3.3.

Table 3.3: Precursor combinations in laboratory scale deep mixing piles experiment

Sample ID	Soil	Binder				Activator		
		Total binder	Slag	Fly Ash	Cement	Total Activator	NaOH	Na <sub>2</sub> SiO <sub>3</sub>
C5B0	95	5	-	-	5	-	-	-
C5B15	65	20	11.25	3.75	5	15	4.29	10.71
C0B25	50	25	18.75	6.25	-	25	7.14	17.86

### 3.7 Development of Deep Mixing Pile Machine

The concept of developing a laboratory scale deep mixing piles machine arrived from literature review (Esmaeili, Astaraki and Khajehei,2017) and practical machine used in site.

### 3.8 Flow Diagram

The machine was developed with a simple flow diagram. Figure 3.15 manifests the simple flow of the work.

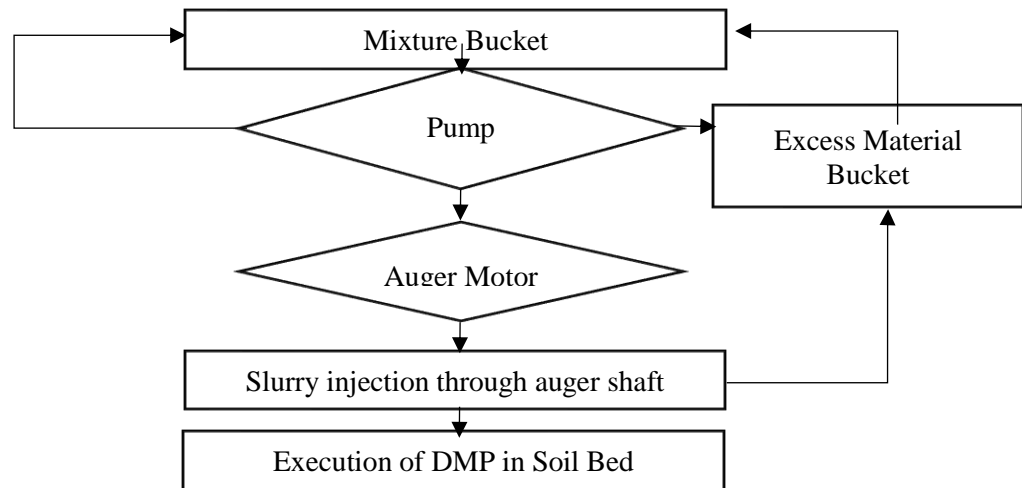


Fig. 3.15: Flow chart of deep mixing piles working procedure.

### 3.9 Components and Features

The machine consists of twelve main components. These are control unit, pump with regulator, mixture bucket, excess material store bucket, supply pipe, vertical control for shaft, auger motor, auger shaft with blades with a provision of slurry flow through the hollow shaft, manual direction control-1, manual direction control-2, wiring and frame. Control unit is used to control the pump on/off option and controlling movement of auger shaft clockwise and anti-clockwise direction with six buttons. Pump itself has a regulator through which the speed of the suction and delivery of the slurry can be controlled. Pump drives the slurry through the supply pipe to the auger setup. Mixture bucket is made of plastic where cement, geopolymers and activators are mixed. Bucket has the setup of continuous rotation of the slurry which keeps it running and impedes slurry from getting hard. There is also an excess material store bucket in which excess slurry gets in from auger setup. Supply pipe connects the pump with the auger setup. Vertical control of the shaft is attached with the auger which is used to control the shaft in digging and lifting towards the soil bed. Auger motor transfers the slurry to the bed through auger shaft. Auger has blades which help cutting the soil and mixing the slurry into the soil. Manual direction controller-1 is used to move the auger setup in front and rear direction to create pile on different position of the soil bed. Manual direction controller-2 is used to move the auger setup in left and right direction horizontally. Figure 3.16 shows the deep mixing piles machine concept.

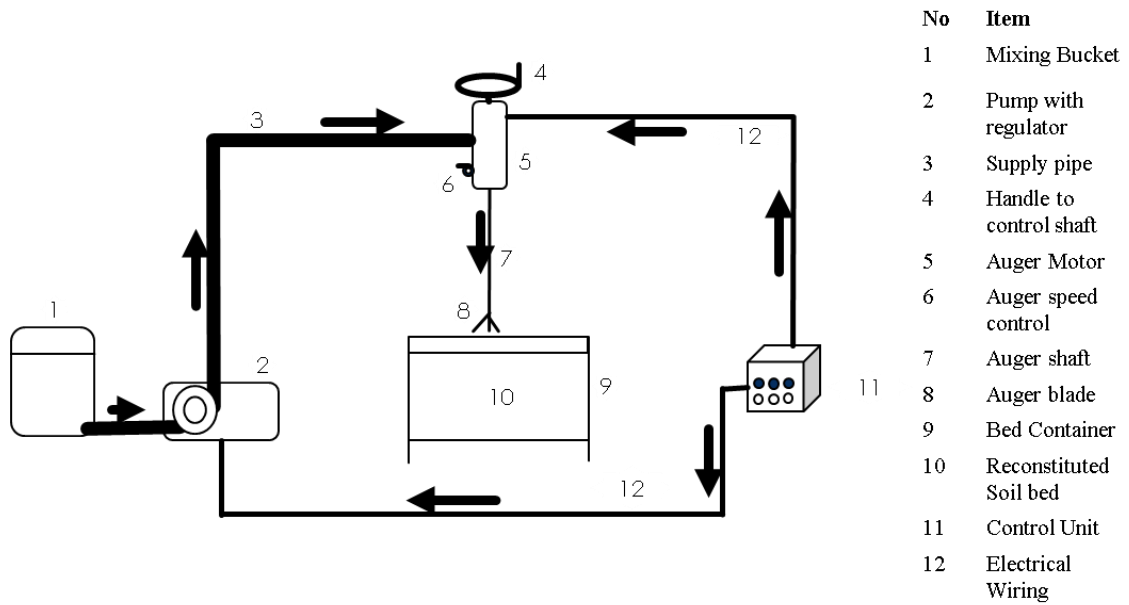


Fig. 3.16: Concept of Miniature deep mixing piles machine with components.

Based on the miniature deep mixing piles machine concept, the laboratory scale deep mixing machine was constructed. Figure 3.17 shows the laboratory scale deep mixing machine with its components.



No	Item	No	Item
1	Control Unit	7	Vertical control shaft
2	Pump with regulator	8	Auger Motor
3	Mixture Bucket-1	9	Auger shaft with blade
4	Reconstitute Bed	10	Direction control unit-1
5	Mixture Bucket-2	11	Direction control unit-2
6	Supply pipe	12	Frame

Fig. 3.17: Miniature deep mixing pile machine.

Here wiring setup is done to connect the devices with the electric supply and control unit. Finally, the frame is made to accommodate the total setup. A 600 x 400 x 500 mm steel container was prepared to accommodate the reconstituted soil bed.

### 3.10 Method of Drilling the Deep Mixing Column in Soil Bed

Drilling and lifting of the auger shaft consists of a total four operations. These are drilling towards the bed in clockwise rotation of shaft with no slurry injection, lifting from the bed in anti-clockwise rotation of shaft with 50% injection of the slurry, drilling towards the bed in clockwise rotation of the shaft with 30% slurry injection, lifting from the bed in anti-clockwise rotation of the shaft with 20% injection of the slurry. The drilling and lifting rate were kept in range of 0.1 m/min to .2 m/min. Rotation speed of the auger was kept in the range of 7.3 rotation/min to 63.2 rotation/min. Injection pressure was found with numbers of trial for different combination of slurry to maintain the slurry percentage. Figure 3.18 shows the steps in a graphical manner where all the four steps are shown. Table 3.4 shows the injection time of slurry when executing the piles.

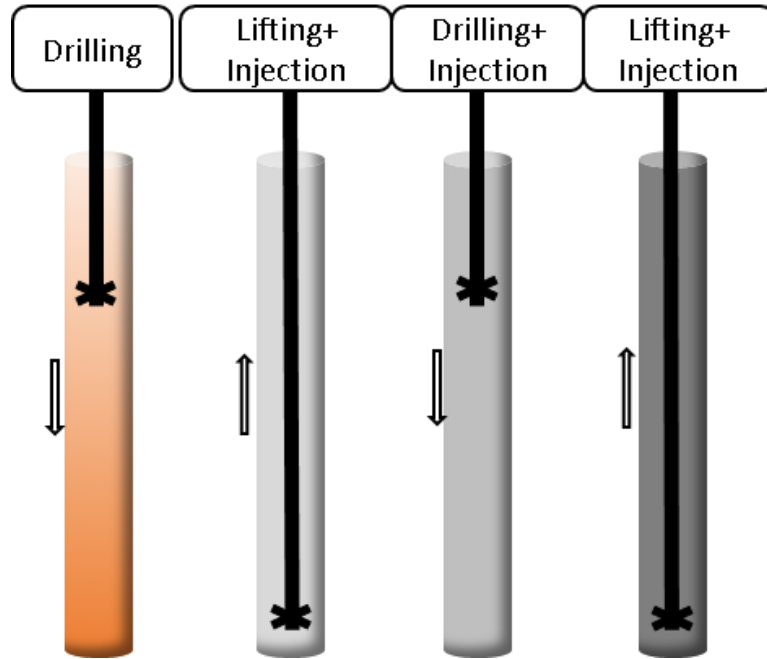


Fig. 3.18: Drilling and lifting steps.

Table 3.4: Injection time of slurry

Sample ID	Time required for 50% injection (sec)	Time required for 30% injection (sec)	Time required for 20% injection (sec)
C5B0	60	36	25
C5B15	60	36	25
C0B15	60	36	25

### 3.11 Reconstituted Soil Bed

The container used to make reconstituted had a volume of  $0.12 \text{ m}^3$ . Bottom of the container was made perforated so that the water can drain out easily without any obstruction. Geotextile was used in all surfaces of soil main bed to facilitate the smooth water drain. The soil sample was mixed with water with  $1.5 \times \text{LL}$  which became  $1.0 \times \text{LL}$  after consolidation with a gradual load application. The loading rate is monitored on an interval of 2 hours, and load application was done considering the strain value from the strain gauge. Total of  $4.2 \text{ kPa}$  load was placed to the bed. Figure 3.19 shows the strain monitoring arrangement. Figure 3.20 shows the final output before execution of the deep mixing piles.



Fig. 3.19: Strain reading monitoring.



Fig. 3.20: Reconstituted bed.

### **3.12 Tests Conducted in Laboratory Scale Deep Mixing Pile Experiment**

Two types of tests were performed for second experimental phase including micro structure analysis of the pile cores. For the selected three combinations, UCS test is conducted according to ASTM D1633 (2017). In addition, split tensile test for the cores extracted from reconstituted bed were conducted according to ASTM C496 (2017). SEM and EDS analysis were also conducted for the extracted cores to investigate the bonding characteristics and properties.

## CHAPTER 4 RESULTS AND DISCUSSION

### 4.1 General

Individual properties of the materials were determined and based on preliminary mixed combination of the materials; deep mixing piles of the selected combinations were executed in reconstituted soil bed through the laboratory scale deep mixing piles machine. Later, the deep mixing piles are extruded from the soil bed and strength tests were performed. Details of the results are discussed in this chapter.

### 4.2 properties of Soil

The clay used is mainly silty clay collected from the catchment area of Padma river at Mawa end. All standard sieves from no 4 to no 200 were used for particle size distribution of soil. For particles passing no 200, hydrometer analysis was performed. Gradation curve is illustrated in Fig 4.1.

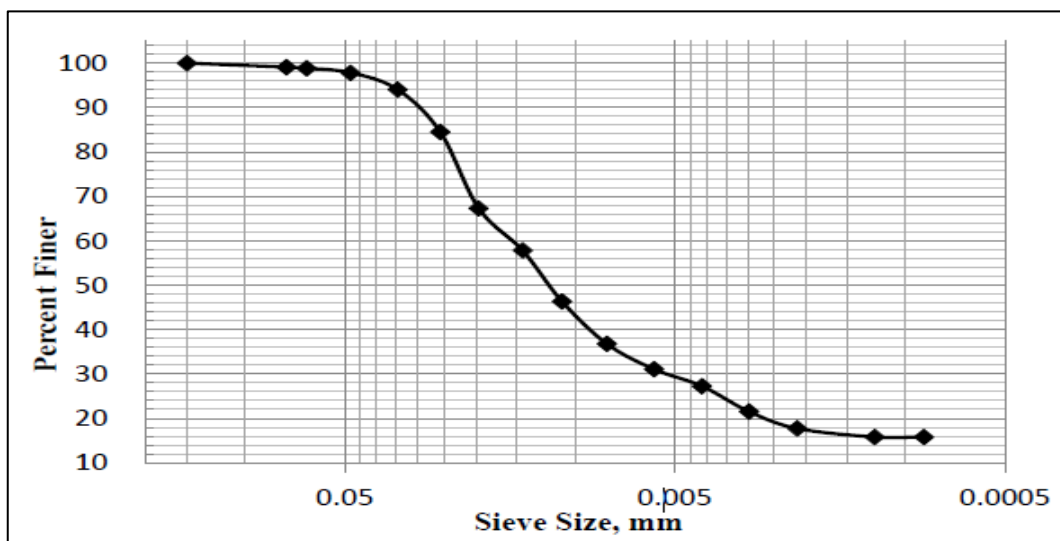


Fig. 4.1: Grain size analysis of soil.

Liquid limit of soil was found 29% and plasticity index was found 6.82 through Atterberg Limit Test. As the plasticity index lies between (4-7) % and LL is below 30. So, the soil is CL-ML (low plasticity clay or low compressive silt). Specific gravity of soil was found 2.85. It lies within the range of 2.65 to 2.85. Soils containing organic matter and porous particles may have specific gravity values below 2.0. Soils having heavy substances may have values above 3.0.

### 4.3 Properties of Slag

About 11.69% particles of slag were found 0.075 mm or less than 0.075 mm as illustrated in Fig 4.2.

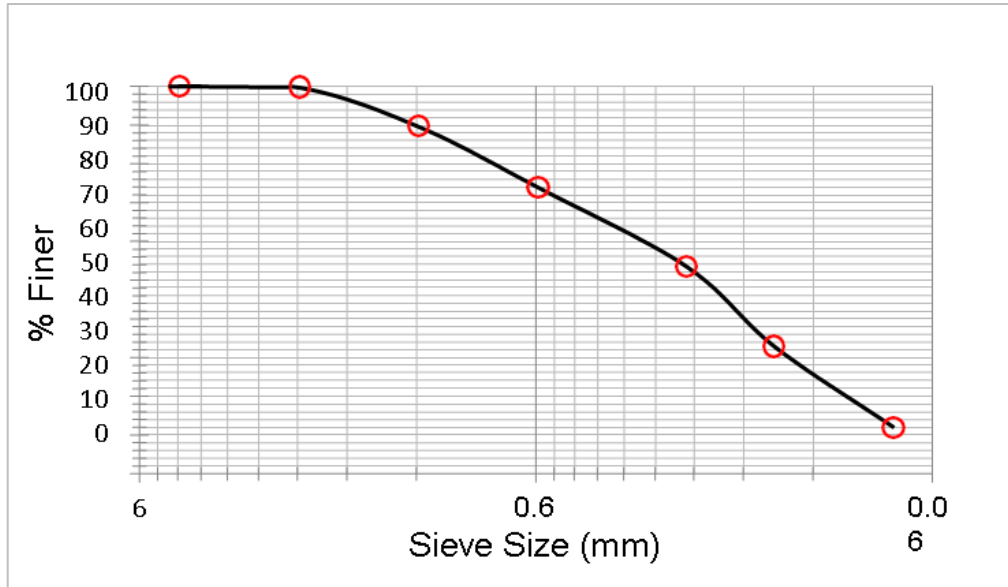


Fig. 4.2: Grain size distribution curve of slag.

### 4.4 Properties of Fly Ash

Fly ash was found to be rich in silicon dioxide and aluminum oxide. Grain size distribution of fly ash is illustrated in Figure 4.3.

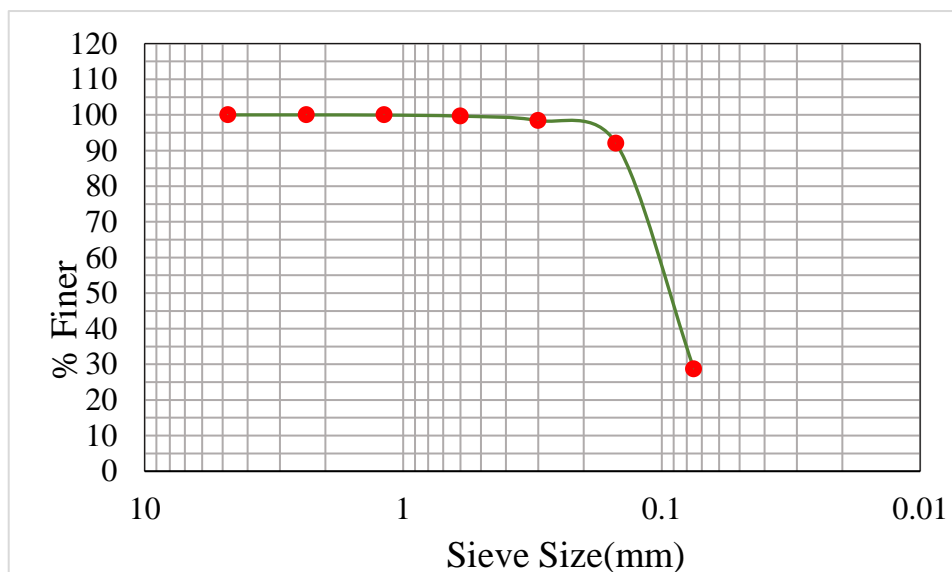


Fig. 4.3: Grain size distribution curve of fly ash

## 4.5 Unconfined Compressive Strength in Laboratory Based Experiments

Unconfined compressive strength of six different combinations in four different curing conditions are described in subsequent sub sections.

### 4.5.1 Curing in Humid Condition

Unconfined compressive strength of the six different combinations after 14 days and 28 days curing in humid conditions are shown in Table 4.1. Strength increment of different combination is shown in Fig 4.4.

Table 4.1: Unconfined compressive strength at humid condition

Sample ID	Humid Condition	
	14 days (kPa)	28 days (kPa)
C5B0	585	756
C5B15	470	792
C0B20	76	141
C0B25	231	407
C0B30	185	349
C0B35	160	325

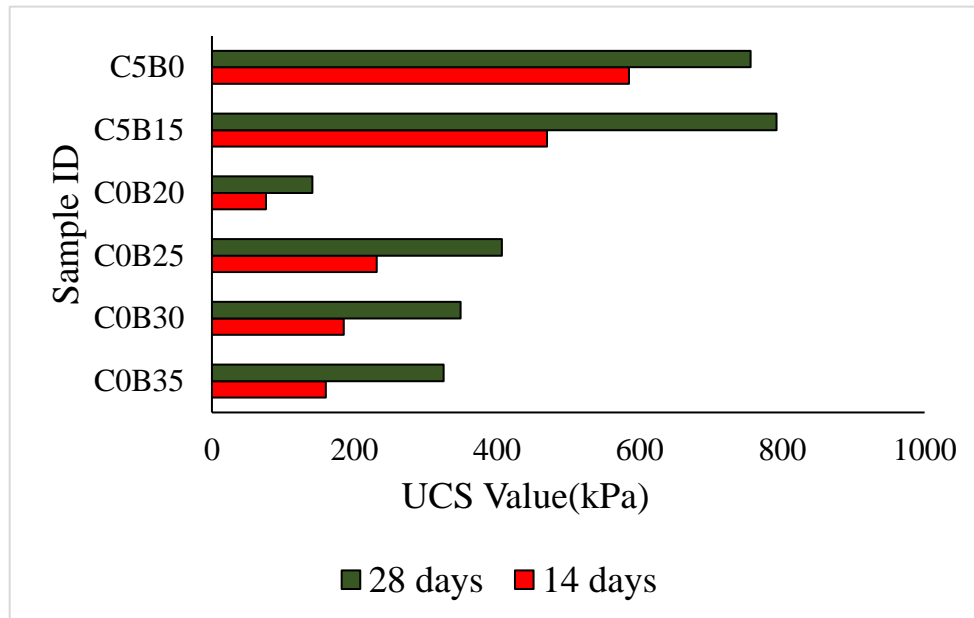


Fig. 4.4: Strength increment of samples at humid condition.

From Fig 4.4, increment of strength with time is noticeable in 14 days and 28 days. 20%

binder combination showed the lowest strength of 76 kPa at 14 days and 141 kPa at 28 days. 25% binder combination showed highest strength of 231 kPa at 14 days and 407 kPa at 28 days considering only the binder contents combinations. In case of all combination, higher strength was observed at 585 kPa initially at 14 days with 5% cement combination but later after 28 days, 5% cement with 15% binder showed the highest strength of 792 kPa.

#### 4.5.2 Humid Curing followed by Heat Curing before Test

Unconfined compressive strength after humid curing followed by heat curing before test condition is shown in Table 4.2. Strength increment of different combination is shown in Fig 4.5.

Table 4.2: Unconfined compressive strength after humid curing followed by heat curing before test.

Combination	Heat curing before test	
	14 days (kPa)	28 days (kPa)
C5B0	1296	2194
C5B15	3104	4158
C0B20	1221	1524
C0B25	3165	3987
C0B30	2105	3010
C0B35	1734	2488

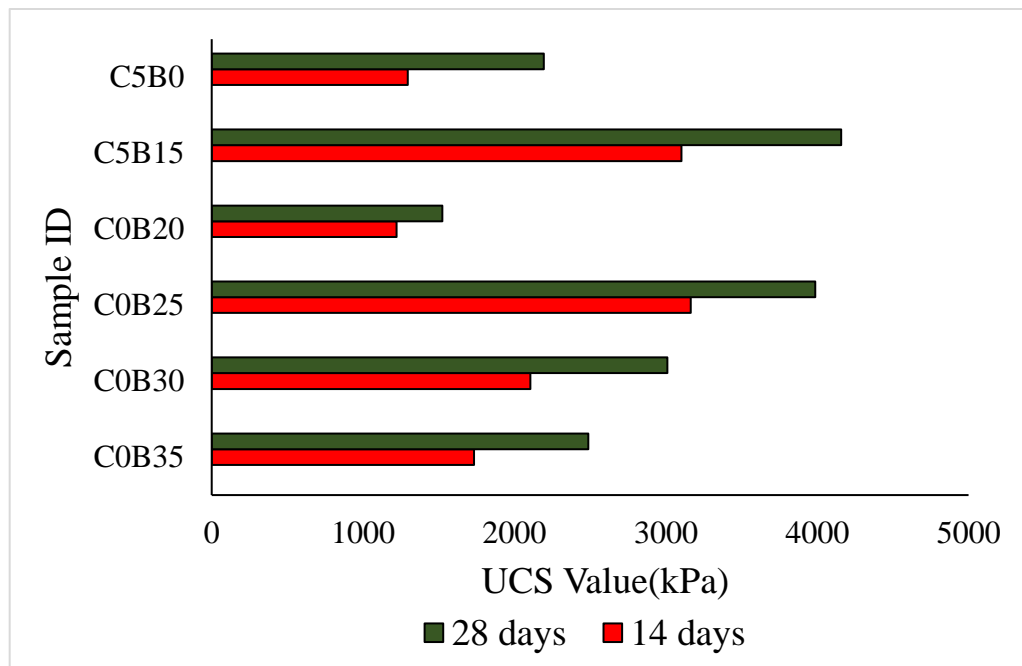


Fig. 4.5: Strength increment at humid condition followed by heat curing before test.

It can be observed that 20% binder combination showed the lowest strength formation of

1221 kPa and 25% binder combination showed the highest strength of 3165 kPa at 14th day in heat curing before test from Fig 4.5. But in 28 days, 5% cement with 15% binder combination had achieved the highest compressive strength of 4158 kPa. 20% binder combination had lowest strength of 1524 kPa in 28 days. 25% binder combination had highest strength initially at 14 days but later 5% cement with 15% binder combination had the highest strength. From Fig 4.4 and 4.5 it can be observed that, 5% cement with 15% binder had gained the highest compressive strength in both humid and heat curing before test condition after 28th days among all combinations. Combination with only cement (5% cement) had achieved the highest early strength in humid condition where water acts as an activator for cement. But after 28 days, 5% cement with 15% binder had the highest strength. Addition of 15% slag and fly ash with 5% cement led to strength increment by 89.51% in heat curing before test condition and only 4.76% increment was observed in humid condition.

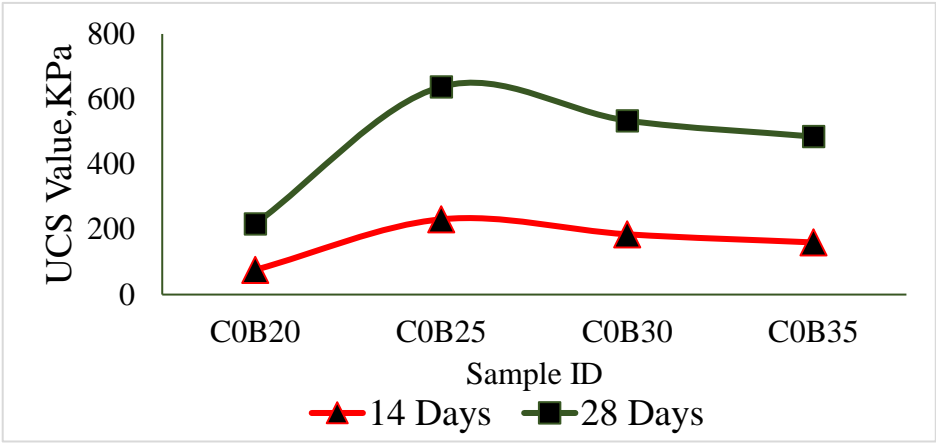


Fig. 4.6: Strength variations of alkali activated samples at humid condition.

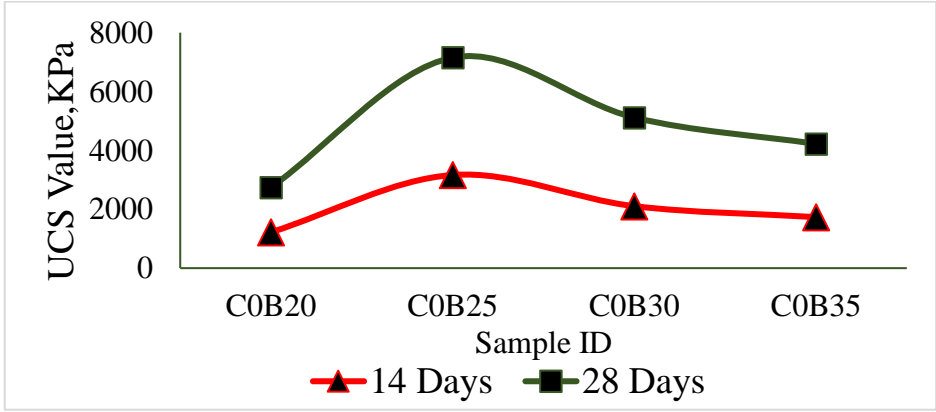


Fig. 4.7: Strength variations of alkali activated samples at heat curing before test

Figure 4.6 and 4.7 show that all including the alkali activated samples gained strength with the increment of curing time. Among the alkali activated samples, 25% binder had higher values of compressive strength as shown in Fig 4.6 and 4.7. With the increment of binder contents in combination, strength value reached a peak value with 25% binder content and then gradually decreased. This trend is noticeable in both conditions and ages.

### 4.5.3 Immediate Heat followed by Ambient Curing

Further investigation was done with immediate heat curing of sample at oven with 100°C temperature for twenty four hours and then curing in ambient condition for 14 and 28 days. UCS tests were done after 1 day, 14 days and 28 days as shown in Table 4.4.

Table 4.3: Unconfined compressive strength of immediate heat followed by ambient curing condition

Sample ID	Immediate Heat followed by Ambient Curing Condition		
	1 day (kPa)	14 days (kPa)	28 days (kPa)
C5B0	1252	1260	1270
C5B15	1400	1413	1428
C0B20	901	915	925
C0B25	1069	1075	1082
C0B30	852	862	880
C0B35	606	611	616

From Table 4.3, it is noticeable that maximum strength was found at 5% cement with 15% binder combination in immediate heat curing condition. This result indicates that water in specimens had major effect in initial strength formation. Both water and binder contents were factors in strength gaining but with the increment of binder, it was evident that strength reduced after obtaining a pick value for 25% binder combination.

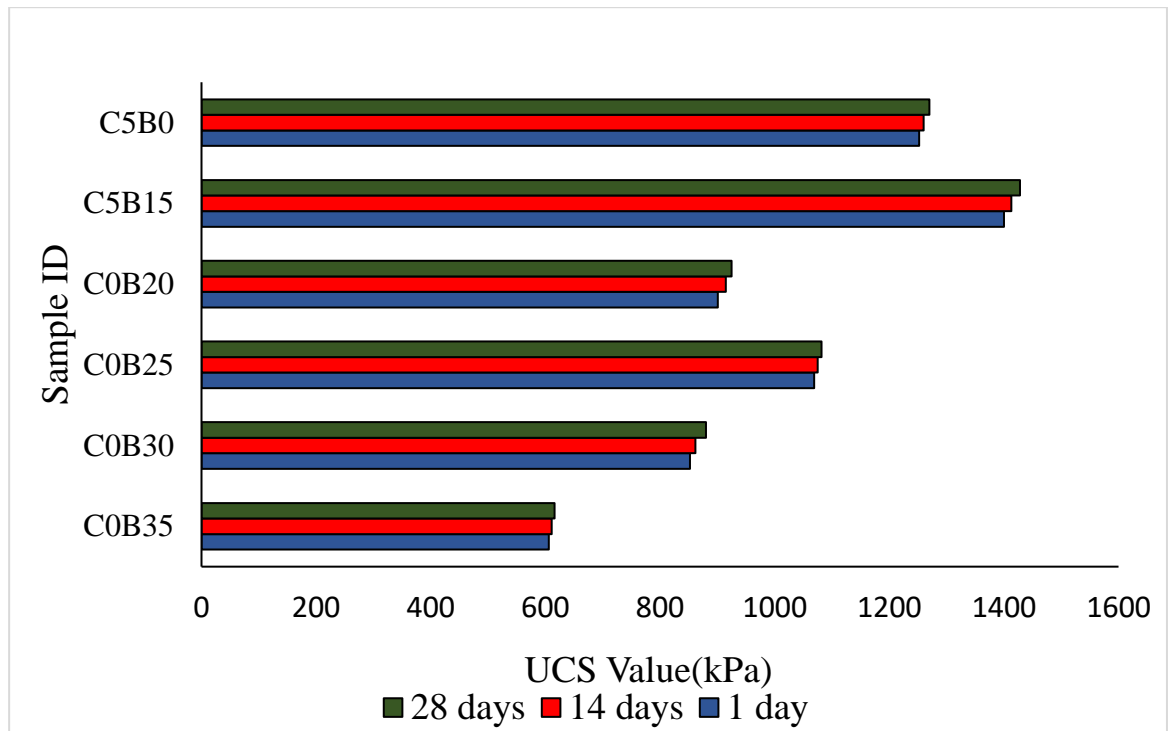


Fig. 4.8: Compressive strength at immediate heat followed by ambient curing.

From the Fig 4.8, it was observed that 28 days strength was almost similar to the strength gained after one day heat curing. This trend was almost identical to the trend of sole binder mortar strength investigated by (Adam, 2014).

#### 4.5.4 Ambient Curing Condition

Specimens were kept in room temperature and UCS tests were done after curing for 14 and 28 days. UCS test results are shown in Table 4.4.

Table 4.4: Unconfined compressive strength value at ambient curing condition

Sample ID	Strength 14days (kPa)	Strength 28days (kPa)
C5B0	442	571
C5B15	487	821
C0B20	260	460
C0B25	286	504
C0B30	257	485
C0B35	197	400

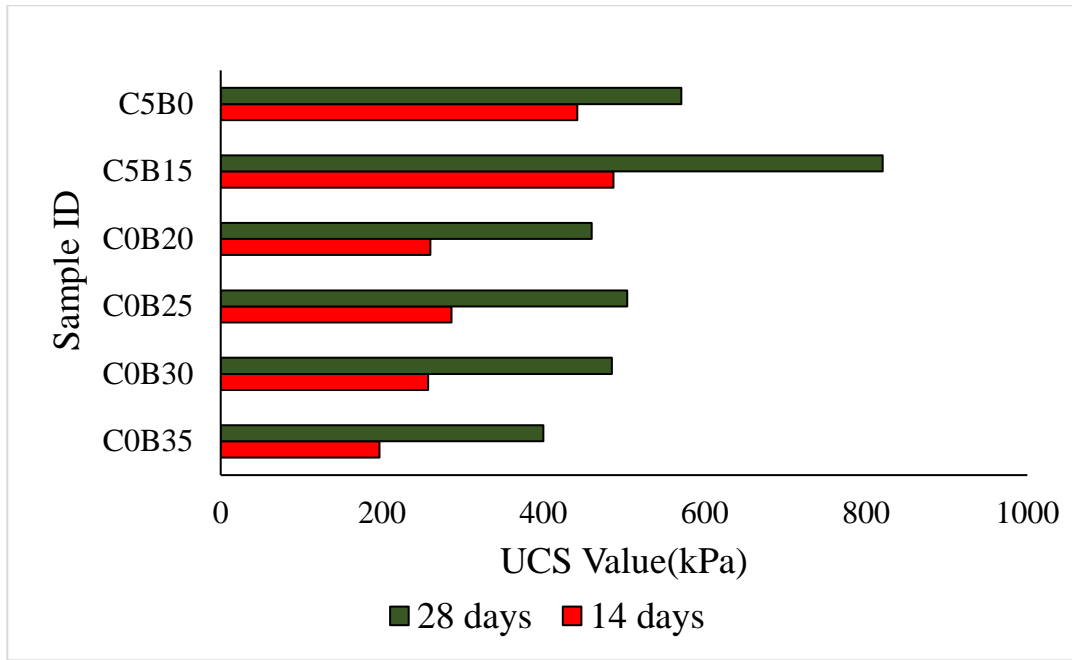


Fig. 4.9: Compressive strength after ambient curing.

Maximum strength of 821 kPa was observed at 5% cement with 15% binder combination as shown in Fig 4.9. As water acts as an activator for cement and the specimens were exposed to weather gathering moisture over the curing period, 5% cement combination had the second highest strength. 35% binder combination had the lowest strength of 400 kPa in this curing condition.

#### 4.6 Split Tensile Strength

Split tensile strength as shown in Table 4.5 and Fig 4.10 was conducted after 14 days of curing period for humid curing followed by heat curing condition.

Table 4.5: Split tensile strength of specimens

Sample ID	Tensile Strength (kPa)
C5B0	408
C5B15	371
C0B20	185
C0B25	232
C0B30	214
C0B35	155

Split tensile strength of soil was found maximum in 5% cement combination. The 5% cement combination had 408 kPa strength. From Fig 4.11, it is noticeable that 25% binder had maximum strength among sole binder combinations but the strength was at the lowest for 35% binder.

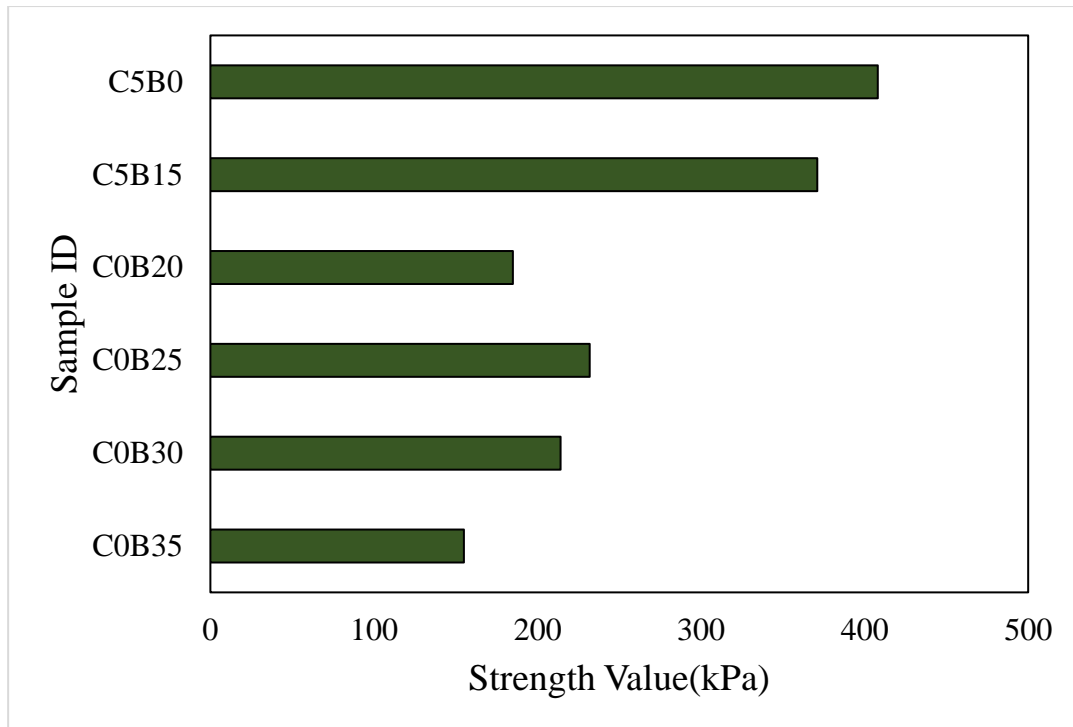


Fig. 4.10: Split tensile strength of all combinations.

#### 4.7 Water Effect on Specimens

Water seemed to have great influence on the strength of the specimens. To ensure liquidity in grout for the deep soil mixing process, water percentage in the total sample increased with respect to the increment of binder content. It is visible from Table 4.6 and Fig 4.11 that water percentage increases with the increase of binder percentage.

Table 4.6: Water percentage in sole binder specimens

Sample ID	Water Percentage (%)
C0B20	23.69
C0B25	25.02
C0B30	26.31
C0B35	27.55

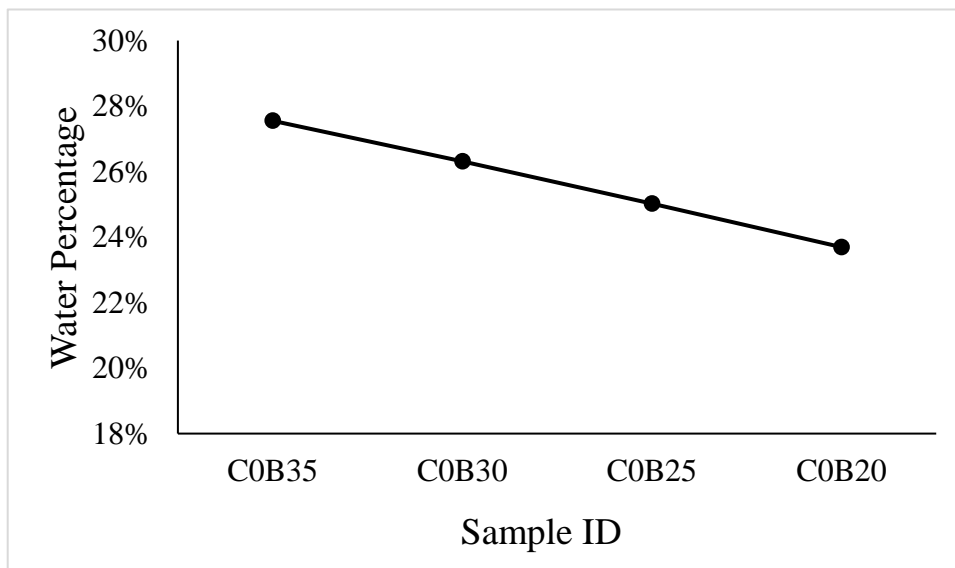
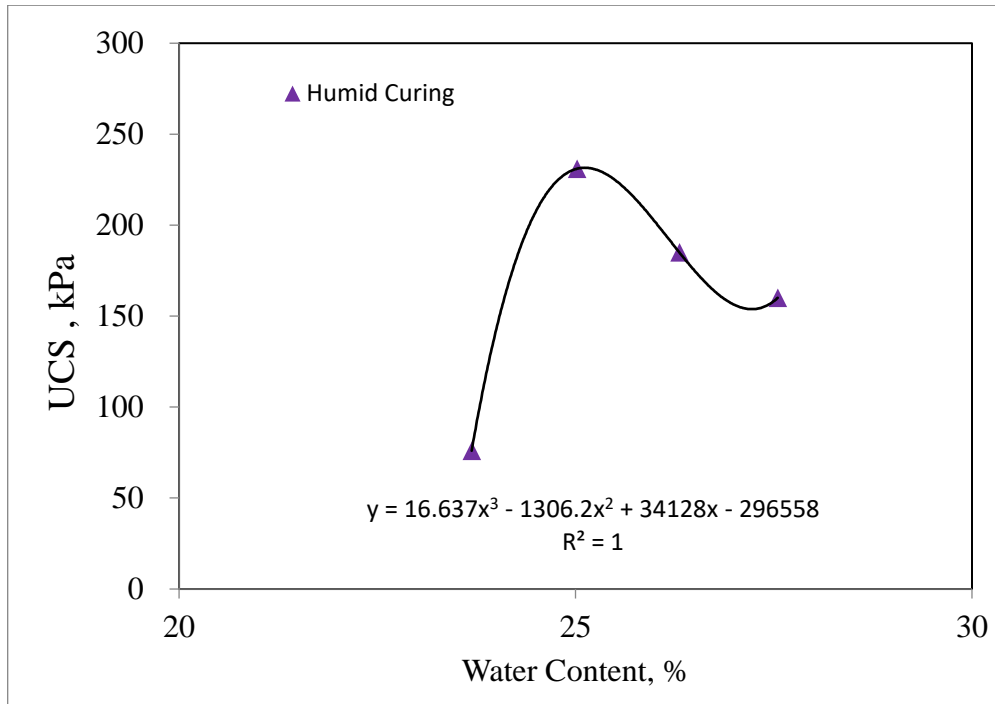
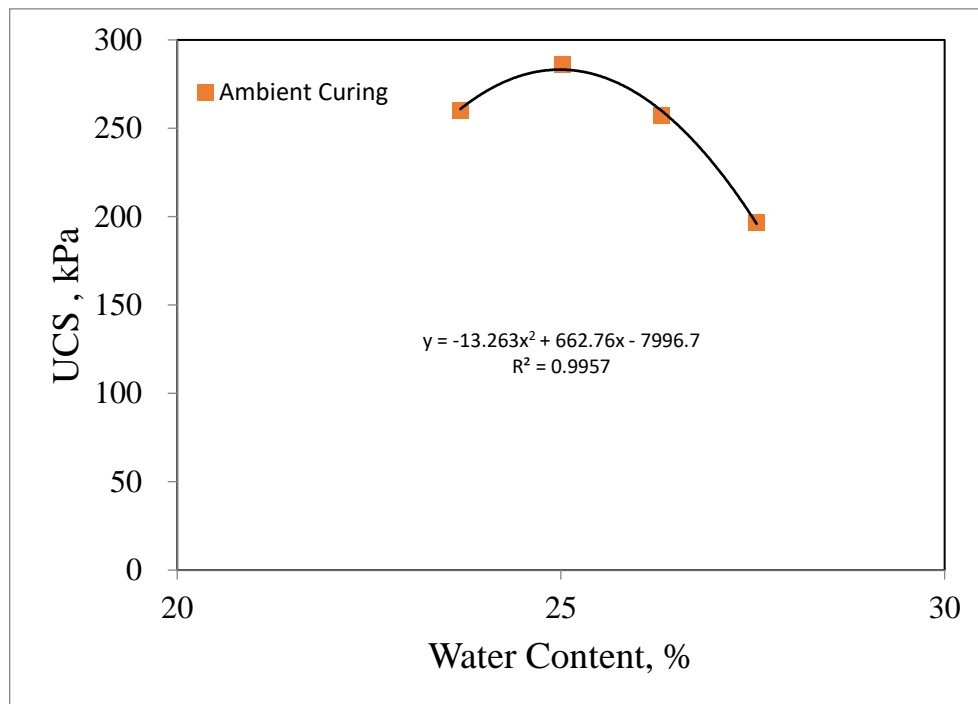


Fig. 4.11: Water percentage in sole binder combinations.

As the binder percentage was getting increased, the water percentage same way got increased. And this phenomenon resulted in diminution of the strength of the specimen except for 25% binder combination. Figure 4.12 below shows the effect of water on strength of the specimen.

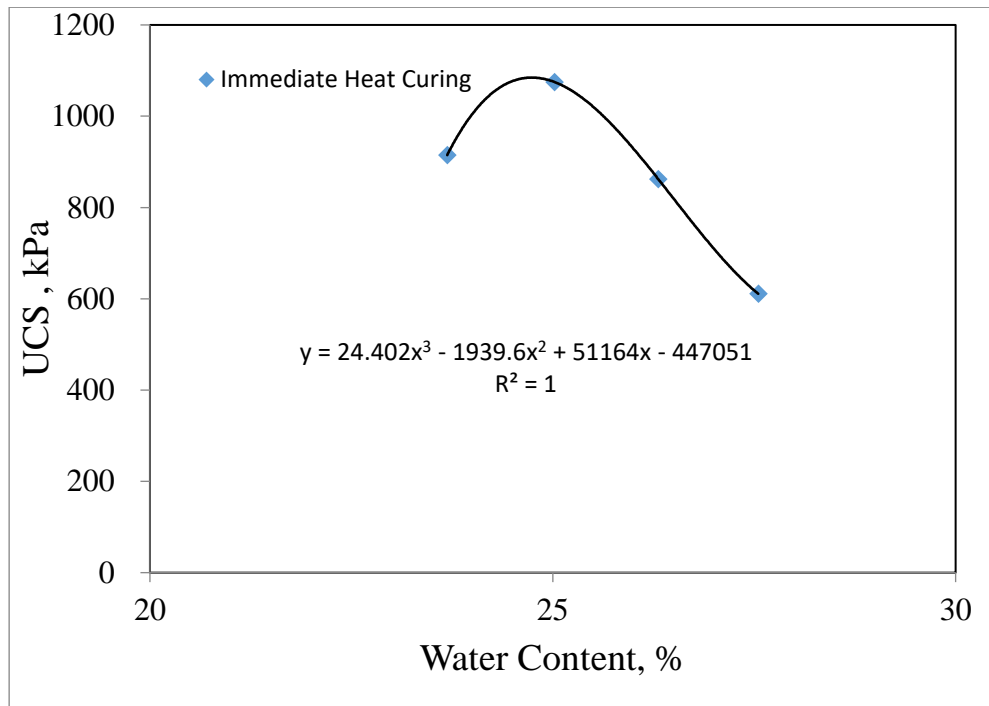


(a)

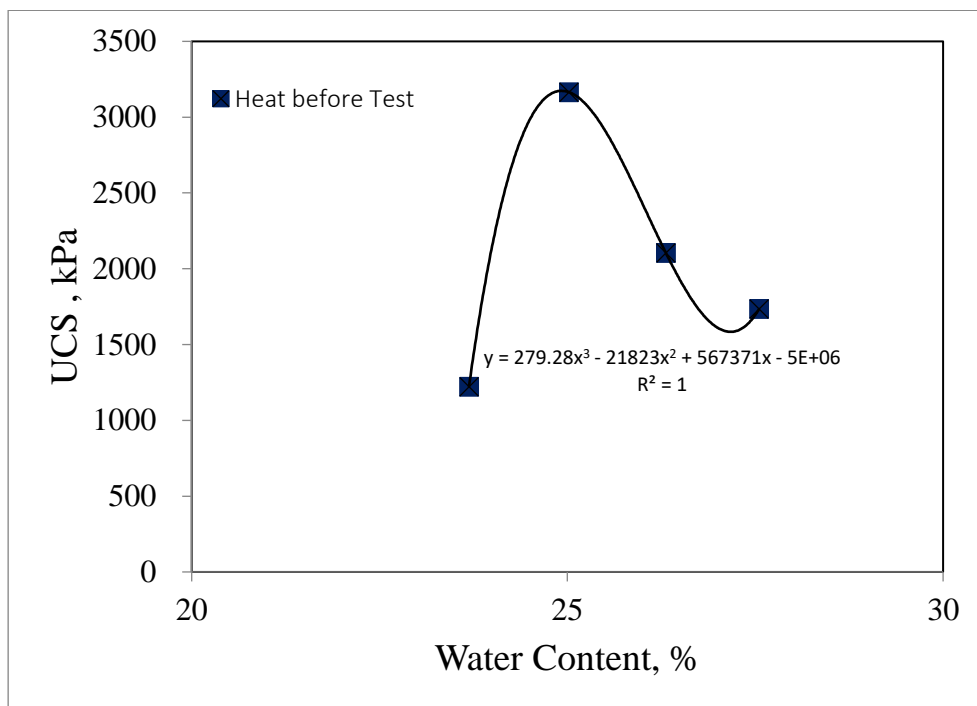


(b)

Fig. 4.12: Effect of water content in strength formation for (a) Humid Curing Condition, (b) Ambient Curing Condition



(c)



(d)

Fig. 4.12: Effect of water content in strength formation for (c) Immediate Heat Curing Condition, (d) Heat before Test Condition

#### 4.8 Comparison of Strength among different Combinations

Split Tensile test was done for 14 days. Considering UCS values of heat curing before test condition of 14 days and split tensile strength of 14 days, a relative ranking is presented in Table 4.7.

Table 4.7: Compressive strength and tensile strength at 14th day

Sample ID	Compressive Strength (kPa)	Tensile Strength (kPa)
C5B0	1296	408
C5B15	3104	371
C0B20	1221	185
C0B25	3165	232
C0B30	2105	214
C0B35	1734	155

In case of unconfined compressive strength test, 25% binder combination had the most compressive strength. It had the max tensile strength among only fly ash-slag combinations. The 5% cement combination had the maximum tensile strength but its compressive strength was the 2nd lowest of all combinations. On the other hand, 5% cement with 15% binder combination showed the tensile value of 371 kPa which is second highest among the combinations. It can be observed that compressive and tensile strength followed a trend which indicates that these combinations had gained both tensile and compressive strength proportionately. Figure 4.13 shows correlation between tensile strength and compressive strength.

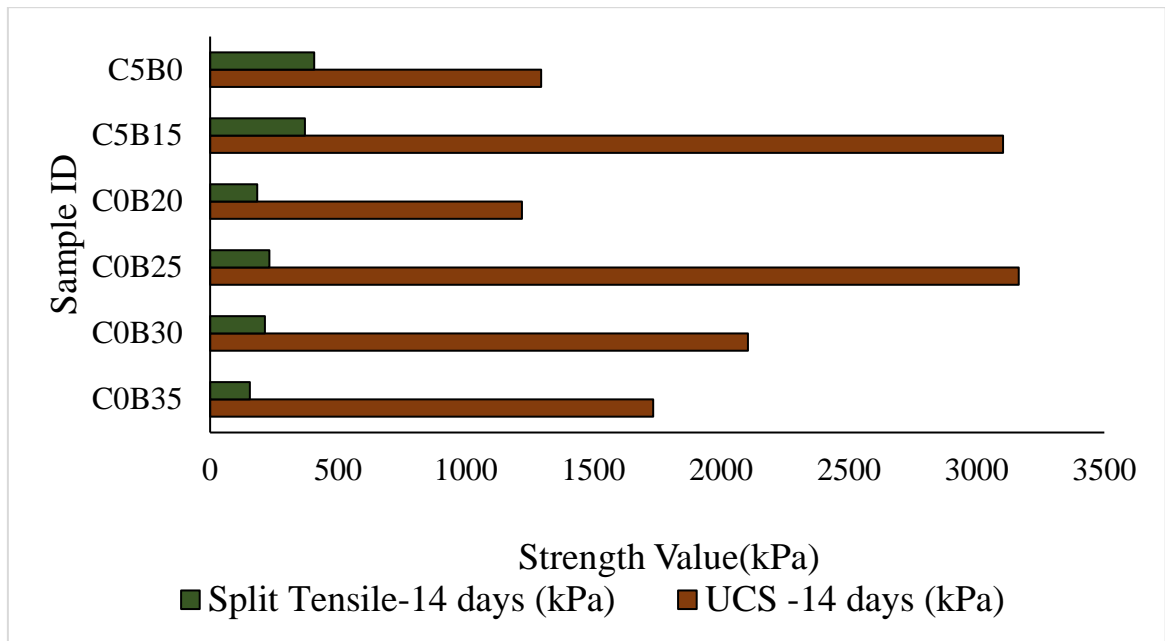


Fig. 4.13: Correlation between tensile strength and compressive strength.

#### 4.9 Strength Comparison for different Combination at different Curing Condition

Strength varies with the mix ratios of the precursors and curing condition. The strength variations are presented in Table 4.8. In case of UCS test, 25% binder combination had the maximum compressive strength in all curing condition within the solely binder combinations. 5% cement and 15% binder combination displayed maximum strength among all combinations in each curing condition. It is also evident that humid condition followed by heat before test condition demonstrated maximum strength. Figure 4.14 shows strength comparison among different curing condition.

Table 4.8: Strength comparison among the combinations of different curing condition

Sample ID	Initial Heat Condition (100°C)	Ambient Condition (25±2°C)	Humid Condition (24±2°C)	Heat before Test (100°C)
C5B0	1270	571	756	2194
C5B15	1428	821	792	4158
C0B20	925	460	141	1524
C0B25	1082	504	407	3987
C0B30	880	485	349	3010
C0B35	616	400	325	2488

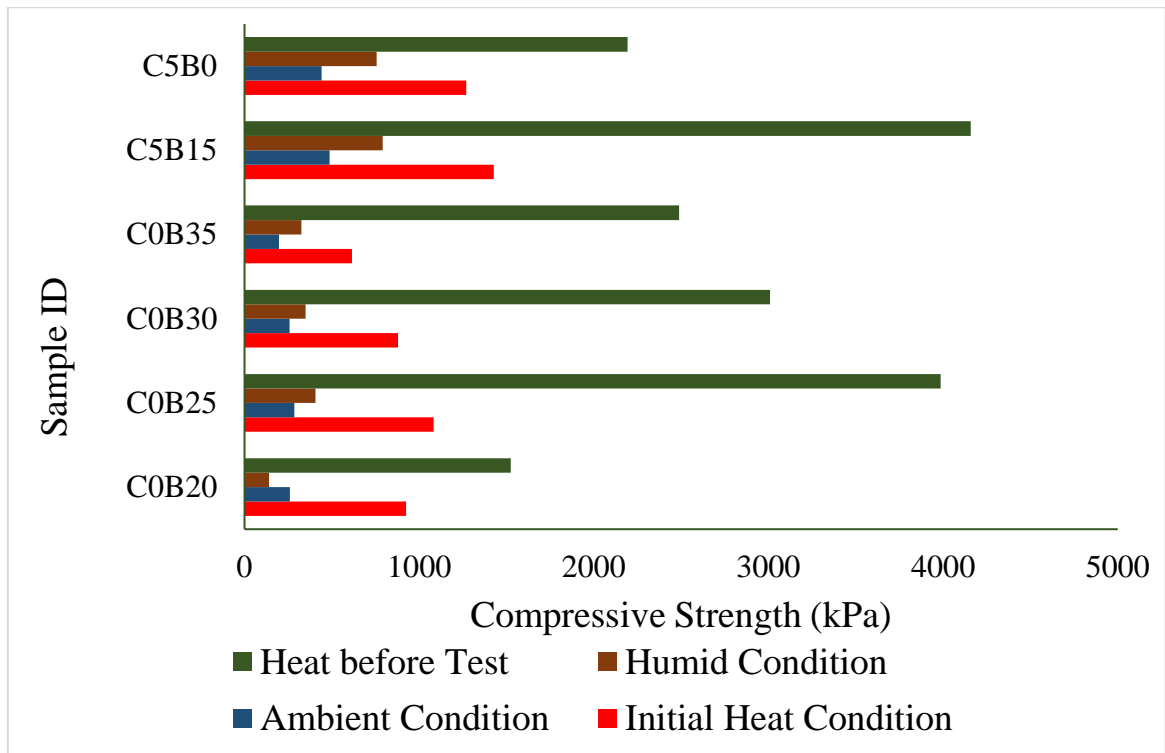


Fig. 4.14: Strength Comparison among different curing condition.

#### 4.10 Deep mixing pile Execution with Selected Combinations

A total of 3 combinations were selected for further analysis. These are 5% cement, 5% cement with 15% binder and 25% binder considering the results in Table 4.7. Preliminarily determined proportion of the materials were used for deep mixing piles. Deep mixing pile machine was used to execute the deep mixing piles and later cured for 28 days inside the reconstituted soil bed. UCS, split tensile and SEM tests were performed to investigate the behavior.

##### 4.10.1 Consolidation of Reconstituted Soil Bed

Figure 4.15 shows how settlement of soil bed occurred with course of time. Theoretical calculation portrays that, to achieve a condition of 1xLL from 1.5xLL, 52.5 mm of settlement would require, where 102.3 kg load would be applied and 12.6 kg water would be removed from the bed. Practically when the settlement reached to 51.37 mm, moisture was calculated with speedy moisture tester and moisture found was 1xLL.

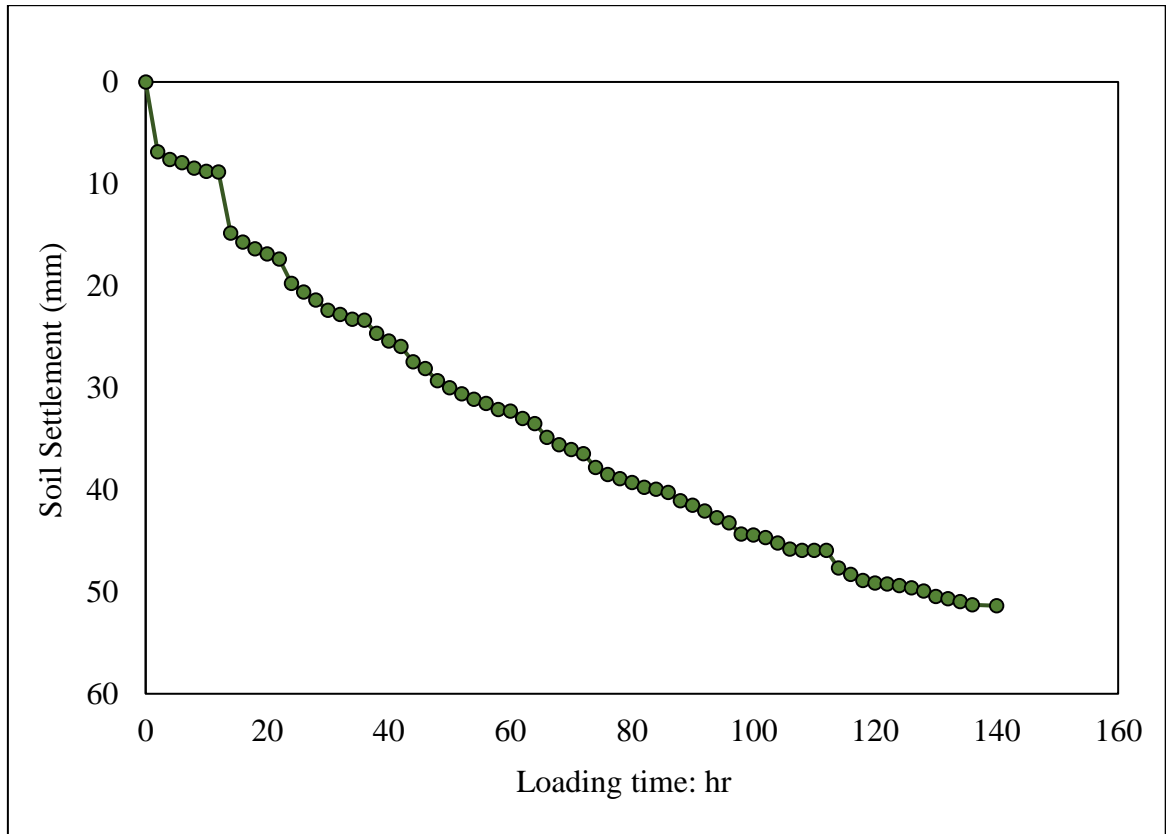


Fig 4.15: Time vs settlement graph for reconstituted soil bed.

#### 4.10.2 Unconfined Compressive Strength of Deep Mixing Piles

Unconfined compressive strength of three different sets of piles executed in the laboratory with three different combinations after 28 days curing is shown in Table 4.9. Samples of 38mm diameter were extruded from the executed deep mixing piles.

Table 4.9: Strength values of deep mixing pile specimens after 28 days

Sample ID	28 days (kPa)
C5B0	480
C5B15	527
C0B25	455

From each deep mixing pile, two specimens were extruded. And they were subjected to UCS test. Combination 5% cement with 15% binder had the higher compressive values (527 kPa) comparing others. The 5% cement pile specimen gave a mean value of 480 kPa. 25% binder showed lower result than 5% cement combination showing a mean value of

455 kPa. On the basis of strength value, 5% cement with 15% binder showed the best strength value among all, then 5% cement came up and lastly 25% binder. Figure 4.16 manifests how the unconfined compressive strength values were obtained.

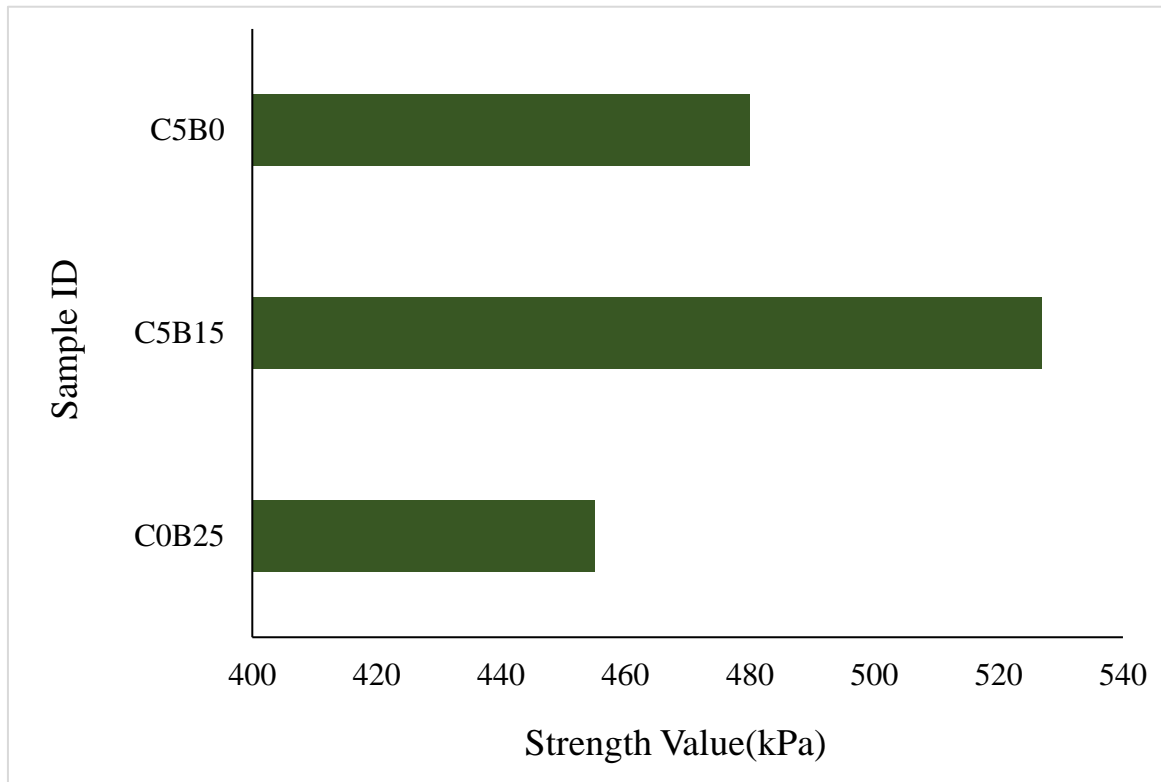


Fig. 4.16: Strength comparison of various combinations.

It is observed that, strengths obtained in deep mixing pile were nearest to the UCS obtained from humid condition samples in laboratory experiments. As the condition of reconstituted soil bed consisting 1 x LL of water provided water intrusion in the deep mixing piles, the 5% cement and 5% cement with 15% binder combination piles demonstrated less strength than that of the molds cured in humid condition. However, heat curing could not be performed for the pile construction, which could show better strength as demonstrated in experiments by the molds in the laboratory. Figure 4.17 and Table 4.10 shows the strength comparison among deep mixing piles and laboratory samples.

Table 4.10: Strength comparison between mold strength in laboratory and deep mixing piles

Sample ID	Humid Condition(kPa)	DMP(kPa)
C0B25	407	455
C5B15	792	527
C5B0	756	480

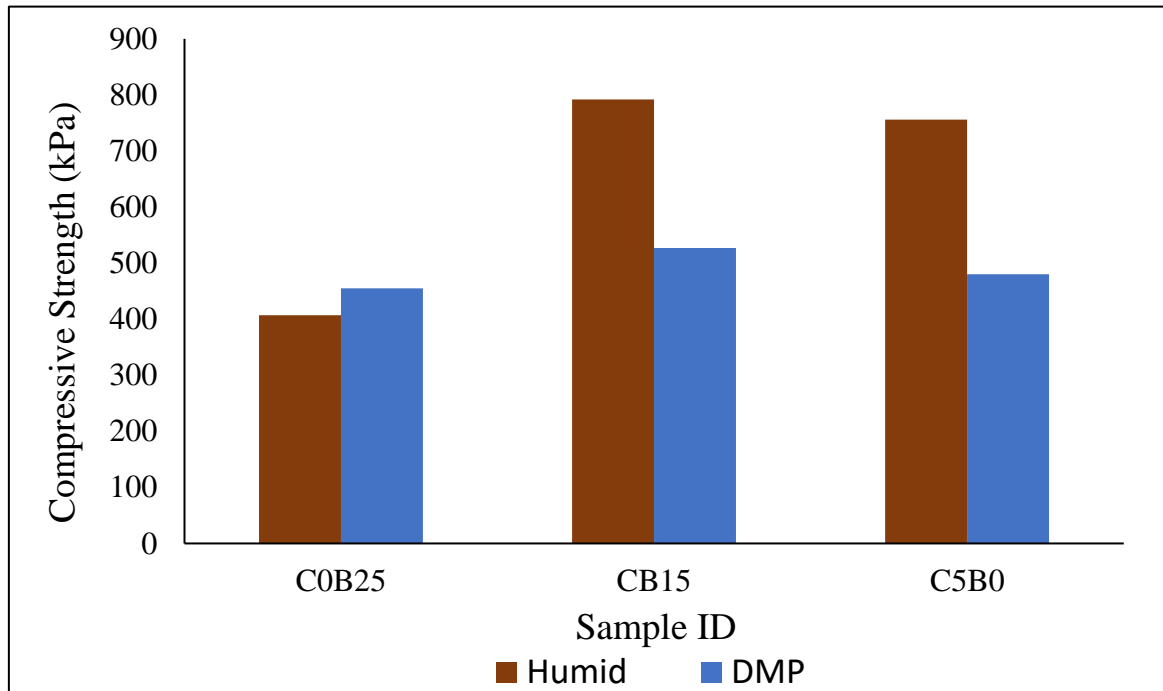


Fig. 4.17: Strength comparison between mold strength in laboratory and deep mixing piles

#### 4.10.3 Split Tensile Strength of Deep Mixing Piles

Specimens extruded from deep mixing piles were put in the split tensile test. The curing period was 28 days. The strength trend was similar to the strength demonstrated in laboratory experiments by molds. The 5% cement with 15% binder pile gave the best strength value with 63 kPa. 25% binder was a bit lower than 5% cement with 15% binder with a strength value of 49 kPa. And lastly 5% cement exhibited the lowest strength value among them; it showed 46 kPa. Figure 4.18 below shows how the strength value from split tensile test varied from each other following the UCS trend.

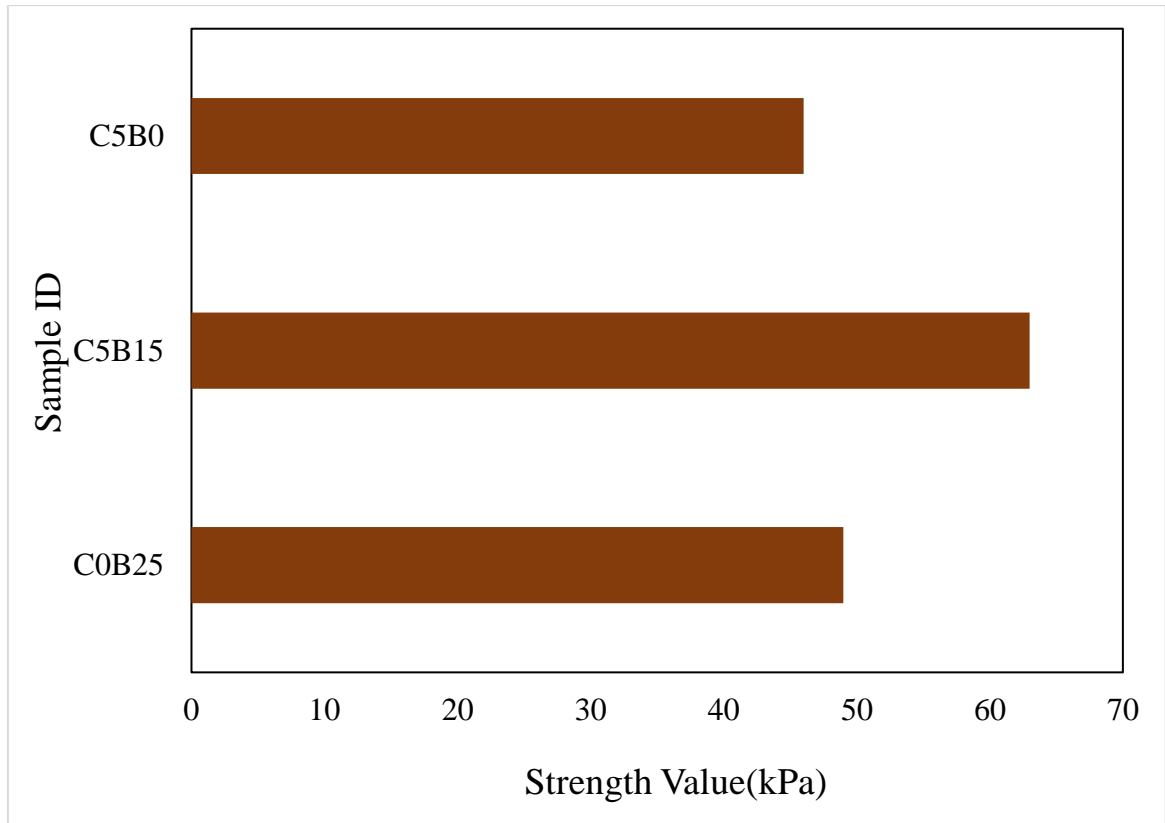


Fig. 4.18: Split tensile test of deep mixing pile samples.

#### 4.10.4 Micro Structure Analysis

There was visible difference in the SEM images for different samples. Cement makes ettringite crystals which were evident in the Fig 4.19 and 4.21, whereas Fig 4.20 manifested less ettringite crystals. Below SEM images also manifested significant difference in void availabilities among the samples. Figure 4.19 had moderate void whereas Fig 4.20 showed less void. Figure 4.21 also manifested higher void. In conclusion, the 15% binder and 5% cement showed higher strength for ettringite crystals. The 25% binder may show higher strength value in solo fly ash-slag combinations as there is less void. So, void was the key factor for strength gaining in only fly ash-slag combinations. The 5% cement had higher void but higher amount of ettringite crystals.

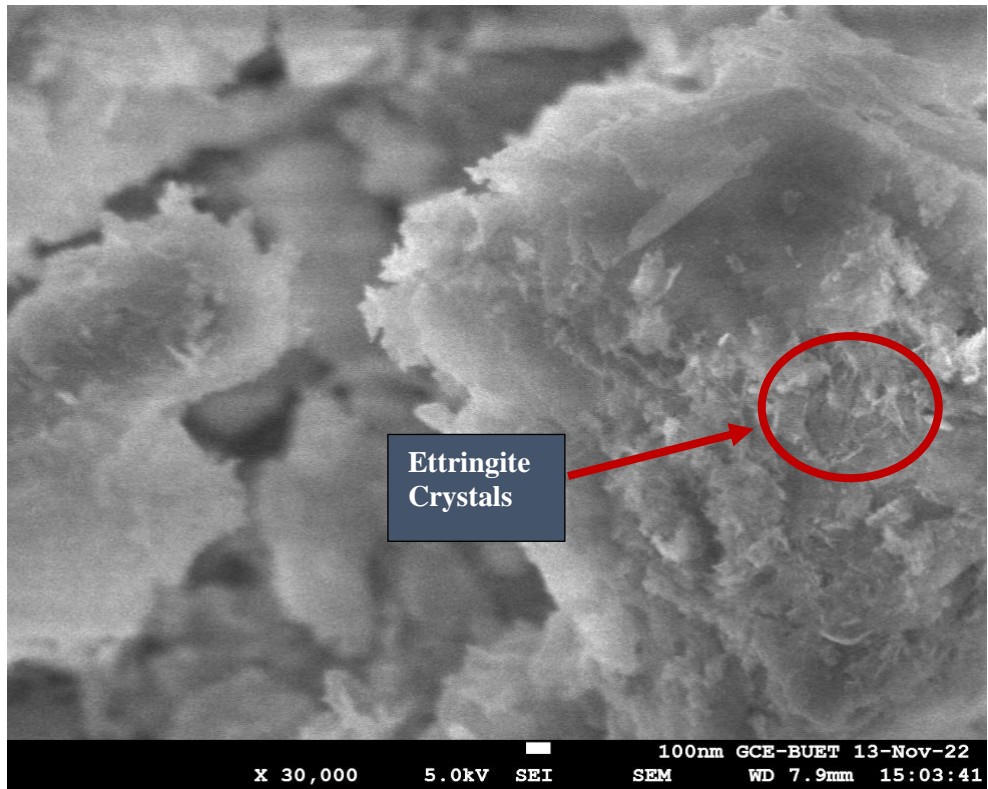


Fig. 4.19: 5% Cement SEM Image.

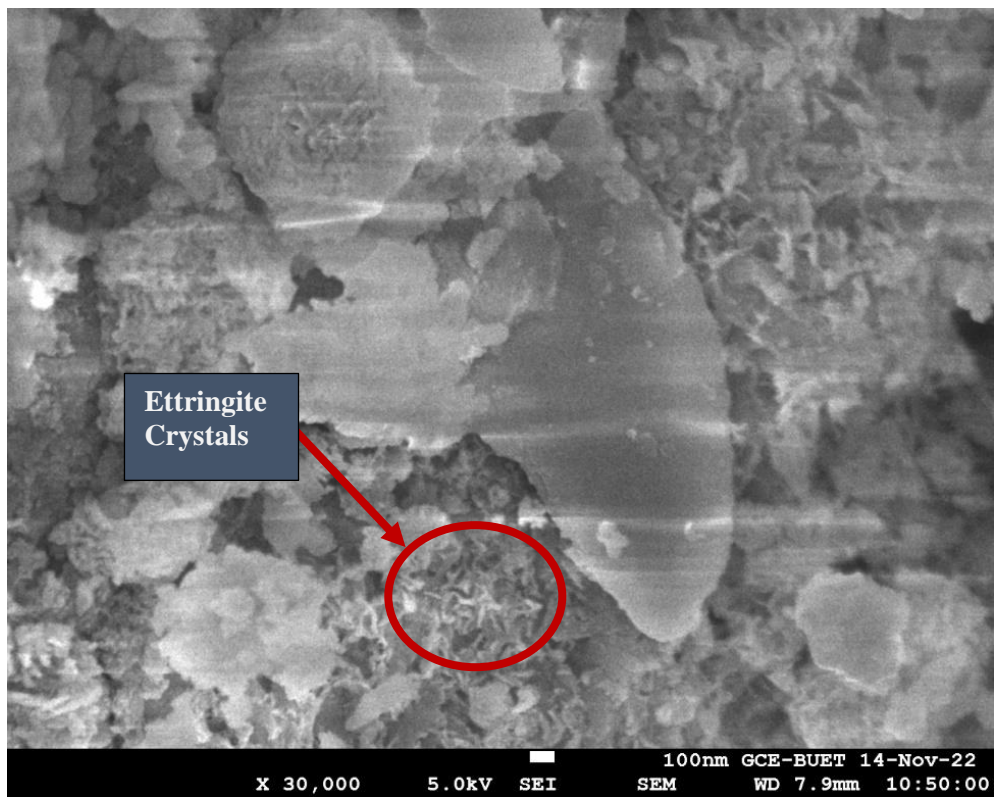


Fig. 4.20: 25% Binder SEM Image.

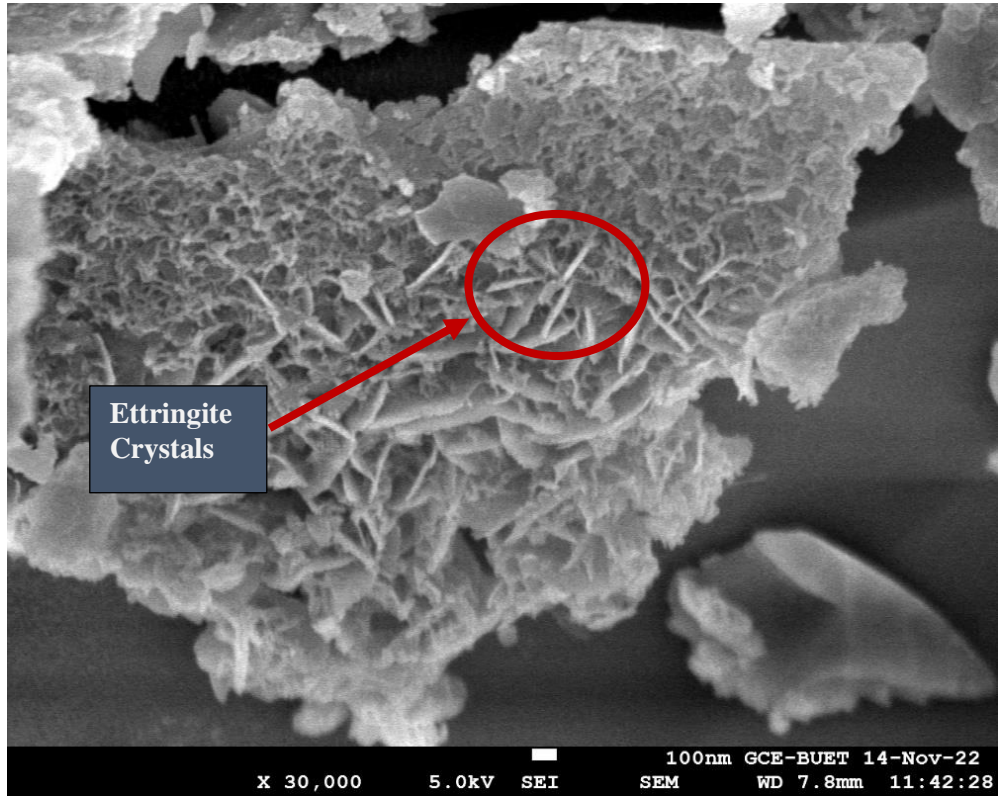


Fig. 4.21: 5% Cement with 15% binder SEM Image.

In the element identification from EDS analysis, it was evident that percentage of oxygen was found to be 58% by mass for 5% cement combination, 57% for 25% binder and 44.25% for 5% cement with 15% binder. In the combination with geopolymer (25% binder and 15% binder with 5% cement), Sodium amount was significant in comparison to 5% cement (Fig 4.22, 4.23, 4.24).

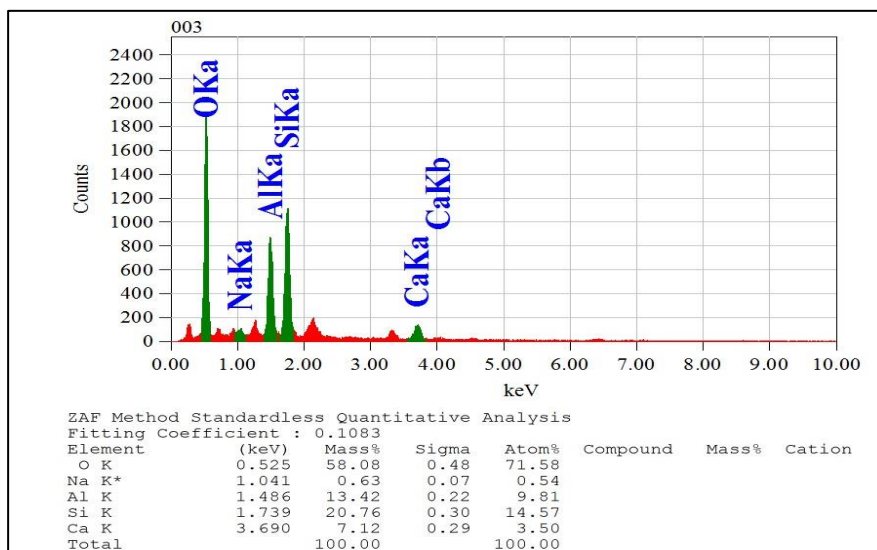


Fig. 4.22: 5% Cement EDS element identification.

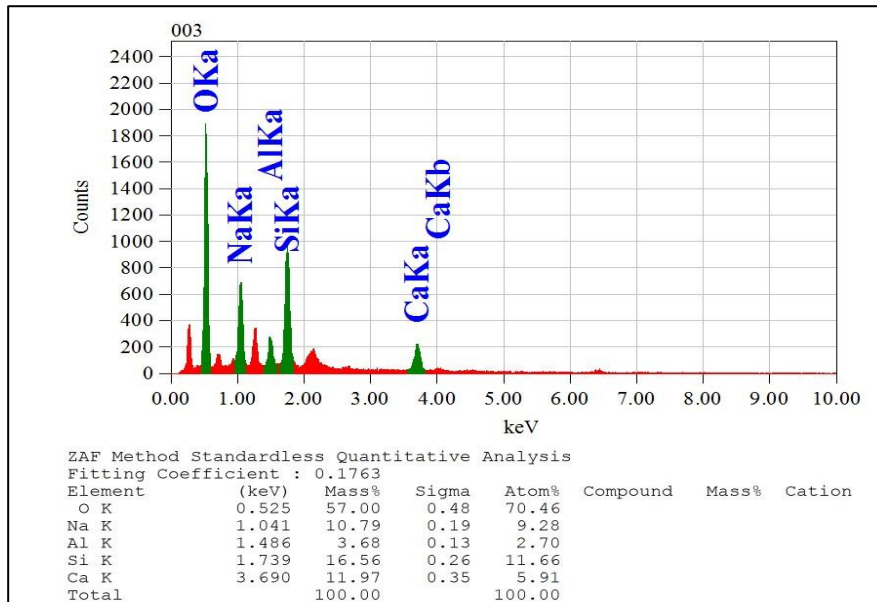


Fig. 4.23: 25% Binder EDS element identification.

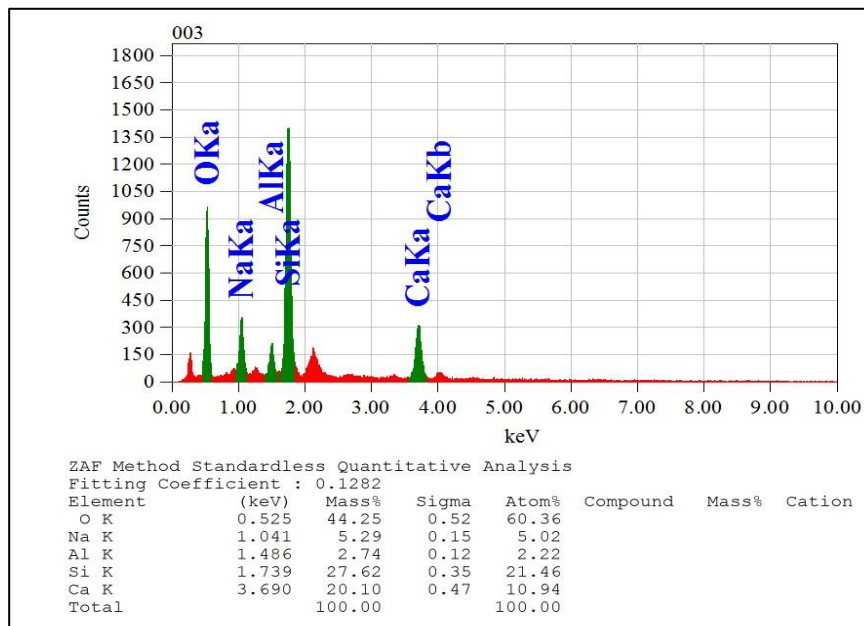


Fig. 4.24: 5% Cement with 15% binder EDS element identification.

A key element, calcium was found to be higher in order from 5% cement with 15% binder, 25% binder and 5% cement. This varying amount of calcium had the trend same as strength values. Aluminum had higher value in 5% cement than other two combination. There was also availability of silicon.

## **CHAPTER 5**

### **CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY**

#### **5.1 General**

The primary purpose of this study was to compare among the laboratory based specimen made with alkali activated slag and fly ash combination with varied curing condition for using as an alternative to cement soil mixing piles. The variation in the binder content, water content and curing condition effected the strength properties. This study correlated the properties based on strength. And finally, three specimens were selected to execute deep mixing piles on reconstituted bed through a laboratory scale deep mixing pile machine which was designed and constructed by the author. The executed piles were extruded and compared again with laboratory based specimens. In addition, the results in both conditions were compared to each other based on curing condition. UCS tests, split tensile tests and structural analysis were done for the extruded piles and comparisons were made. The main outcome of this study was to introduce a green and effective alternative to cement in the field of deep mixing pile. This chapter will provide the conclusion and recommendations for further study based on the performed tests.

#### **5.2 Conclusion**

This study utilizes fly ash and slag based geopolymer to construct deep mixing piles. The study concludes with the following findings.

- (i) Primarily in laboratory condition, for only geopolymer combination, soil mixed with 25% geopolymers showed maximum compressive strength among all four curing conditions, which were 407 kPa in humid condition, 504 kPa in ambient curing, 1082 kPa in initial heat followed by ambient condition and 3987 kPa in humid followed by heat curing condition. Though strength reached to the peak at 25% geopolymer, it reduced gradually with further increment of geopolymer. Among all combinations, 5% cement with 15% geopolymer showed highest strength value in all six combinations.
- (ii) In laboratory condition, among all curing conditions, humid curing followed by heat before test showed highest strength of 4158 kPa for 5% cement with 15% geopolymer, and gradually the strength decreased from initial heat condition to

ambient condition and lowest value was found in humid condition which indicates heating up the samples had a significant effect on strength increment.

- (iii) Water content plays an important role in strength formation of the geopolymer samples. With the increment of binder, the water content of the samples increases. However, with the increment of the water content, 25% geopolymer combination showed maximum strength for all combinations and further increment of water-binder ratio decreased the strength gradually. The Fig 4.13 may be used as a guideline to water effect in geopolymer in various curing condition.
- (iv) Finally, in the deep mixing pile experimental scheme, the machine functioned well in drilling deep mixing piles in the laboratory. Among the three combinations, 5% cement with 15% binder showed highest strength value of 527 kPa whereas 5% cement showed a value of 480 kPa and 25% binder showed a value of 455 kPa. The experiments showed that the strength value of deep mixing pile was close to humid condition strength value determined in the laboratory based experiments. However, there was a visible strength reduction in the specimen extracted from deep mixing piles comparing to the laboratory condition specimens. The main factor that causing this strength reduction was the moisture that intruded from surrounding moist soil of reconstituted soil bed. And additional moisture lowers the strength value was evident from preliminary experiments.
- (v) Split tensile values were almost around 10% of the UCS values in both laboratory condition and deep mixing pile condition. This trend is similar in both the experimental stages.
- (vi) In the micro structure analysis, ettringite crystals were significant in 5% cement with 15% binder piles. Moreover, the 25% binder combination had the lowest amount of ettringite crystal available. In EDS analysis, the increment of sodium and silica in geopolymer based piles indicated higher strength than only cement based piles.

### **5.3 Recommendation for Further Studies**

This study was confined to 28 days curing for all combinations. The effect of further curing period was not evaluated. Again, though it was evident from the study that, geopolymer based molds in the laboratory showed greater strength while heat cured for 24 hours, the effect of heat in the deep mixing piles could not be studied. Hence, attempt can be made for further study in the following topics:

- (i) Strength development for Geopolymer based deep mixing piles for a longer period of curing may be investigated.
- (ii) Method of exertion of heat on geopolymer based deep mixing piles on ground condition may be investigated.

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