Stabilization of Expansive Soils using Alkali Activated Fly Ash

A thesis
Submitted by

Partha Sarathi Parhi
(212CE1479)

In partial fulfillment of the requirements
for the award of the degree of

Master of Technology
In
Civil Engineering
(Geotechnical Engineering)
Department of Civil Engineering

National Institute of Technology Rourkela
Odisha -769008, India
May 2014

Stabilization of Expansive Soils using Alkali Activated Fly Ash

A thesis

Submitted by

Partha Sarathi Parhi

(212CE1479)

In partial fulfillment of the requirements for the award of the degree of

Master of Technology

In

Civil Engineering

(Geotechnical Engineering)

Under the Guidance of

Dr. S.K Das

Department of Civil Engineering

National Institute of Technology Rourkela

Odisha, -769008, India

May 2014

Dedicated to my Grandfather
Late Shri. Udaya Narayan Parhi,
who has been a constant inspiration for me.

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA, ODISHA-769008

CERTIFICATE

This is to certify that the thesis entitled, "***Stabilization of Expansive Soils using Alkali Activated Fly Ash***" is submitted by **PARTHA SARATHI PARHI**, bearing Roll No. **212CE1479** in partial fulfillment of the requirements for the award of Master of Technology degree in Civil Engineering with specialization in "Geotechnical Engineering" during 2012-2014 session at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

Date: 26-May-2014
Place: NIT, Rourkela, Odisha

Dr. S.K Das
Department of Civil Engineering
National Institute of Technology,
Rourkela

ACKNOWLEDGEMENTS

It would not have been possible to complete the thesis without the help and support of the kind people around me, to only some of whom it is possible to give particular mention here.

First and foremost, I would like to express my gratitude and sincere thanks to my esteemed supervisor **Dr. Sarat Kumar Das** for his consistent guidance, valuable suggestions and encouragement throughout the work and in preparing this thesis.

His inspiring words always motivated me to do hard labour which helped me to complete my work in time.

I am grateful to the Dept. of Civil Engineering, NIT Rourkela, for giving me the opportunity to execute this project, which is an important part of the curriculum in M.Tech programme.

I also thank my friends who have directly or indirectly helped in my project work. Many special thanks to my senior **Lasyamayee Garnayak** and my friend **Rupashree Sahoo** for their help & co-operation with me in my work.

I would also like to thank all the Laboratory staff of Geotechnical engineering, Environmental Engineering and Physics Dept., for their help, without which this work would not have been possible to execute.

Last but not the least I would like to thank my family for providing me this platform for study and their support as and when required.

PARTHA SARATHI PARHI

ABSTRACT:-

This research work presents the efficacy of sodium based alkaline activators and class F fly ash as an additive in improving the engineering characteristics of expansive Black cotton soils. Sodium hydroxide concentrations of 10, 12.5 and 15 molal along with 1 Molar solution of sodium silicate were used as activators. The activator to ash ratios was kept between between 1 and 2.5 and ash percentages of 20, 30 and 40 %, relatively to the total solids. The effectiveness of this binder is tested by conducting the Unconfined compressive strength (UCS) at curing periods of 3,7 and 28 days and is compared with that of a common fly ash based binder, also the most effective mixtures were analysed for mineralogy with XRD. Suitability of alkaline activated fly ash mix as a grouting material is also ascertained by studying the rheological properties of the grout such as, setting time, density and viscosity and is compared with that of common cement grouts. Results shows that the fluidity of the grouts correlate very well with UCS, with an increase in the former resulting in a decrease in the latter.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Chapter -1

Introduction

1.1 Expansive soils:-

Expansive soils also known as swelling soils or shrink-swell soils are the terms applied to those soils, which have a tendency to swell and shrink with the variation in moisture content. As a result of which significant distress in the soil occurs, causing severe damage to the overlying structure. During monsoon's, these soils imbibe water, swell, become soft and their capacity to bear water is reduced, while in drier seasons, these soils shrinks and become harder due to evaporation of water. These types of soils are generally found in arid and semi-arid regions of the world and are considered as a potential natural hazard, which if not treated well can cause extensive damages to not only to the structures built upon them but also can cause loss of human life. Soils containing the clay minerals montomorillonite generally exhibit these properties. The annual cost of damage to the civil engineering structures caused by these soils are estimated to be ₤ 150 million in the U.K., $ 1,000 million in the U.S. and many billions of dollars worldwide.

Expansive soils also called as Black soils or Black cotton soils and Regur soils are mainly found over the Deccan lava tract (Deccan Trap) including Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh and in some parts of Odisha, in the Indian sub-continent. Black cotton soils are also found in river valley of Tapi, Krishna, Godavari and Narmada. In the the north western part of Deccan Plateau and in the upper parts of Krishna and Godavari, the depth of black soil is very large. Basically these soils are residual soils left at the place of their formation after chemical decomposition of the rocks such as basalt and trap. Also these type of soils are formed due to the weathering of igneous rocks and the cooling of lava after a volcanic eruption. These soils are rich in lime, iron, magnesia and alumina but lack in the phosphorus, nitrogen and organic matter.

Their colour varies from black to chestnut brown, and basically consists of high percentage of clay sized particles. On an average, 20% of the total land area of our country is covered with expansive soils. Because of their moisture retentiveness, these soils are suitable for dry farming and are suitable for growing cottons, cereals, rice, wheat, jowar, oilseeds, citrus fruits and vegetables, tobacco and sugarcane.

During the last few decades damage due to swelling action has been clearly observed in the semiarid regions in the form of cracking and breakup of pavements, roadways, building foundations, slab-on-grade members, channel and reservoir linings, irrigation systems, water lines, and sewer lines.

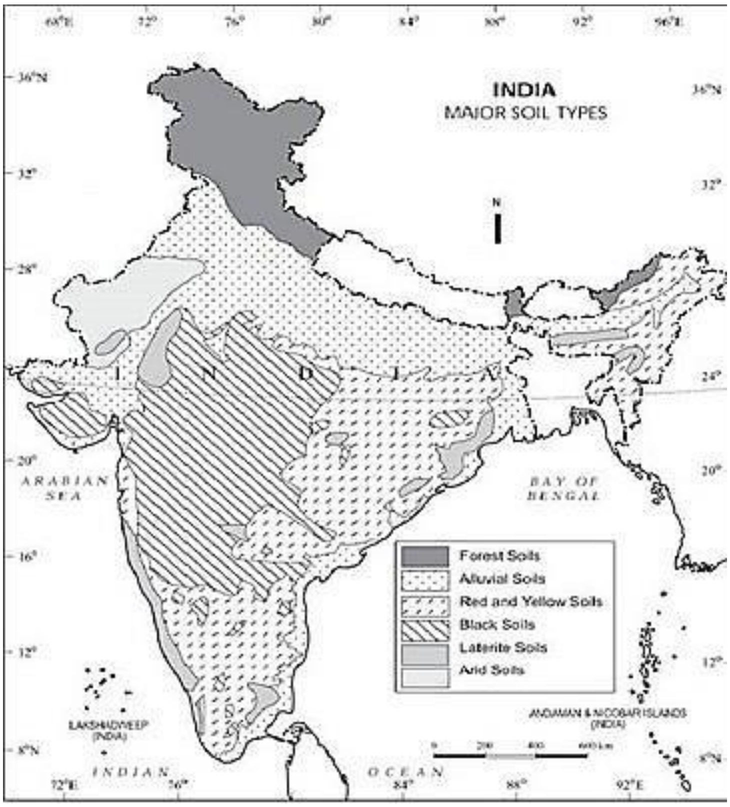

Figure 1.1 Major Soil Types in India

1.2 Fly Ash

Fly ash is a waste material, which is extracted from the flue gases of a coal fired furnace. These have close resemblance with the volcanic ashes, which were used as hydraulic cements in ancient ages. These volcanic ashes were considered as one of the best pozzolans used till now in the world.

Now a day due to rapid urbanization and industrialization the demand of power supply has been grown up, this results in setting up of a numerous number of thermal power plants. These thermal power plants use coal to produce electricity and after the coal is burnt, whatever mineral residue is left is called as Fly ashes. These fly ashes are collected from the Electro static precipitator (ESPs) of the plants.

Safe disposal and management of fly ash are the two major issues concerned with the production of fly ash. Generally the wastes which are generated from the industries possess very complex characteristics and are very hazardous, therefore it is necessary to safely and effectively dispose these wastes, so that it will not disturb the ecological system and will not cause any catastrophe to natural and human life. There should be provision of pre-treatment of these industrial wastes before its disposal and storage; otherwise it will cause environmental pollution.

Generally the fly ashes are micro sized particles which essentially consist of alumina, silica and iron. These particles are generally spherical in size, which makes them easy to flow and blend, to make a suitable mixture. The fly ash contains both amorphous and crystalline nature of minerals. Its composition varies according to the nature of the coal burned and basically is a non-plastic fine silt. At present, the generation of fly ash is far in excess of its utilization. Fly ash is also a potential material for waste liners. In combination with lime and bentonite, fly ash can also be used as a barrier material

1.2.1 Fly ash Generation and Disposal

For generation of steams, generally coal is used as a fuel in thermal power plants. In the past coal in the forms of lumps were used to generate steam from the furnaces of boilers, but that method proves to be non-energy efficient. Hence to optimize the energy from coal mass, the thermal power plants use pulverized coal mass. Firstly the pulverized coal mass is injected into combustion chamber, where it burns efficiently and instantly. The output ash is known as fly ash, which consists of molten minerals. When the coal ash moves along with the flue gases, the air stream around the molten mass makes the fly ash particle spherical in shape. The economizer is subjected, which recovers the heat from fly ash and stream gases. During this process, the temperature of fly ashes reduced suddenly. If the temperature falls rapidly, the fly ashes are resulting amorphous or glassy material and if the cooling process occurs gradually, the hot fly ashes becomes more crystalline in nature. It shows that the implements of economizer, improves its reactivity process.

When fly ash is not subjected to economizer, it forms 4.3% soluble matter and pozzolanic activity index becomes 94%. When it subjected to economizer, it forms 8.8% soluble matter and pozzolanic activity index becomes 103%. Finally, the fly ashes are removed from the flue gases by mechanical dust collector, commonly referred to electrostatic precipitator (ESPs) or scrubbers. The flue gases which are almost free from fly ashes are subjected to chimney into the atmosphere.

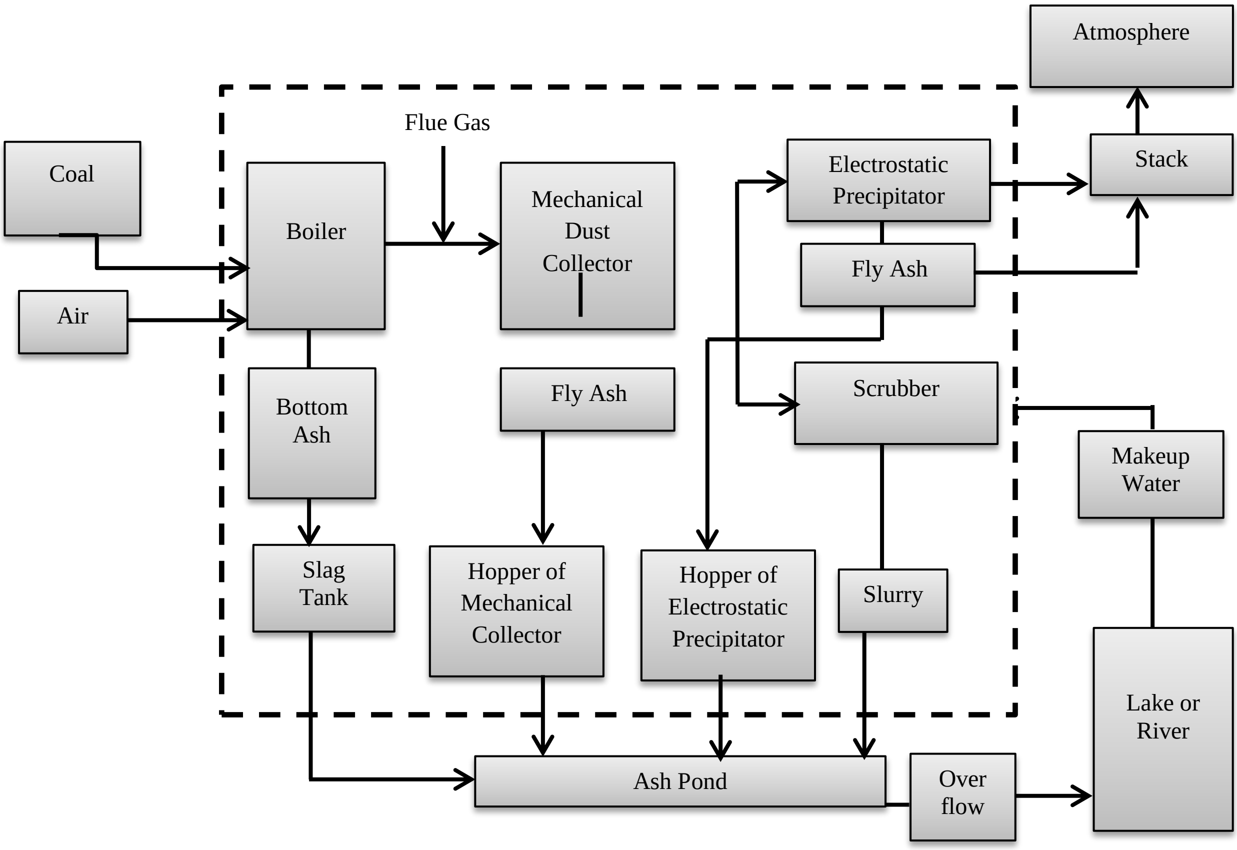

Fig1.2 Schematic view of a typical coal based thermal power plant (data source Prakash and Sridharan 2007)

The ESPs have the more efficiency about 90% - 98% for the removal of lighter and finer fly ash particles. Generally ESPs consists of four to six hoppers, which are known as field and the fineness of fly ash particles are proportional to number of fields available. Hence, if fly ashes are collected from first hopper, the specific surface area found to be 2800 cm^2/gm, where the collection is from last hopper, it is high about 8200 cm^2/gm. The pulverized coal being burnt, 80% of coal ashes are removed from flue gases and it recovers as fly ashes, next 20% of coal ashes, if coarser in size, and then collected from bottom of the furnace. This material is called as bottom ash. This can be removed in dry form or it can be collected from water filled hopper, from the bottom of the furnace. When sufficient amount of bottom ash filled the hopper, it can transferred by water jets or water sluice to a disposal pond, where it is called as pond ash. Fig1.1 gives the idea of systematically idea of disposal of coal ash, in a coal base thermal power plant.

1.2.2 Fly Ash Utilization

Utilization of fly ash in particular, can be broadly grouped into three categories.

- **The Low Value Utilizations** includes, Road construction, Embankment and dam construction, back filling, Mine filling, Structural fills, Soil stabilization, Ash dykes etc.
- **The Medium Value Utilizations** includes Pozzolana cement, Cellular cement, Bricks/Blocks, Grouting, Fly ash concrete, Prefabricated building blocks, Light weight aggregate, Grouting, Soil amendment agents etc.
- **The High Value Utilizations** includes Metal recovery, Extraction of magnetite, Acid refractory bricks, Ceramic industry, Floor and wall tiles, Fly ash Paints and distempers etc.

Instead of these, there is large wastage of fly ash material, so large number of technologies developed for well management of fly ashes. This utilization of fly ash increased to 73 MT upto the year 2012. Fly ash has gained acceptance from the year 2010-12. The present production of fly ashes in the country India are about 130 MT per year and expected to increase by 400 MT by year 2016-17 by 2nd annual international summit for FLYASH Utilization 2012 scheduled on 17th & 18th January 2013 at NDCC II Convention Centre, NDMC Complex, New Delhi.

Table1.1 Production & Utilization of fly ashes in different country

Ref: Alam and Akhtar , Int Jr of emerging trends in engineering and development , Vol.1 [2] (2011)

Country	Annual ash production, MT	Ash utilization in %
India	131	56
China	100	45
Germany	40	85
Australia	10	85
France	3	85
Italy	2	100
USA	75	65
UK	15	50
Canada	6	75
Denmark	2	100
Netherland	2	100

From the above Table1.1, the fly ash utilization in India is 56% for the country during the year 2010-12, hence rest of the fly ashes are waste material. Now, it's necessary to use all of fly ash, considering its adverse effect on environment. Lots of effort has been made to utilize the fly ash upto 100%. For this mission, energy foundation announces 2nd international summit on 2013 for fly ash utilization. The mission is also gathering some knowledge, information about solution for development of suitable utilization of fly ash. The well planned coal utilization, concentrated on its bulk utilization. This is possible only when, we make geotechnical applications such as back filling, embankment construction, and pavement construction like this. We can utilize more than 60% fly ash for low value applications, if execution is proper.

From, present scenario, India depend 65-70% production of electricity with coal based power plant, in which the fly ash production in India is, 110 MT/year. Table 1.2 shows the current ash utilization in India.

Table 1.2 Utilization of fly ash for different purpose Data source: Ministry of Environment & Forests

Mode of Fly Ash Applications	% Utilization
Dykes	35
Cement	30
Land Development	15
Building	15
Others	5

1.2.3 Classification of Fly Ash

After Pulverizations, the fuel ash extract from flue gases, by electrostatic precipitator is called fly ash. It is finest particles among Pond ash, Bottom ash and Fly ash. The fly ashes are extracted from, high stack chimney. Fly ash contains non-combustible particulate matter, with some of unburned carbon. Fly ashes are generally contains silt size particles. Based on lime reactivity test, fly ashes are classified in four different types, as follows:

- Cementitious fly ash

- Cementitious and pozzolanic fly ash
- Pozzolanic fly ash
- Non-pozzolanic fly ash

The fly is called cementitious, when it has free lime and negligible reactive silica. A pozzolanic fly ash is one which has reactive silica and negligible free lime content. The cementitious and pozzolanic fly ash contains, both free lime and reactive silica predominantly. Non-pozzolanic fly ash contains neither of free lime nor of reactive silica. The non pozzolanic fly ash do not take part in self cementing or pozzolanic reactions. Main difference is that, cementitious material hardens, when come in contact with water and pozzolanic fly ash hardens only after , get in contact with activated lime with water. The second and third category of fly ashes found widely.

Another way of classification of fly ash is that, class C and class F category of fly ashes, based upon chemical composition. Class C category of fly ashes obtained from burning lignite and sub-bituminous type of coal, which contains more than 10% of calcium oxide. Class F category of fly ashes obtained from, burning bituminous and anthracite type of coal, which contains less than 10% of calcium oxide. The chemical compositions of any fly ashes, which are categorize into class C or class F fly ashes are as follows in Table 1.3:

Table 1.3 Chemical requirement of class C and class F fly ashes (data source: ASTM C618-94a)

Particulars		**Fly ash**	
		Class F	**Class C**
$SiO_2 + Al_2O_3 + Fe_2O_3$	**% minumum**	70.0	50.0
SO_3	**% maximum**	5.0	5.0
MC	**% maximum**	3.0	3.0
LOI	**% maximum**	6.0	6.0

1.3 Alkali Activated Fly ash

The alkali activation of waste materials has become an important area of research in many laboratories because it is possible to use these materials to synthesize inexpensive and ecologically sound cement like construction materials. Alkali activated fly ashes is the cement for the future. The alkali activation of waste materials is a chemical process that allows the user to transform glassy structures (partially or totally amorphous and/or metastable) into very compact well-cemented composites.

Alkaline activation is a chemical process in which a powdery alumina-silicate such as fly ash is mixed with an alkaline activator to produce a paste capable of setting and hardening within a reasonably short period of time.

The alkaline activation of fly ash is consequently of great interest in the context of new and environmentally friendly binders with properties similar to or that improve on the characteristics of conventional materials.

In general terms, alkaline activation is a reaction between alumina-silicate materials and alkali or alkali earth substances, namely: ROH, $R(OH)_2$), R_2CO_3, R_2S, Na_2SO_4, $CaSO_4.2H_2O$, $R_2.(n)SiO_2$, in which R represents an alkaline ion like sodium (Na) or potassium (K), or an alkaline earth ion like Ca. It can be described as a poly-condensation process, in which the silica (SiO_2) and alumina (AlO_4) tetraedrics interconnect and share the oxygen (O) ions. The process starts when the high hydroxyl (OH) concentration of the alkaline medium favours the breaking of the covalent bonds Si–O–Si, Al–O–Al and Al–O–Si from the vitreous phase of the raw material, transforming the silica and alumina ions in colloids and releasing them into the solution. The extent of dissolution depends upon the quantities and nature of the alumina and silica sources and the pH levels. In general, minerals with a higher extent of dissolution will result in higher compressive strength after the process is complete.

At the same time, the alkaline cations Na^+, K^+ or Ca^{2+} act like the building blocks of the structure, compensating the excess negative charges associated with the modification in aluminium coordination during the dissolution phase.

1.3.1 Reaction Mechanism

A highly simplified diagram of the reaction mechanism in alkaline activation process is shown in figure 1.3 which outlines the key processes occurring in the transformation of a solid aluminosilicate source into a synthetic alkali aluminosilicate (N-A-S-H) gel.

For the sake of simplicity, the figure does not show the grinding or heating of raw materials required to vary the reactivity of aluminium in the system. Though presented linealy, these processes essentially occur concurrently. The dissolution of the solid aluminosilicate source by alkaline hydrolysis (consuming water) yields aluminate and silicate species. The surface dissolution of solid particles and the concomitant release of (very likely monomeric) alumina and silica into the solution have always been assumed to be the mechanism responsible for the conversion of the solid particles during alkaline activation.

Once dissolved, the species released are taken up into the aqueous phase, which may contain silica, a compound present in the activating solution. A complex mix of silicate, aluminate and aluminosilicate species is thereby formed, whose equilibrium in these solutions has been studied extensively. Amorphous aluminosilicate dissolves rapidly at high pH, quickly generating a supersaturated aluminosilicate solution. In concentrated solutions this leads to the formation of a gel as the oligomers in the aqueous phase condense into large networks. This process releases the water that was nominally consumed during dissolution. Water then plays the role of a reaction medium while nonetheless residing inside gel pores. This type of gel structure is commonly referred to as biphasic, the two phases being the aluminosilicate binder and water.

The time required for the supersaturated alumionosilicate solution to form a continuous gel varies considerably, depending on raw material processing conditions, solution composition and synthesis condition. After the gel forms, rearrangement and reorganisation continue in the system as intra-connectivity increases in th gel network. The end result is the 3-D aluminosilicate network commonly attributed to N-A-S-H gels. This is depicted in Figure 1.3 in the form of multiple 'gel' stages, consistent with recent experimental observations. And numerical modelling for fly ash based materials. Figure 1.3 describes the activation reaction as the outcome of two successive, process-controlling stages. The first, nucleation or dissolution of the fly ash and the formation of polymeric series, is highly dependent on the thermodynamic and kinetic parameters. Growth is the stage during which the nuclei reach a critical size and crystals begin to develop. These structural reorganisation processes determine the microstructure and pore distribution of the material, which are critical to determining many physical properties.

When the fly ashes are submitted to the alkaline solution, a dissolution process of the Al and Si occurs. Then the higher molecules condense in a gel (polymerization and nucleation) and the alkali attack opens the spheres exposing small spheres on the inside which will be also dissolved until the spheres, became almost dissolved with the formation of reaction products inside and outside the sphere (Fig 1.4).

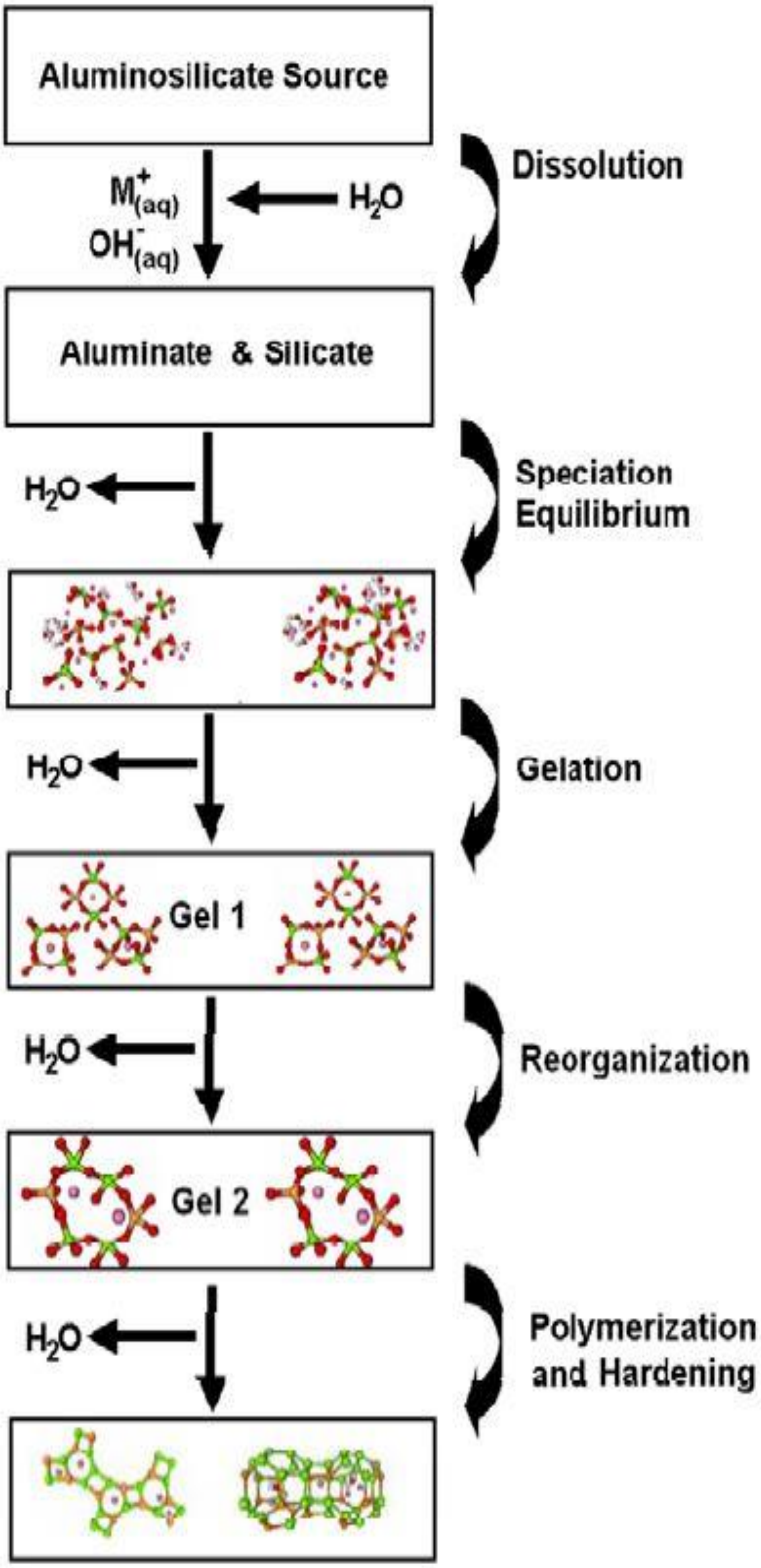

Fig 1.3 Conceptual model for alkaline activation processes

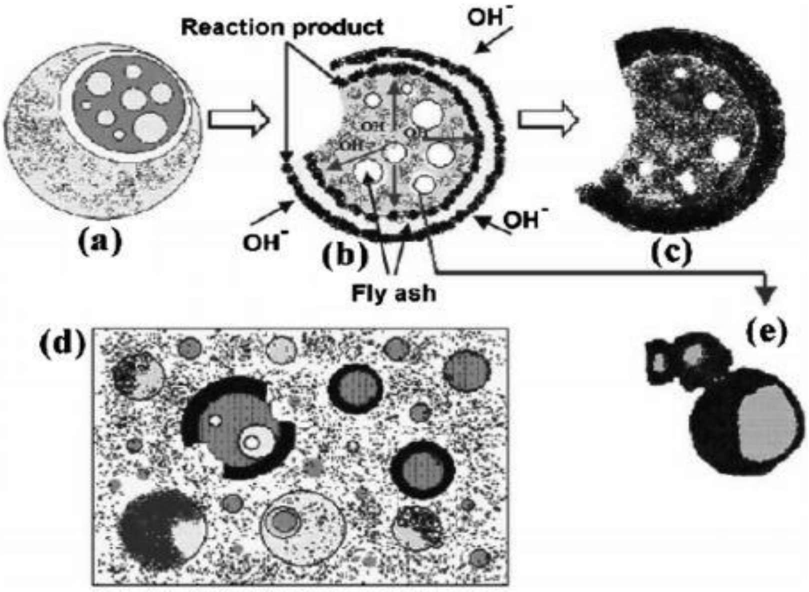

Fig 1.4 Descriptive model of the alkaline activation processes of fly ash

1.3.2 Applications for alkali-activated fly ash

The most recent research findings have confirmed the following:

- Concretes made with these materials can be designed to reach compressive strength values of over 40 Mpa after short thermal curing times.
- Concrete made with alkali-activated fly ash performs as well as traditional concrete and even better in some respects, exhibiting less shrinkage and a stronger bond between the matrix and the reinforcing steel.
- In addition to its excellent mechanical properties, the activated fly ash is particularly durable and highly resistant to aggressive acids, the aggregate-alkali reaction and fire.
- This family of materials fixes toxic and hazardous substances very effectively.

1.4 Justification of the Research

In India, almost 20% of the total area is covered by expansive soil, now due to rapid industrialization and huge population growth of our country, there is a scarcity of land, to meet the human needs. And also the cost of rehabilitation and retrofitting of the civil engineering structures founded over these soils are increasing day by day. On the other hand, the safe disposal of fly ash from thermal power industries has been a challenging issue demanding urgent solution because of the decline effect of these materials on the environment and the hazardous risk it pose to the health of humanity. However, production of cement require lime-stone and with the rate with which we are utilising cement, the day is not so far when the lime stone mines will get depicted, and this is a matter of fact that for every 1 kg of cement manufacturing, 1 kg of carbon dioxide is released into the atmosphere, which in turn increases the carbon foot print and also possess serious threat to the global warming. Thus there is a need to find out alternative binder, which is environmental friendly as well as depended like cements.

Hence, this research is justifiable in the use of alkali-activated fly ash to stabilize Black Cotton soil.

1.5 Objective and Scope

The objective of the current research work is to ascertain the suitability of alkali-activated fly ash as a soil stabilizing agent.

SCOPE:.

- Preparation of alkali-activated fly ash by using sodium silicate and 10, 12.5 and 15 molal sodium hydroxide solutions.
- Evaluation of unconfined compressive strength of fly ash treated soil on an interval of 3, 7 and 28 days (mixed with 20, 30 and 40% fly ash with total solid to water ratio ranging from 0.15 to 0.25)

- Evaluation of unconfined compressive strength of alkaline activated fly ash treated soil on an interval of 3, 7 and 28 days (mixed with 20, 30 and 40% fly ash with total solid to activator ratio ranging from 0.15 to 0.25).
- Rheological Study for assessment of alkali-activated solution as a grouting material.

This research is focused on stabilizing black cotton soil treated with various percentages of Fly Ash (20%, 30% and 40 by dry weight of soil, and water content varying from 15% to 30%) and alkali-activated fly ash (containing 20%, 30% and 40 by dry weight of soil, activator to total solids ratio varying from 15% to 25%).

1.6 Thesis Outline

This thesis consists of eight chapters and the chapters has been organised in the following order. After brief introduction in chapter 1, the Literature review is presented in the chapter 2 and the materials and methodology are described in the chapter 3.

Chapter 4 and 5 describes the results of stabilisation of expansive soils with application of Fly ash and alkali-activated fly ash and a comparison is made between the results of the two admixtures is also presented in chapter 6. In Chapter 7, the rheological studies of alkali-activated fly ash has been presented, while in chapter 8 conclusions drawn from various studies and scope for the future studies are presented. The general layout of the thesis work based on each chapter is presented in a flow diagram as shown below.

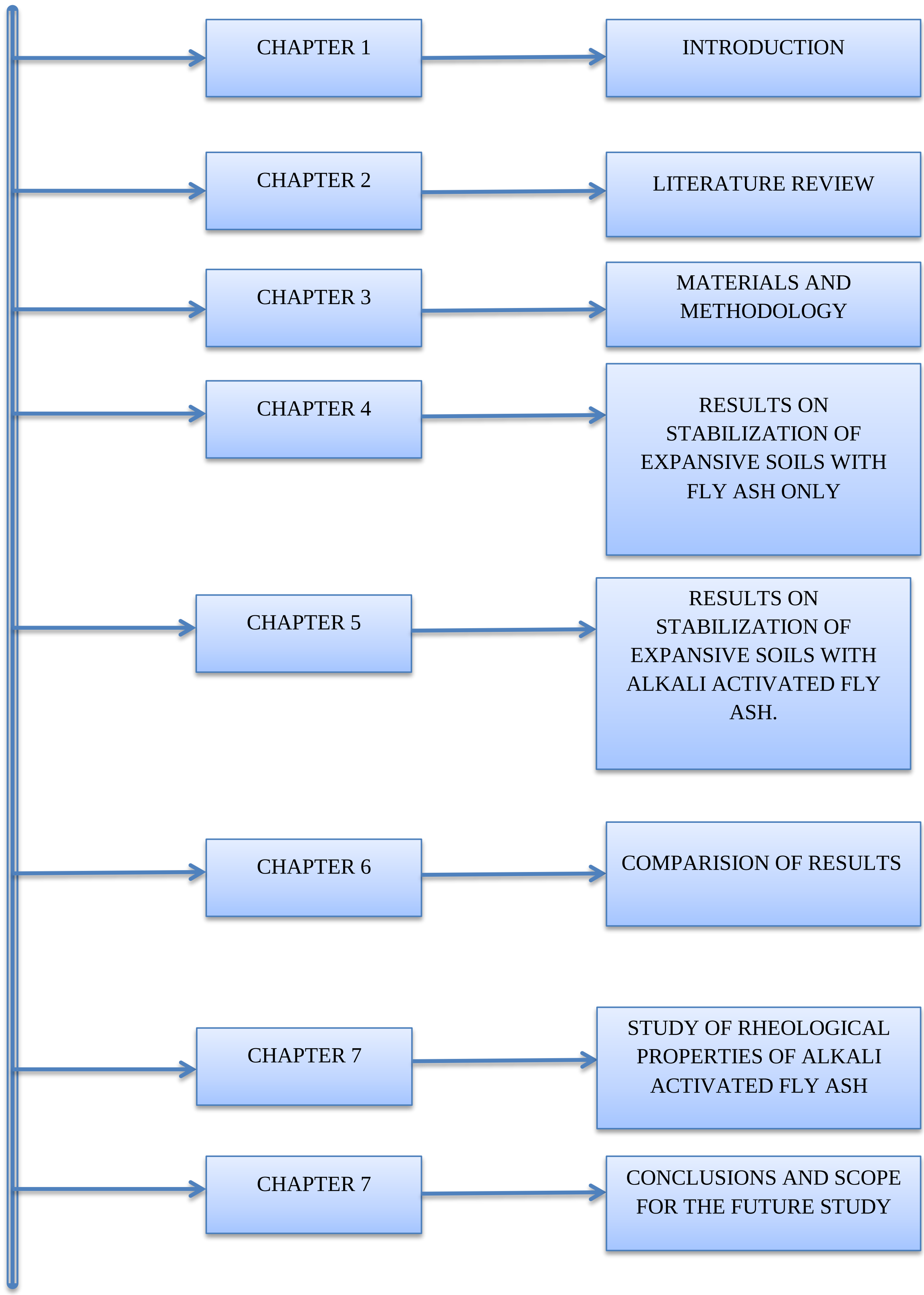

Figure 1.5 Basic outline of the thesis.

Chapter -2

Literature Review

2.1 INTRODUCTION

Stabilization is one of the methods of treating the expansive soils to make them fit for construction. Variety of stabilizers may be divided into three groups (Petry 2002): (a) traditional stabilizers (lime, cement etc.), (b) by-product stabilizers (fly ash, quarry dust, phosphor-gypsum, slag etc.) and (c) non-traditional stabilizers (sulfonated oils, potassium compounds, polymer, enzymes, ammonium chlorides etc.). Disposal of large quantities of industrial by products as fills on disposal sites adjacent to industries not only requires large space but also create a lot of geo-environment problems. Attempts are being made by various organizations and researchers to use them in bulk at suitable places. Stabilization of expansive soil is one way of utilization of these by products. Some of the research work conducted by earlier researchers on the above has been described below.

2.1.1 Stabilization using fly ash

Sharma *et al*. (1992) studied stabilization of expansive soil using mixture of fly ash, gypsum and blast furnace slag. They found that fly ash, gypsum and blast furnace slag in the proportion of 6: 12: 18 decreased the swelling pressure of the soil from 248 kN/m^2 to 17 kN/m^2 and increased the unconfined compressive strength by 300%.

Srivastava *et al*. (1997) studied the change in micro structure and fabric of expansive soil due to addition of fly ash and lime sludge from SEM photograph and found changes in micro structure and fabric when 16% fly ash and 16% lime sludge were added to expansive soil. Srivastava *et al*. (1999) have also described the results of experiments carried out to study the consolidation and swelling behaviour of expansive soil stabilized with lime sludge and fly ash and the best stabilizing effect was obtained with 16% of fly ash and 16% of lime sludge.

Cokca (2001) used up to 25% of Class-C fly ash (18.98 % of CaO) and the treated specimens were cured for 7 days and 28 days. The swelling pressure is found to decrease by 75% after 7 days curing and 79% with 28 days curing at 20% addition of fly ash.

Pandian *et al*. (2001) had made an effort to stabilize expansive soil with a class –F Fly ash and found that the fly ash could be an effective additive (about 20%) to improve the CBR of Black cotton soil (about 200%) significantly.

Turker and Cokca (2004) used Class C and Class F type fly ash along with sand for stabilization of expansive soil. As expected Class C fly ash was more effective and the free swell decreased with curing period. The best performance was observed with soil , Class C fly ash and sand as 75% , 15% and 10% respectively after 28 days of curing.

Satyanarayana *et al.* (2004) studied the combined effect of addition of fly ash and lime on engineering properties of expansive soil and found that the optimum proportions of soil: fly ash: lime should be 70:30:4 for construction of roads and embankments.

Phani Kumar and Sharma (2004) observed that plasticity, hydraulic conductivity and swelling properties of the expansive soil fly ash blends decreased and the dry unit weight and strength increased with increase in fly ash content. The resistance to penetration of the blends increased significantly with an increase in fly ash content for given water content. They presented a statistical model to predict the undrained shear strength of the treated soil.

Baytar (2005) studied the stabilization of expansive soils using the fly ash and desulpho-gypsum obtained from thermal power plant by 0 to 30 percent. Varied percentage of lime (0 to 8%) was added to the expansive soil-fly ash-desulphogypsum mixture. The treated samples were cured for 7 and 28 days. Swelling percentage decreased and rate of swell increased with increasing stabilizer percentage. Curing resulted in further reduction in swelling percentage and with 25 percent fly ash and 30 percent desulphogypsum additions reduced the swelling percentage to levels comparable to lime stabilization.

Amu *et al.* (2005) used cement and fly ash mixture for stabilization of expansive clayey Soil. Three different classes of sample (i) 12% cement, (ii) 9% cement + 3% fly ash and (iii) natural clay soil sample were tested for maximum dry densities (MDD), optimum moisture contents (OMC), California bearing ratio (CBR), unconfined compressive strength (UCS) and the undrained Triaxial tests. The results showed that the soil sample stabilized with a mixture of 9% cement + 3% fly ash is better with respect to MDD, OMC, CBR, and shearing resistance compared to samples stabilized with 12% cement, indicating the importance of fly ash in improving the stabilizing potential of cement on expansive soil.

Sabat *et al*. (2005) observed that fly ash-marble powder can improve the engineering properties of expansive soil and the optimum proportion of soil: fly ash: marble powder was 65:20: 15

Punthutaecha *et al*. (2006) evaluated class F fly ash, bottom ash, polypropylene fibers, and nylon fibers as potential stabilizers in enhancing volume change properties of sulfate rich expansive subgrade soils from two locations (Dallas and Arlington) in Texas, USA. Ash stabilizers showed improvements in reducing swelling, shrinkage, and plasticity characteristics by 20–80% , whereas fibers treatments resulted in varied improvements. In combined treatments, class F fly ash mixed with nylon fibers was the most effective treatment on both soils. They also discussed the possible mechanisms, recommended stabilizers and their dosages for expansive soil treatments.

Phanikumar and Rajesh (2006) discussed experimental study of expansive clay beds stabilized with fly ash columns and fly ash-lime columns. Swelling was observed in clay beds of 100 mm thickness reinforced with 30 mm diameter fly ash columns and fly ash-lime column. Heave decreased effectively with both fly ash and fly ash-lime columns, with, lime-stabilised fly ash yielded better results.

Wagh (2006) used fly ash, rock flour and lime separately and also in combination, in different proportion to stabilize black cotton soil from Nagpur Plateau, India. Addition of either rock-flour or fly ash or both together to black cotton soil improve the CBR to some extent and angle of shearing resistance increased with reduced cohesion. However, in addition to rock-flour and fly ash when lime is mixed to black cotton soil CBR value increases considerably with increase in both cohesion and frictional resistance.

Phani Kumar and Sharma (2007) studied the effect of fly ash on swelling of a highly plastic expansive clay and compressibility of another non-expansive high plasticity clay. The swell potential and swelling pressure, when determined at constant dry unit weight of the sample (mixture), decreased by nearly 50% and compression index and coefficient of secondary consolidation of both the clays decreased by 40% at 20% fly ash content.

Kumar *et al*. (2007) studied the effects of polyester fiber inclusions and lime stabilization on the geotechnical characteristics of fly ash-expansive soil mixtures. Lime and fly ash were added to an expansive soil at ranges of 1–10% and 1–20%, respectively. The samples with optimum proportion of fly ash and lime content (15% fly ash and 8% lime) based on compaction, unconfined compression and split tensile strength, were added with 0, 0.5, 1.0, 1.5, and 2% plain and crimped polyester fibers by weight. The MDD of soil-fly ash-lime mixes decreased with increase in fly ash and lime content. The polyester fibers (0.5–2.0%) had no significant effect on MDD and OMC of fly ash-soil-lime-fiber mixtures. However, the unconfined compressive strength and split tensile strength increased with addition of fibers.

Buhler *et al*. (2007) studied the stabilization of expansive soils using lime and Class C fly ash**.** The reduction in linear shrinkage was better with lime stabilization as compared to same % of Class C fly ash.

2.1.2 Stabilization using quarry dust

The quarry dust/ crusher dust obtained during crushing of stone to obtain aggregates causes health hazard in the vicinity and many times considered as an aggregate waste.

Gupta *et al*. (2002) made a study on the stabilization of black cotton soil using crusher dust a waste product from Bundelkhand region, India and optimal % of crusher dust(quarry dust) found to be 40%. There was decrease in liquid limit (54.10% to 24.2%), swelling pressure (103.6 kN/m^2 to 9.4 kN/m^2) and increases in shrinkage limit(12.05% to 18.7%), CBR value (1.91 % to 8.06%), UCS value (28.1 kN/m^2 to 30.2 kN/m^2) with 40% replacement of expansive soil with crusher dust.

Stalin *et al*. (2004) made an investigation regarding control of swelling potential of expansive clays using quarry dust and marble powder and observed that LL and swelling pressure decreased with increase in quarry dust or marble powder content.

Gulsah (2004) investigated the swelling potential of synthetically prepared expansive soil (kaolinite and bentonite mixture), using aggregate waste (quarry dust), rock powder and lime. Aggregate waste and rock powder were added to the soil at 0 to 25% by weight with lime varying from 0 to 9% by combined weight. There was reduction in the swelling potential and the reduction was increased with increasing percent stabilizers and days of curing.

Jain and Jain (2006) studied the effect of addition of stone dust and nylon fiber to Black cotton soil and found that mixing of stone dust by 20% with 3% randomly distributed nylon fibers decreased the swelling pressure by about 48%. The ultimate bearing capacity increased and settlement decreased by inclusion of fiber to stone dust stabilized expansive soil.

2.1.3 Stabilization using rice husk ash

Rice husks are the shells produced during dehusking operation of paddy, which varies from 20% (Mehta 1986) to 23% (Della *et al*. 2002) by weight of the paddy. The rice husk is considered as a waste material and is being generally disposed of by dumping or burning in the boiler for processing paddy. The burning of rice husk generates about 20% of its weight as ash (Mehta 1986). The silica is the main constituent of rice husk ash (RHA) and the quality (% of amorphous and unburnt carbon) depend upon the burning process (Nair *et al*. 2006). The RHA is defined as a pozzolanic material (ASTM C 168 ASTM 1997) due to its high amorphous silica content (Mehta 1986).

Rajan and Subramanyam (1982) had studied regarding shear strength and consolidation characteristics of expansive soil stabilized with RHA and lime and observed that RHA contributes to the development of strength as a pozzolanic material when used as a secondary additive along with lime and cement. Under soaked conditions, the soil stabilized with rice husk ash had low strength. The RHA, lime combination also decreased the compression index of stabilized soil.

Bhasin *et al*. (1988) made a laboratory study on the stabilization of Black cotton soil as a pavement material using RHA, bagasse ash, fly ash, lime sludge and black sulphite liquor with and without lime. The bagasse ash and black sulphite liquor are found to be not effective as a stabilizing agent. The addition of lime sludge alone to black cotton soil improves the CBR values marginally but reduces the UCS values. Lime sludge in combination with lime improves the strength parameters of black cotton soil sufficiently for its use as a sub-base material. The rice-husk ash causes greater improvement than that caused by fly ash and bagasse ash due to presence of higher % of reactive silica in rice-husk ash in comparison to fly ash and bagasse ash. In conjunction to lime both rice husk ash and fly ash improves the properties of black cotton soil sufficiently meriting its use as a sub-base material.

Muntohar and Hantoro (2000) used rice husk ash and lime for stabilization of expansive soil by blending them together. The RHA used were 7.5%, 10% and 12.5% and lime as 2%, 4%, 6%, 8%, 10% and 12% as replacement of expansive soil. Their PI (plasticity index) decreased from 41.25% to 0.96% and swell potential decreased from 19.23% to insignificant with 12-12.5% of RHA-lime mixture. There was also increase in CBR value (3 % to 16 %), internal friction angle (5^{0} to 24^{0}) and cohesion (54.32 kN/m^2 to 157.19 kN/m^2), there by increased bearing capacity to 4131 kN/m^2 from 391.12 kN/m^2

Chandrasekhar *et al.* (2001) presented the results of laboratory and field investigations carried out to understand the characteristics of black cotton soil with stabilizing agents like calcium chloride and sodium silicate in comparison with conventional RHA-lime stabilization**.** The RHA-lime stabilization resulted in maximum improvement and strength compared to all other treatment. Calcium chloride treated road stretch showed maximum reduction in ground heave compared to lime, sodium silicate and RHA stabilized stretches, but maximum reduction in shrinkage is observed in lime treated stretch, when additives are used individually. When additives are used in combination, Calcium chloride – sodium silicate treated stretched showed maximum reduction in heave compared to RHA– lime and calcium chloride-RHA stabilized stretches whereas highest reduction in shrinkage is observed in RHA- lime stabilized stretch.

Ramakrishna and Pradeep Kumar (2006) had studied combined effect of rice husk ash (RHA) and cement on engineering properties of black cotton soil. RHA up to 15% in steps of 5% and cement up to 12% in steps of 4% were added. RHA and cement reduced the plasticity of the expansive soil. The dry density of soil increased marginally with increase in

OMC after 4% cement addition. MDD of soil decreased and OMC increased with the increase in the proportion of RHA- cement mixes. The UCS of Black cotton soil increased linearly with cement content up to 8% and at 12%, strength rate reduced. The soaked CBR of the soil was found to be increased with cement and RHA addition. Similar trends to that of UCS were observed with the increase in CBR rate. At 8% cement content, CBR value of soil was 48.57% and with combination of RHA at 5%, 10% and 15%, the values were 54.68%, 60.56% and 56.62%, respectively.

Sharma *et al*.(2008) had studied the engineering behavior of a remolded expansive clay blended with lime, calcium chloride and Rice-husk ash . The amount of RHA, lime and calcium chloride were varied from 0 to 16%, 0 to 5% and 0 to 2% respectively by dry weight of soil . The effect of additives on UCS & CBR was found. The stress–strain behavior of expansive clay improved upon the addition of up to 5% lime or 1% calcium chloride. A maximum improvement in failure stress of 225 & 328% was observed at 4% lime & 1% calcium chloride. A RHA content of 12% was found to be the optimum with regard to both UCS & CBR in the presence of either lime or calcium chloride. An optimum content of 4% in the case of lime and 1% in the case of calcium chloride was observed even in clay – RHA mixes.

2.1.4 Stabilization using Copper Slag (CS)

Copper slag is produced as a by product of metallurgical operations in reverberatory furnaces. It is totally inert material and its physical properties are similar to natural sand.

Al-Rawas *et al*. (2002) made an investigation regarding the effectiveness of using cement by-pass dust, copper slag , granulated blast furnace slag, and slag-cement in reducing the swelling potential and plasticity of expansive soils from Al-Khod (a town located in Northern Oman). The soil was mixed with the stabilizers at 3, 6 and 9 % of the dry weight of the soil. The treated samples were subjected to liquid limit, plastic limit, swell percent and swell pressure tests. The study showed that copper slag caused a significant increase in the swelling potential of the treated samples. The study further indicated that cation exchange capacity and the amount of sodium and calcium cations are good indicators of the effectiveness of chemical stabilizers used in soil stabilization.

Saravan *et al*. (2005) stabilized the expansive soil using 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70% and 80% of dry weight of copper slag. The MDD increased, OMC decreased with increase in CS content and free swell index decreased by 60% corresponding to soil + 70% CS. However, the soaked CBR improved only after addition of 2% of cement and the expansive soil found to be suitable as a sub-grade material by utilizing 50% copper slag waste along with 2% cement.

2.1.5 Stabilization using silica fume (SF)

Silica fume, a co-product from the production of silicon or ferrosilicon metal, is an amorphous silicon dioxide - SiO_2 which is generated as a gas in submerged electrical arc furnaces during the reduction of very pure quartz. This gas vapor is condensed in bag house collectors as very fine powder of spherical particles that average 0.1 to 0.3 microns in diameter with a surface area of 17 - 30 m^2/g

Dayakar *et al*. (2003) conducted laboratory investigation for stabilization of expansive soil using silica fume and tannery sludge with percentage of solid wastes varying from 0, 10, 20, 30, 40, 50, 60- 70%. The addition of wastes did not improve the index properties & maximum dry density but there was gain in strength of the expansive soil with both tannery sludge and silica fume up to 15%.

El-Aziz *et al*. (2004) investigated the effect of the engineering properties of clayey soils when blended with lime and Silica Fume (SF). Based on a series of laboratory experiments with lime percentage varying from 1%, 3%, 5%, 7%, 9% and 11% and SF at 5%, 10% and 15%, the plasticity Index and swell potential decreased from 40.25% to 0.98% and from 19.0% to insignificant, respectively, at 11% lime and 15% of SF. There was considerable improvement in CBR value (3.0% to 17.0%), angle of internal friction (6^0 to 25^0) and cohesion (55.52 kN/m^2 to 157.54 kN/m^2). The consolidation settlement was lowered from 0.025 to 0.007m.

Khare *et al*. (2005) observed that addition of silica fume and aluminum sludge did not improve the index properties and maximum dry density of the expansive soil, but UCS values increased up to 10%. As the above wastes/ stabilizing agent have cementitious components, curing further increased its UCS value.

Kalkan and Akbulect (2004) studied the effect of silica fume on the permeability, swelling pressure and compressive strength of natural clay liners. The test results showed that the compacted clay samples with silica fume exhibit quite low permeability, swelling pressure and significantly high compressive strength as compared to raw clay samples.

2.1.6 Stabilization using other industrial wastes

Srinivasulu and Rao (1995) studied the effect of baryte powder as a soil stabilizer and added up to 20% of baryte powder to expansive soil. The PI, OMC and cohesion decreased and MDD, angle of internal friction and CBR values increase with increase in baryite powder and hence can be effectively used for any pavement construction in cohesive soil zones and for rural roads at minimum cost.

Swami (2002) had made the feasibility study for utilization of marble dust in highway sector. The marble dust was added up to 60% by an increment of 15% and found the optimum proportion of expansive soil: marble powder as 75:25. Plasticity Index decreased from 25.1% to 7% with 35% marble dust PI value at 15% and 25% marble powder were observed to be 15.37 %and 8.3%

respectively. The dry density increased from 17.56 kN/m^3 to 18.34 kN/m^3 with 45% marble dust, but CBR value increased (4.59 to 6.81%) upto 25% marble dust and decreased with further increase in marble powder.

Mishra and Mathur (2004) studied the stabilization of expansive soil with phosphogypsum (a waste product from phosphoric acid industry) and observed that soil mixed with different proportions of phosphogypsum reduces its liquid and plasticity limit thereby making the soil more workable. The free swell of the soil reduced considerably and the CBR value of the soil increased from 2% to 9 %, when 40% phosphogypsum was added. When the proportion of phosphogypsum was increased beyond 40%, the mix could not be compacted properly.

Wagh *et al*. (2004) added sludge's from three type of industry textile industry, paper mill and sugar factory, by 10%, 15%, 20% and 25% for improvement in soil properties of expansive soil. With addition of textile industry sludge the free swell index (FSI) decreased and MDD and UCS increased. Adding paper mill sludge UCS increased but decrease in MDD and no considerable effect on FSI. The FSI and MDD decreased and UCS increased with addition of sugar factory sludge.

Parsons *et al.* (2004) presented a summary of the performance of a wide range of soils (CH, CL, ML, SM, and SP) treated with cement kiln dust (CKD), to improve the texture, increase strength and reduce swell characteristics. Treatment with cement kiln dust was found to be an effective; strength and stiffness were improved and plasticity and swell potential were substantially reduced. Durability of CKD treated samples in wet-dry testing was comparable to that of soil samples treated with the other additives, while performance was not as good in freeze thaw testing. CKD treated samples performed very well in leaching tests and in many cases showed additional reductions in plasticity and some strength gains after leaching..

Koyuncu *et al*. (2004) used three types of ceramic waste, namely, ceramic mud wastes (CMW), crushed ceramic tile wastes (CCTW) and ceramic tile dust wastes (CTDW) for stabilization of expansive soil with Na-bentonite. Swelling pressure and swelling percent of Na-bentonite clay mixed with 40% CCTW decreased 86% and 57%, respectively.

Al-Rawas (2004) investigated the physical, engineering, chemical and microfabric characteristics of two soils from Oman treated with incinerator ash produced at Sultan Qaboos University. The soils were mixed with the incinerator ash at 0%, 10%, 15%, 20%, 25% and 30% by dry weight of the soils. The results showed that the incinerator ash used was a non-hazardous waste material. All treated samples showed a reduction in swell percent and cohesion, and an increase in angle of internal friction with the addition of incinerator ash for all curing periods and 20% and 30% additive showed reduction of swell percent of the soils

Amu *et al.* (2005) studied the effect of eggshell powder (ESP) on the stabilizing potential of lime on an expansive soil. Based on different engineering tests the optimal percentage of lime-ESP combination was attained at a 4% ESP + 3% lime. But, MDD, CBR value, UCS and undrained triaxial shear strength values indicated that lime stabilization at 7% is better than the combination of 4% ESP + 3% lime.

Mughieda *et al*. (2005) studied the feasibility of using composed olive mills solid by product (COMSB), a solid byproduct which causes environmental problems, in stabilization of expansive soil. With addition of COMSB by 2%-8% by weight, the PI, DD and UCS decreased. It was also found that the swell potential was reduced by 56%-65% and the swelling pressure reduced by 56%-72% corresponding to untreated soil. Slow direct shear test indicated that the stabilizing agent decreased the cohesion intercept while the angle of internal friction was increased by 45%-65%.

Nalbantoglu and Iawfin (2006) studied the stabilizing effect of Olive cake residue on expansive Soil. Olive cake residue is a by-product after olives have been pressed and olive oil extracted. Olive cake residue was heated up to 550 ^{O}C about 1 hour and the ash produced as a result of heating was added into the soil with 3, 5 and 7% by dry weight of soil. With olive cake residue upto 3%, there was reduction in plasticity, volume change, and an increase in unconfined compressive strength, but with further increase in olive cake residue UCS decreased and compressibility increased.

Red mud is a waste material generated by the Bayer Process widely used to produce alumina from bauxite throughout the world. Approximately, 35% to 40% per ton of bauxite treated using the Bayer Process ends up as red mud waste. Kalkan (2006) studied utilization of red mud as a stabilization material for the preparation of clay liners. The test results showed that compacted clay samples containing red mud and cement–red mud additives have a high compressive strength and decreased hydraulic conductivity and swelling percentage as compared to natural clay samples.

Degirmenci *et al*. (2007) investigated phosphogypsum with cement and fly ash for soil stabilization. Atterberg limits, standard Proctor compaction and unconfined compressive strength tests were carried out on cement, fly ash and phosphogypsum stabilized soil samples. Treatment with cement, fly ash and phosphogypsum generally reduces the plasticity index with increase in MDD with cement and phosphogypsum contents, but decreased as fly ash content increased. The OMC decreased and UCS increased with addition of cement, fly ash and phosphogypsum.

Seda *et al*. (2007) used waste tyre rubber for stabilization of highly expansive clays. The index properties and compaction parameters of the rubber, expansive soil, and expansive soil-rubber (ESR) mixture were determined. While the ESR mixture is more compressible than the untreated soil, both the swell percent and the swelling pressure are significantly reduced by the addition of rubber to the expansive soil. Attom *et al*. (2007) investigated the effect of shredded waste tire on the shear strength, swelling and compressibility properties of the clayey soil from northern part of Jordan. The shredded tires passed US sieve number 4 were added to the soil at 2%, 4%, 6%, and 8% by dry weight of soil. The test results showed that increasing the amount of shredded waste tires increased the shear strength and decrease plasticity index, maximum dry density, permeability, swelling pressure, swell potential and the compression index of the clayey soil.

Okagbue (2007) evaluated the potential of wood ash to stabilize clayey soil. Results showed that the geotechnical parameters of clay soil are improved substantially by the addition of wood ash. Plasticity was reduced by 35%, CBR, UCS increased by 23–50% and 49–67%, respectively, depending on the compactive energy used. The highest CBR and strength values were achieved at 10% wood ash.

Peethamparan and Jain (2008) studied four CKD with different chemical and physical characteristics in stabilizing Na-Montmorillonite Clay. All CKDs considerably decreased the plasticity index, thereby improving the workability of the clay, while they also considerably increased the initial pH value of clay, providing a favourable environment for further chemical pozzolanic reaction. The addition of CKDs and subsequent compaction substantially increased the UCS and the stiffness of the clay, thus improving its structural properties. The extent of improvement of the clay characteristics was found to be a function of the chemical composition of the particular CKD, specifically its free lime content. It was also found that the length of curing period after compaction had a major role in the stabilization process

Cokca *et al*. (2008) had utilized granulated blast furnace slag (GBFS), and GBFS -Cement (GBFSC) to overcome or to limit the expansion of an artificially prepared expansive soil sample (Sample A). GBFS and GBFSC were added to Sample A in proportions of 5 to 25 percent by weight. Effect of these stabilizers on grain size distribution, Atterberg's limits, swelling percentage and rate of swell of soil samples were determined. Effect of curing on swelling percentage and rate of swell of soil samples were also determined. Leachate analysis of GBFS, GBFSC and samples stabilized by 25 percent GBFS and GBFSC was performed. Use of stabilizers successfully decreased the amount of swell while increasing the rate of swell. Curing samples for 7 and 28 days resulted in less swell percentages and higher rate of swell. He had concluded that GBFS and GBFSC should not be used to stabilize expansive soils in regions near to the drinking water wells.

A concise literature review as above is presented in Table 2.1. From the studies of the available literature it is observed that various efforts have been made to study the possible utilisation of different industrial wastes for stabilisation of expansive soil.

Table 2.1 Comprehensive study on the stabilization of expansive soil using Industrial Wastes

SL.No	Types of waste	Investigation	Findings	Reference
1	Fly ash, Lime and Gypsum	SP and UCS	SP reduced and UCS of the soil increased	Sharma *et al*. (1992)
2	a)Fly ash and Lime sludge b)Fly ash and Lime sludge	a)Microstructure and Fabric b)Consolidation and SP	a)Remarkable change in micro structure and fabric, b) Improvement in consolidation and reduction in SP	a)Srivastava etal.(1997) b)Srivastava *et al*. (1999)
3	Class-C fly ashes	SP	75% decrease in SP with 7 days curing and 79% decrease in SP with 28 days curing	Cocka. (2001)
4	Class F Fly ash	CBR	20% addition of fly ash increased the CBR by 200%	Pandian etal.(2001)
5	Fly ash and randomly distributed Coir fibre	CBR	CBR values are improved and fibre inclusion increases both the strength and stiffness of the mix	Sivarama Krishna, K., *et al* .(2002)
6	Class C and F fly ash with sand	Swelling test	decrease in free swell	Turker *et al*. (2004)
7	Class F Fly ash and Lime	UCS, CBR and SP	UCS, CBR increased SP decreased.	SatyaNarayan *et al*. (2004)
8	Class F Fly ash	PI, K, SP, MDD, resistance to penetration	PI, K, SP, decreased MDD and resistance to penetration increased.	Phani Kumar *et al*.(2004)
9	Class F Fly ash and desulphogypsum	Swelling percentage and rate of swell	Swelling percentage and rate of swell decreased	Bayter (2005)

SL.No	Types of waste	Investigation	Findings	Reference
10	Fly ash and cement	Compaction, CBR, Shear	Improvement in MDD, OMC, Bearing Capacity and Shearing Resistance	Amu *et al*.(2005)
11	Fly ash and marble powder	UCS,CBR,SP	decrease in SP and increase in UCS and CBR	Sabat *et al* (2005)
12	Class F Fly ash, bottom ash, polypropylene fibers and Nylon fiber	Swelling, shrinkage and plasticity	Swelling and plasticity decreased , shrinkage limit increased	Punthutaecha *et al*. (2006)
13	Fly ash columns and Fly ash –Lime column	Sp	Sp decreased	Phani Kumar *et al*. (2006)
14	Fly ash, Lime and rock flour	CBR	CBR increased	Wagh(2006)
15	Fly ash	S_p, SP, Cc and coefficient of secondary consolidation.	S_p, SP, C_c and coefficient of secondary consolidation decreased.	Phani Kumar *et al*. (2007)
16	Fly ash ,lime and polyster fiber	UCS,CBR	Increase in strength and stiff ness	Kumar *et al* (2007
17	Class C fly ash, Lime	Linear shrinkage	Linear shrinkage reduced	Buhler *et al*.(2007)
18	Crusher dust	PI, SL, CBR, UCS , SP and FSI	PI, SP, FSI decreased, SL, CBR, UCS increased	Gupta *et al* (2002)
19	Quarry dust and Marble powder separately	SP, Sp, LL,	Ps, S_p, LL decreased	Stalin *et al*.(2004)

SL.No	Types of waste	Investigation	Findings	Reference
20	Aggregate waste, rock powder and lime	Particle size, PI, SL, Swelling potential	Increase in particle size and SL, reduction in PI and swelling potential,	Gulsah *et al*.(2004)
21	Saw Dust	Atterberg's limits, DFSI, CBR, Shear and K	Increased the LL, PL,, and SL,t but reduced the DFSI, CBR value both Soaked and Unsoaked increased by almost 100%, a marginal increase in shear strength and increase in K was also found.	Jain *et al*.(2006)
22	Rice Husk Ash (RHA) and Lime	Consolidation, and Shear strength	RHA slightly increased the Cv. In combination with lime it further increased Cv. RHA in combination with lime considerably decreases Cc	Rajan *et al*.(1982)
23	RHA, Fly ash, bagasse ash, Black sulphite liquor, Lime sludge with and without lime	UCS and CBR	UCS and CBR increased up to addition of certain % waste and lime and then decreased. However Black sulphite liquor, and bagasse ash did not improved the strength.	Bhasin *et al*.(1988)
24	Rice husk ash and Lime	PI, CBR, Sp Consolidation. Shear	PI, Sp, decreased, CBR,Φ, C, increased, consolidation settlement decreased	Muntohar *et al*.(2000)
25	$Cacl_2$, lime , Sodium Silicate (Na_2Sio_3) RHA , Lime + RHA, $Cacl_2$+RHA, ($Cacl_2$)+ (Na_2Sio_3)	Field and laboratory Investigation. UCS and CBR(lab) In-situ heave test & In-situ strength test	Lime –RHA treatment resulted in maximum improvement in strength and highest reduction in shrinkage.	Chandrasekhar *et al*. (2001)

SL.No	Types of waste	Investigation	Findings	Reference
26.	Rice husk ash and lime	UCS and CBR	UCS and CBR values change with changes in molding water content	Ramakrishna *et al*. (2008)
27.	Rice husk ash , $cacl_2$ and lime	UCS and CBR	Improvement in UCS and CBR values	Sharma *et al*. (2008)
28.	Cement by-pass dust, copper slag, granulated blast furnace slag, and slag-cement	Sp and PI,	Copper slag caused a significant increase in the Sp, Other stabilizers reduced the Sp and plasticity at varying degrees.	Al-Rawas *et al*.(2002)
29.	Copper slag, Cement	FSI,CBR	FSI decreased ,CBR increased	Sarvan Kumar *et al*. (2005)
30.	Silica fume ,Tannery sludge(separately)	Index properties, Compaction, and UCS	Index properties and MDD did not improved.UCS increased up to 10% addition of waste, curing further increased strength	Dayakar(2003)
31.	Silica Fume and lime	PI, SP , CBR and Shear	PI, Sp, and Consolidation settlement was decreased CBR value, Internal friction angle and Cohesion increased.	El-Aziz *et al*.(2004)
32.	Silica fume	K,SP,, UCS, and lechate test	K, SP, decreased, UCS increased and lechate did not affect.	Kalkan(2004)

SL.No	Types of waste	Investigation	Findings	Reference
33.	Silica fume, aluminium sludge	Index properties, MDD & UCS	Index properties and MDD did not improve. UCS increased up to 10% addition of sludge.	Khare(2005)
34.	Baryte powder	P.I. ,Compaction, shear, UCS, CBR, DFS	PI, DFS, OMC decreased, MDD, CBR increased.	Srinivasulu (1995)
35.	Marble dust	PI, Compaction, CBR	PI decreased ,MDD and CBR increased	Swami *et al* (2002)
36.	Phosphogypsum	PI. Free Swell percentage, UCS, Soaked CBR, Direct Shear	The plasticity index of the soil goes decreasing up to 40% addition, The free swell of the soil reduced considerably and the CBR value of the soil increased from a value of 2%, to a value of 9 %, when 40% phosphogypsum was added.	Mishra(2004)
37.	Textile industry paper mill & sugar factory sludge	FSI,MDD,UCS	(i) Textile industry sludge -FSI decreased , MDD & UCS increased ii)paper mill sludge- No considerable effect on FSI , UCS increased but MDD decreased iii)sugar factory sludge -FSI,MDD decreased but UCS increased	Wagh(2004)
38.	Cement Kiln dust	Strength ,swell, durability and leaching	Improvement in properties were found but performance was not good in freeze –thaw cycles.	Person(2004)
39.	Crushed ceramic tile	Sp and SP	Sp and SP of Na-bentonite clay mixed with 40% crushed ceramic tile wastes (CCTW) decreased 86%	Koyuncu(2007)

SL.No	Types of waste	Investigation	Findings	Reference
	wastes		and 57%, respectively.	
40.	Incinerator ash	LL,,PL,, Sp,, direct shear, curing for 1, 7 and 14 days and SEM	Increase in PL, Reduction in LL, Sp, and C, and an increase in Φ with the addition of incinerator ash for all curing periods. The use of 20% and 30% additive showed clearly the development of aggregations that contributed to reduction of swell per cent of the soils	Al-Rawas(2004)
41.	Eggshell Powder(ESP)	Compaction, UCS,CBR	MDD, CBR, UCS and Undrained triaxial shear strength test all indicated that lime stabilization at 7% is better than the combination of 4% ESP + 3% lime.	Ammu (2005)
42.	Composted olive mills solid by product(COMSB)	Atterberg's limits, UCS,, direct shear strength, standard Proctor density, and Ps	Decrease in PI, MDD, UCS. Sp was reduced by up to 56% to 65% and the SP was reduced by up to 55% to 72%, decrease in C and Φ was increased by up to 45% to 67%.	Mugheida *et al.*(2005)
43.	Olive Cake residue	PI, UCS, Consolidation	An addition only 3% burned olive waste in the soil causes a reduction in Plasticity, volume change, and an increase in UCS, a greater amount than 3% caused a decrease in UCS , increase in compressibility.	Nalbantoglu (2006)
44.	Red mud and Cement	PI , K, UCS, Sp	The test results show that compacted clay samples containing red mud and cement–red mud additives have a high compressive strength and decreased the hydraulic conductivity and Sp as compared to natural clay samples.	Kalkan *et al.*(2006)
45.	Phosphogypsum with cement and fly ash	Atterberg's limits, standard Proctor	Reduced the PI. , MDD increased as cement and phosphogypsum contents increased, but decrease as fly ash content increases. Generally optimum	DegirMenci *et al.*(2006)

SL.No	Types of waste	Investigation	Findings	Reference
		compaction and UCS	moisture contents of the stabilized soil samples decrease with addition of cement, fly ash and phosphogypsum. UCS of untreated soils was in all cases lower than that for treated soils. The cement content has a significantly higher influence than the fly ash content.	
46.	Waste tire rubber	a) Sp and SP b) PI, compaction. Ps, Sp, consolidation	a) Sp and SP both decreased. b) Increasing the amount of shredded waste tires will increase the shear strength and decreased, PI, MDD,K, Sp and SP and Cc	Seda *et al*. (2007)
47.	Waste tire rubber	a) Sp and SP b) PI, compaction. Ps, Sp, consolidation	a) Sp and SP both decreased. b) Increasing the amount of shredded waste tires will increase the shear strength and decreased ,PI, MDD,K, Sp and Ps and Cc	Attom *et al*. (2007)
48.	Wood ash	PI, CBR	PI was reduced and CBR and strength increased by 23–50% and 49–67%, respectively, depending on the comp active energy used. The highest CBR and strength values were achieved at 10% wood ash. Curing improved the strength of the wood ash-treated clay.	Okagbue(2007)
49.	Cement kiln dusts	PI, Compaction, UCS	Decreased the PI, increased the UCS and the stiffness	Peethamparan *et al*.(2008)
50.	Granulated Blast Furnace Slag (GBFS), GBFS -Cement	Grain size distribution, Atterberg's limits, Swelling	Decreased the amount of swell while increasing the rate of swell. Curing samples for 7 and 28 days resulted in less	Cokca *et al*. (2008)

SL.No	Types of waste	Investigation	Findings	Reference
	(GBFSC)	percentage and Rate of swell. Effect of curing on swelling percentage and rate of swell, Leachate analysis	swell percentages and higher rate of swell	

2.1.7 Alkali activated Fly Ash:

Under replacement of 30% and 60% cement by gypsum activated class F fly ash (addition of gypsum is 3% and 6% respectively); strength is gradually increased which is comparable with no activated fly ash- cement paste (Aimin and Sarkar 1991). Compressive strength is directly related to NaOH concentration and curing temperature i.e. fly ash activated by 4M NaOH concentration has maximum compressive strength that cured under 90°C temperature (Katz 1998) and it is concluded that activation of fly ash in blended cement depends on - i) pH of activating material, ii) ratio between activator and fly ash. By author (Fan et al. 1999) AFA behaves as setting as well as hardening accelerator and its pozzolanic reactivity is higher than that of FA in both earlier and longer hydration periods. It is concluded that strength becomes higher at 1 day by adding 5 to 10 % of AFA in cement paste which is continue the same level for 3 days and 28 days of testing. Mechanical strength is affected by temperature of curing and type of activator used. But for class F fly ash that activated by combination of sodium hydroxide and sodium silicate has highest compressive strength at 85°C temperature of curing that maintain for 2hr duration (Palomo et al. 1999). Again author invented that alkali activated fly ash is smooth, glassy, and shiny in nature having good workability condition at very low liquid/solid ratio, but strength is much smaller for 24hr duration of curing. Strength of the fly ash/slag cement which is activated by 10M of sodium hydroxide is higher under 25˚C temperature of curing but it becomes lower at the longer ages of curing (Puertas et al. 2000). Strength of blended cement formed by combination of 47% Portland cement clinker, 50% activated fly ash developed after sintering at 1260°C of pellet of size less than 15mm size (pellet = 75% FA+ 10% LS +10% clay + 5% coke breeze powder + water) and 3% gypsum is observed as like as 33 grade cement (Behera et al. 2000), but it can be satisfactory as per BIS specification up to 40% replacement of that activated fly ash having superior quality than ordinary Portland cement. Brough et al. (2001), it is observed that calcium silicate hydrate (C-S-H), the binding phase normally formed by hydrating cements but zeolites is formed during adiabatic curing up to 90°C. They found the spacing of C-S-H phase in OPC system is 1.1 nm which is more crystalline in nature with longer chain length and higher aluminum content. Again short term mineralogy is greatly affected by changing the curing condition and long term mineralogy is affected by final curing temperature. At last it is concluded that after 14 days of hydration, compressive strength is reduced due to recrystallization of the calcium silicate hydrate or C-S-H gel or its conversion to zeolites. Activation by sodium silicate and potassium hydroxide, kaolinite at different ratio, it is observed that- Ca & Mg salt shorten the setting time through heterogeneous nucleation effect but K salt retard the setting time only to the cement when the initial solution for solid activation is low in soluble silicate concentration (Lee & Deventer 2002). C-S-H product formed by Ca/Si ratio (1.4 approx.) of fly ash-CH paste activated by 0.2 M sodium hydroxide is lower than hydrated of Portland cement (William et al. 2002) but rate of hydration is directly depend on the content of CH-fly ash in the mixture. That activated fly ash possess the mineral phase of calcium bearing complex silicate containing quartz as major and mullite as minor phase (Behera et al. 2002). By same author it is concluded that strength and deformation characteristics of sintered fly ash aggregate concrete is similar to concrete with natural granite aggregate (Behera et al. 2004). Compressive strength of alkali activated fly ash cement paste (i.e. 10% cement + 10% NaOH + 15% sodium silicate + 5% MnO2 + 60% fly ash) is higher i.e. 33.9 MPa which is cured at room temperature after 24hr of moisture curing at 50˚C and compressive strength of concrete using alkali activated fly ash light weight aggregate is 26.47MPa (Jo et al. 2007). Calcium is the major source of expansive nature that formed during gel formation created by alkali-silica reaction and this expansion is less than ordinary Portland cement (Lodeiro et al. 2007). Activated fly ash has better mechanical strength due to formation of amorphous sodium aluminosilicate gel and that zeolite formation is directly related to curing age under the temperature 85°C (Criado et al. 2007). Mechanical activation fly ash has capable to enhanced blended cement, extensively variation of geopolymer products like high strength geopolymer cements (i.e. Up to 120 MPa), self-glazed geopolymer tiles, geopolymer pavement tile (Kumar et al. 2007).

Amorphous gel formation is observed from primary reaction of alkali activated fly ash whose Si/Al ratio depends on curing time and nature of alkaline activator (Criado et al. 2008). However they invented that structure, composition, kinetics of that amorphous gel is caused due to silica which is stable initially by cyclic silicate trimmers which retard the latter reaction of fly ash. Two supplementary materials i.e. Zeolite gives highest strength with best sulfate resistance and bentonite behaves as filler creating more compact structure in alkali activated fly ash (Mingyu et al. 2009). High mechanical strength with low permeability, porosity and water demand is observed in alkali activated fly ash binders by using modified nanosilica as activator (Rodriguez et al. 2013). Mortar formed by fly ash and slag that activated with combination of sodium hydroxide pellet and sodium silicate solution has highest compressive strength and flexural strength than OPC mortar with lower water absorption (Chi & Huang 2013). Pore structure of alkali activated fly ash is lower with increase of curing time and it is caused due to increase the amount of silica and alkali content, but it can be develop with extending the curing time and temperature (Ma et al. 2013). Also author invented that water permeability of activated fly ash is higher at later ages but that become lower with progress of curing time, temperature, and higher content of silica at later ages.

Chapter -3

Materials and Methodology

3.1 Materials

3.1.1 Expansive Soil:-

In the present investigation, expansive black cotton soil was procured from a site having coordinates as N 21° 12' 34.03" and S 79° 09' 29.09", Khairi, Kanli road, Nagpur, Maharashtra. The black cotton soil was collected by method of disturbed sampling after removing the top soil at 500 mm depth and transported in sacks to the laboratory. Little amount of the sample was sealed in polythene bag for determining its natural moisture content. The soil was air dried, pulverized and sieved with 4.75 mm Indian as required for laboratory test. The various geotechnical properties are shown in Table 3.1

Table 3.1 Geotechnical Properties of Expansive soil

SL.NO	PROPERTIES	CONFIRMING TO IS CODE	VALUE
1	Coefficient of uniformity (Cu)	IS 2720 : Part 4 : 1985	2.43
2	Coefficient of curvature (Cc)	IS 2720 : Part 4 : 1985	0.51
3	Specific gravity (G)	IS 2720 : Part 3 : Sec 1 : 1980	2.64
4	Maximum dry density (MDD)	IS 2720 : Part VII : 1980	1.55 gm/cc
5	Optimum moisture content (OMC)	IS 2720 : Part VII : 1980	23.31%
6	Natural moisture content	IS 2720 : Part 2 : 1973	7.11%
7	Free swell index	IS 2720 : Part XL : 1977	100%
8	Liquid limit	IS 2720 : Part 5 : 1985	72%
9	Plastic limit	IS 2720 : Part 5 : 1985	21%
10	Swelling pressure	IS 2720 : Part XLI : 1977	6 kg/cm^2
11	Classification	IS 1498	CH

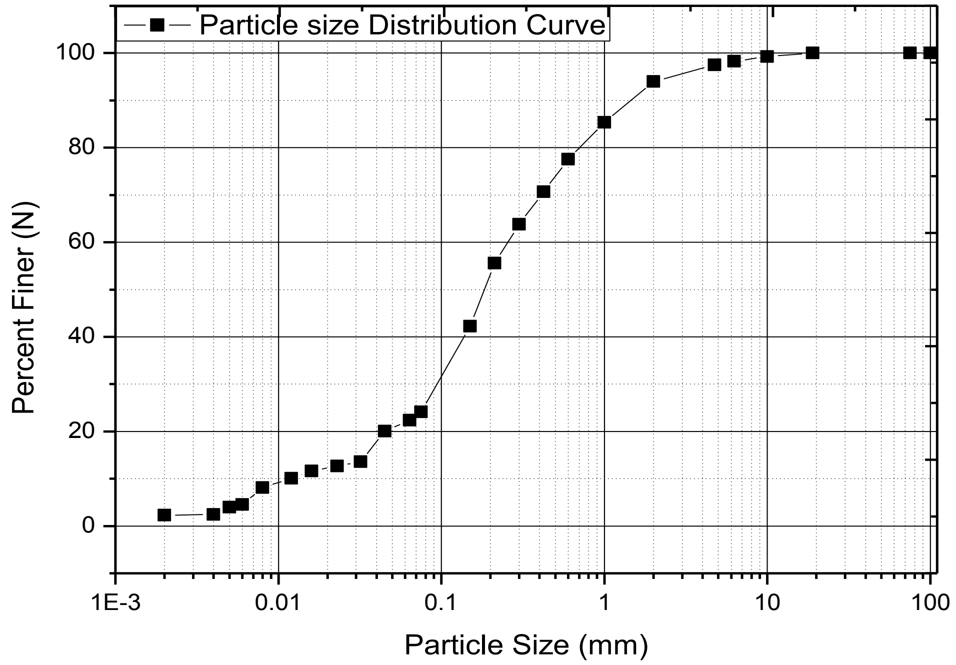

Figure 3.1 Grain size distribution curve of Soil

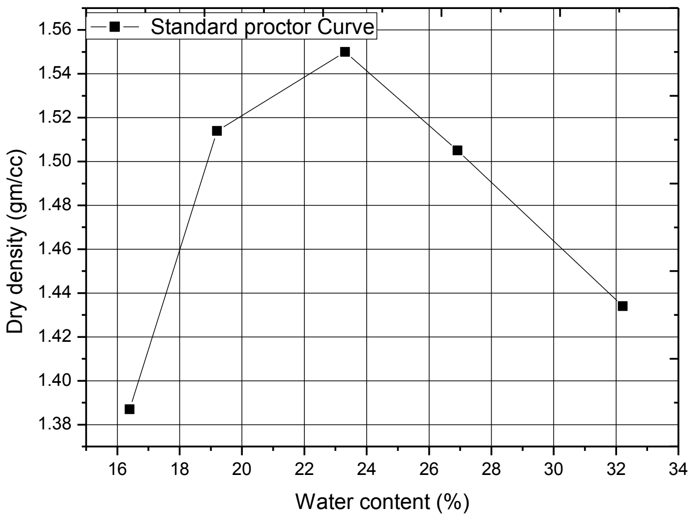

Figure 3.2 Standard proctor curve

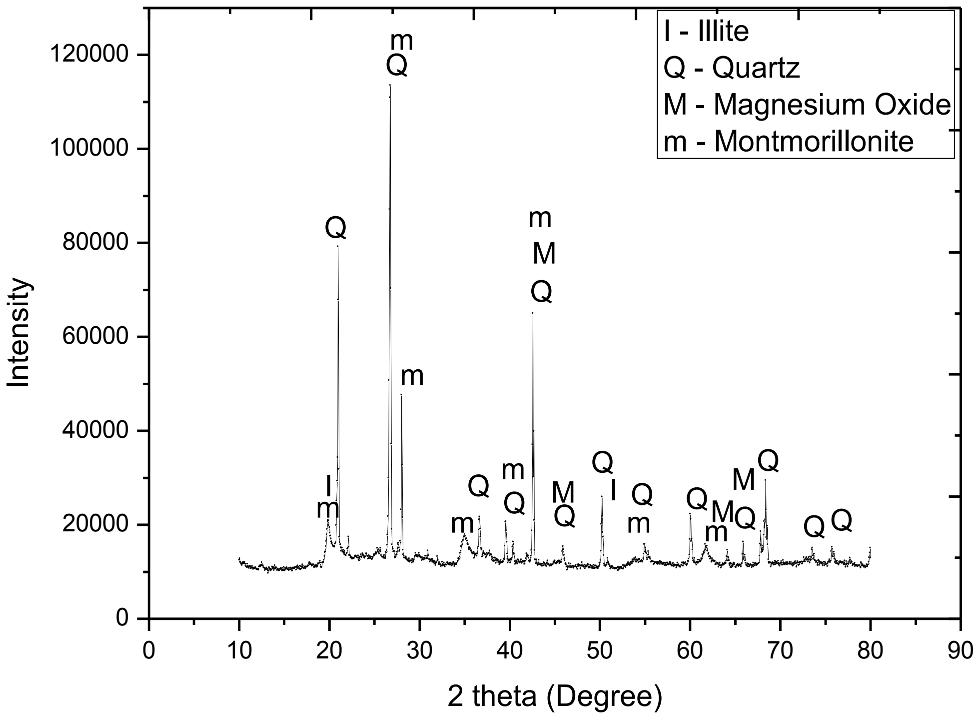

Fig 3.3 XRD analysis of Expansive soil

3.1.2 Fly ash:-

The fly ash is light weight coal combustion by product, which result from the combustion of ground or powdered bituminous coal, sub-bituminous coal or lignite coal. Fly ash is generally separated from the exhaust gases by electrostatic precipitator before the flue gases reach the chimneys of coal-fired power plants. Generally this is together with bottom ash removed from the bottom of the furnace is jointly known as coal ash. The fly ash is highly heterogeneous material where particles of similar size may have different chemistry and mineralogy. There is variation of fly ash properties from different sources, from same source but with time and with collection point (Das and Yudhbir, 2005). Fly ash contains some un-burnt carbon and its main constituents are silica, aluminium oxide and ferrous oxide. In dry disposal system, the fly ash collected at the bottom of the mechanical dust collectors and ESPs. From the dry storage silos also fly ashes are collected in closed wagons or moisture proof bags or metallic bins, if the quality of the fly ash is good. The dry fly ash so collected is then transported to the required locations where it is subjected to further processing before its use in many non-geotechnical applications such as cement industry, brick manufacturing and the like. In the present study fly ashes were collected from the captive power plant of National Aluminium Company Ltd, Angul, Odisha. After procuring, the fly ash samples were screened through 2 mm IS sieve, to separate out the vegetative and foreign material. To get a clear homogeneity, the samples are mixed thoroughly and heated in an oven maintained at 105-110 ^{0}C for 24 hours and then is stored in an air tight container, for subsequent use.

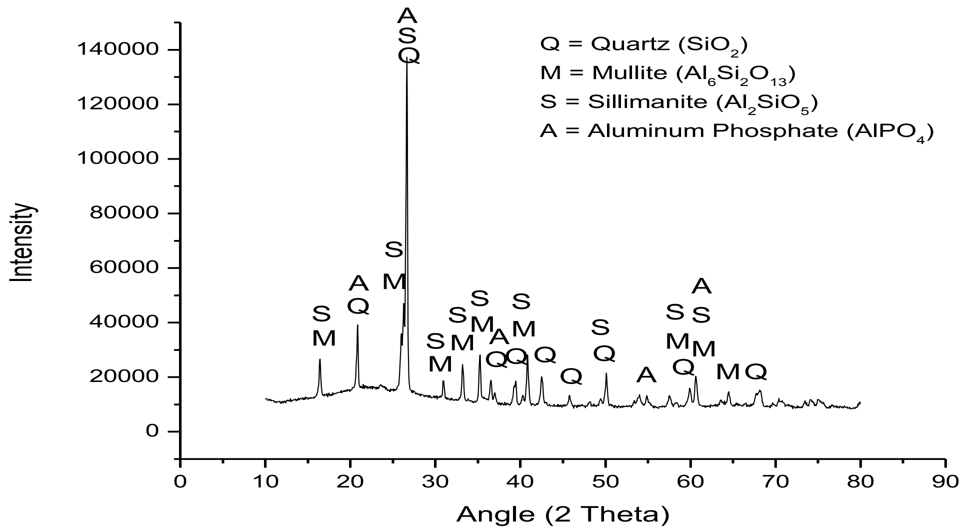

Figure 3.4 XRD analysis of fly ash

Table 3.2 Compounds present in Fly ash

Compounds	Composition (%)
SiO_2	41.65
Al_2O_3	22.38
Fe_2O_3	15.04
MgO	4.76
CaO	4.75

K_2O	5.82
Na_2O	4.72

3.1.3 Activator solution

The alkaline activator solution used was a combination of sodium silicate and sodium hydroxide. The sodium silicate was originally in powder form and is procured Loba Chemie, Thane Maharashtra, having molecular weight of 284.20 gm/mole and specific gravity of 1.5. While the sodium hydroxide was originally in flake form with a molecular weight of 40 gm/mole, and specific gravity of 2.13 at 20º C and 95-99% purity. The sodium hydroxide pellets were procured from Merck specialities Pvt. Ltd. Mumbai, Maharashtra, India.

1 mole of Sodium silicate solution was prepared by adding 284.20 gm of sodium silicate powder to 1 litre of distilled water. NaOH of different concentrations of 10, 12.5, 15 molal were prepared before testing. The ratio of sodium silicate to sodium hydroxide solution by mass was kept as 2. This value was chosen not only because the silicate is considerably cheaper than the hydroxide, but also because several studies that have analysed the influence of the activator composition concluded that higher ratios resulted in higher strength levels.

3.2 Methodology Adopted:-

To evaluate the effect of the ash/soil ratio (by dry mass) on mechanical strength, three different fly ash percentages, regarding the total solids (soil + ash) weight, were used: 20, 30 and 40 %, corresponding to ash/soil ratios of 0.25, 0.43 and 0.67, with activator/total solids ratios of 0.15, 0.2 and 0.25. The details of the experimental specimens are shown in Table 3.3 The soil and the ash were previously homogenised before the activator was added to the mixture. After mixing for 3 min, the samples were cast into 50-mm moulds by tapping the moulds on the lab counter, which were then left in a sealed container. Since the behaviour of the mixtures was that of a viscous fluid, no density control was used during the preparation of the samples. However, when removed from the moulds, every sample was weighted, and an average unit weight of 20 kN/m^3 was obtained, regardless of the fly ash percentage in the mixture. The 15 molal mixtures showed a very high viscosity which made the preparation and handling process more difficult than with the remaining concentrations, to a point where this factor should be considered when designing future studies and/or applications. This effect is related to the SiO2 : Na2O mass ratio of the silicate + hydroxide solution which, for the 15 molal activator, is approximately 1, making the metasilicate solution very unstable and favouring crystallisation. This SiO2 : Na2O mass ratio was, in the original silicate solution, approximately 2, but the addition of the hydroxide solution reduced it significantly, especially in the 15 molal mixtures. After 48 h, the samples were removed from the moulds and wrapped in cling film and left at ambient temperature and humidity conditions (50–60 % RH and 32-35º C). Immediately before testing, at the ages of 3, 7 and 28 days, the samples were trimmed to 100 mm long and tested for unconfined compressive strength (UCS) on an Aimil hydraulic testing machine. Every single result obtained was the average of 3 tested samples. The details of the alkaline activator mixed soil specimens are shown in Table 3.3

Figure 3.5 Photographic image of Samples wrapped in cling film.

Sl No	Name of the specimen	Particular of the mix
1	AF-100-20-15	Soil + 20% fly ash by weight of total solids + 10 molal 15% alkali activator by weight of total solids.
2	AF-100-30-15	Soil + 30% fly ash by weight of total solids + 10 molal 15% alkali activator by weight of total solids.
3	AF-100-40-15	Soil + 40% fly ash by weight of total solids + 10 molal 15% alkali activator by weight of total solids.
4	AF-100-20-20	Soil + 20% fly ash by weight of total solids + 10 molal 20% alkali activator by weight of total solids.
5	AF-100-30-20	Soil + 20% fly ash by weight of total solids + 10 molal 20% alkali activator by weight of total solids.
6	AF-100-40-20	Soil + 20% fly ash by weight of total solids + 10 molal 20% alkali activator by weight of total solids.
7	AF-100-20-25	Soil + 20% fly ash by weight of total solids + 10 molal 25% alkali activator by weight of total solids.
8	AF-100-30-25	Soil + 20% fly ash by weight of total solids + 10 molal 25% alkali activator by weight of total solids.
9	AF-100-40-25	Soil + 20% fly ash by weight of total solids + 10 molal 25% alkali activator by weight of total solids.
10	AF-125-20-15	Soil + 20% fly ash by weight of total solids + 12.5 molal 15% alkali activator by weight of total solids.
11	AF-125-30-15	Soil + 30% fly ash by weight of total solids + 12.5 molal 15% alkali activator by weight of total solids.
12	AF-125-40-15	Soil + 40% fly ash by weight of total solids + 12.5 molal 15% alkali activator by weight of total solids.
13	AF-125-20-20	Soil + 20% fly ash by weight of total solids + 12.5 molal 20% alkali activator by weight of total solids.
14	AF-125-30-20	Soil + 20% fly ash by weight of total solids + 12.5 molal 20% alkali activator by weight of total solids.
15	AF-125-40-20	Soil + 20% fly ash by weight of total solids + 12.5 molal 20% alkali activator by weight of total solids.

16	AF-125-20-25	Soil + 20% fly ash by weight of total solids + 12.5 molal 25% alkali activator by weight of total solids.
17	AF-125-30-25	Soil + 20% fly ash by weight of total solids + 12.5 molal 25% alkali activator by weight of total solids.
18	AF-125-40-25	Soil + 20% fly ash by weight of total solids + 12.5 molal 25% alkali activator by weight of total solids.
19	AF-150-20-15	Soil + 20% fly ash by weight of total solids + 15 molal 15% alkali activator by weight of total solids.
20	AF-150-30-15	Soil + 30% fly ash by weight of total solids + 15 molal 15% alkali activator by weight of total solids.
21	AF-150-40-15	Soil + 40% fly ash by weight of total solids + 15 molal 15% alkali activator by weight of total solids.
22	AF-150-20-20	Soil + 20% fly ash by weight of total solids + 15 molal 20% alkali activator by weight of total solids.
23	AF-150-30-20	Soil + 20% fly ash by weight of total solids + 15 molal 20% alkali activator by weight of total solids.
24	AF-150-40-20	Soil + 20% fly ash by weight of total solids + 15 molal 20% alkali activator by weight of total solids.
25	AF-150-20-25	Soil + 20% fly ash by weight of total solids + 15 molal 25% alkali activator by weight of total solids.
26	AF-150-30-25	Soil + 20% fly ash by weight of total solids + 15 molal 25% alkali activator by weight of total solids.
27	AF-150-40-25	Soil + 20% fly ash by weight of total solids + 15 molal 25% alkali activator by weight of total solids.

Table 3.3 Details of alkali-activated fly ash mixed soil specimens

For the fly ash based mixtures, water to solid of 15, 20, 25 and 30% were tested. In terms of fly ash percentage in the mixtures, values of 20, 30 and 40 % of the total dry weight were used. These values are used so as to have a direct comparison with the activated ash could be established. The details of the mix prepared is as shown in Table 3.4

Sl No	Name of the specimen	Particular of the mix
1	F-15-20	Soil + 20% fly ash by weight of total solids + 15% water by weight of total solids.
2	F-15-30	Soil + 20% fly ash by weight of total solids + 15% water by weight of total solids.
3	F-15-40	Soil + 20% fly ash by weight of total solids + 15% water by weight of total solids.
4	F-20-20	Soil + 20% fly ash by weight of total solids + 20% water by weight of total solids.
5	F-20-30	Soil + 20% fly ash by weight of total solids + 20% water by weight of total solids.
6	F-20-40	Soil + 20% fly ash by weight of total solids + 20% water by weight of total solids.
7	F-25-20	Soil + 20% fly ash by weight of total solids + 25% water by weight of total solids.
8	F-25-30	Soil + 20% fly ash by weight of total solids + 25% water by weight of total solids.
9	F-25-40	Soil + 20% fly ash by weight of total solids + 25% water by weight of total solids.

Table 3.4 Details of fly ash mixed soil specimens

The rheological studies include measurement of density and viscosity of both cement and alkali-activated grouts and comparison between the two, with the purpose of determining how much time is available before mixing with the soil. For this Marsh funnel viscometer confirming to IS 14343:1996 was used to calculate the viscosity of both the grouts. By using this viscometer we can measure the time taken for a known volume of liquid to flow from the base to the bottom end of the inverted funnel. The liquid was poured through the top, saturating the voids in the sand until it reached the top level, which used approximately 1.5 litres. The bottom exit was then released and the liquid flowed into a measuring container, while the time spent was recorded.

Setting time was ascertained by using Vicat's apparatus. Each grout was poured in the mould in the view point of calculating its initial and final setting time.

Figure 3.6 Experimental Setup of Marsh Funnel Viscometer

Chapter -4

Results on stabilization of expansive soils with fly ash

4.1 Introduction:

This chapter presents the results of stabilization of expansive black cotton soil, with fly ash. The increase in strength criteria is ascertained by conducting unconfined compression test on samples, at 3, 7 and 28 days curing. The samples, casted were of 50 mm diameter and 100 mm height, thereby ensuring L/D ratio as 2. These samples contains fly ash in 20, 30 and 40% by weight of dry mass and water to total solid ratio is varied from 15, 20 and 25%. All the samples were covered with cling film, after casting and are kept in a air tight container for 48 hours. After 48 h, the samples were removed from the moulds and wrapped in cling film and left at ambient temperature and humidity conditions (50–60 % RH and 32-35º C). Immediately before testing, at the ages of 3, 7 and 28 days, the samples were trimmed to 100 mm long and tested for unconfined compressive strength (UCS) on an Aimil hydraulic testing machine at constant strain rate of 1.2 mm/min. Every single result obtained was the average of 3 tested samples.

Figure 4.1 Photographic image showing test setup of UCS

4.2 Results

Following are the test results obtained:-

Table 4.1 UCS results of F-15-20, F-15-30, F-15-40

Curing Time (Days)	Unconfined compressive strength (kPa)		
Specimen Name	F-15-20	F-15-30	F-15-40
3	104.97	98.58	82.6
7	283.22	219.64	144.68
28	363.65	279.93	254.9

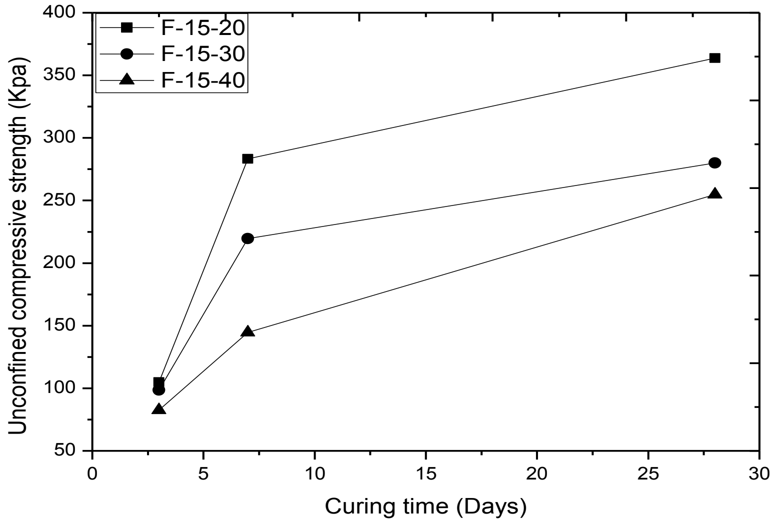

Figure 4.2 UCS results of F-15-20, F-15-30, F-15-40

It is evident from the Table 4.1, that the mix F-15-20, is giving more strength at 3, 7 and 28 days than the other two. The 3 day strength of F-15-20 is 6 % more than that of F-15-30 and 27 % more than that of F-15-40. Similarly the 7 day strength of F-15-20 is 29% more than that of F-15-30 and is about 96% more than that of F-15-40. Moreover the 28 day strength of mix F -15-20 is nearly 30% more than that of F-15-30 and is 43 % more than that of F-15-40. The variations of strength of the mixes are shown in Figure 4.2. and it can be stated as the strength of the mix is directly proportional to the curing period and is inversely proportional to the fly ash content in the mix. Thus it can be concluded that for a constant water to total solid ratio, the strength increases with the curing period and also with the decreased fly ash content.

Table 4.2 UCS results of F-20-20, F-20-30, F-20-40

Curing Time (Days)	Unconfined compressive strength (kPa)		
Specimen Name	F-20-20	F-20-30	F-20-40
3	85.69	120.5	91.7
7	113.98	131.5	101.77
28	141.93	156.25	125.94

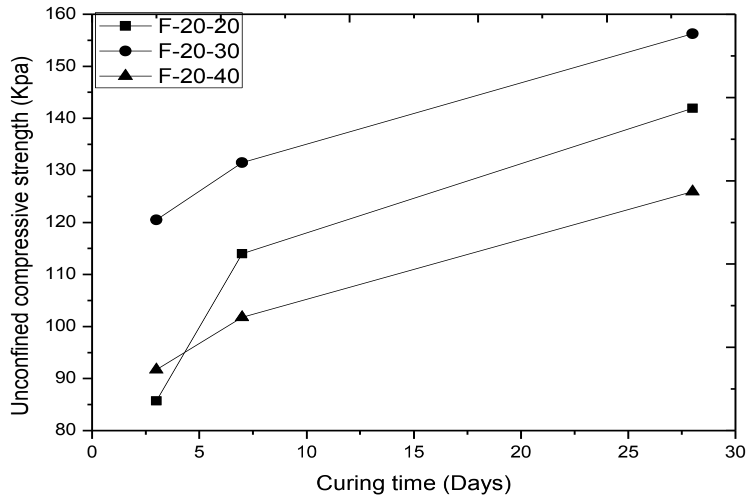

Figure 4.3 UCS results of F-20-20, F-20-30, F-20-40

Table 4.2 shows the UCS values of the samples F-20-20, F-20-30, F-20-40, obtained after 3, 7 and 28 days curing. It is evident from the results depicted in table 4.2 that the mix F-20-30 is giving more strength at 3, 7 and 28 days than the other two. The 3 day strength of F-20-30 is 40 % more than that of F-20-20 and is 31.4 % more than that of F-20-40. Similarly the 7 day strength of F-20-30 is 15.37% more than that of F-20-20 and is about 29.21% more than that of F-20-40. Moreover there is a slight increase in the 28 day strength of mix F-20-30 which is about 10% more than that of F-20-20 and is 24 % more than that of F-20-40. The variations of strength of the mixes are shown in Figure 4.3.

Table 4.3 UCS results of F-25-20, F-25-30, F-25-40

Curing Time (Days)	Unconfined compressive strength (kPa)		
Specimen Name	F-25-20	F-25-30	F-25-40
3	45.13	41.91	38.38
7	52.69	49.88	47.28
28	115.69	98.63	88.27

It is evident from the Table 4.3, that the mix F-25-20, is giving more strength at 3, 7 and 28 days than the other two. There is a slight variation in the 3, 7 and 28 day strength of F-25-20 and F-25-30 which is about 7%, 5% and 17%, but the variation between the 3, 7 and 28 day strength of F-25-20 and F-25-40 is about 18%, 11 % and 31%. The variations of strength of the mixes are shown in Figure 4.4, and it can be stated as the strength of the mix is directly proportional to the curing period and is inversely proportional to the fly ash content in the mix. Thus it can be concluded that for a constant water to total solid ratio, the strength increases with the curing period and also with the decreased fly ash content.

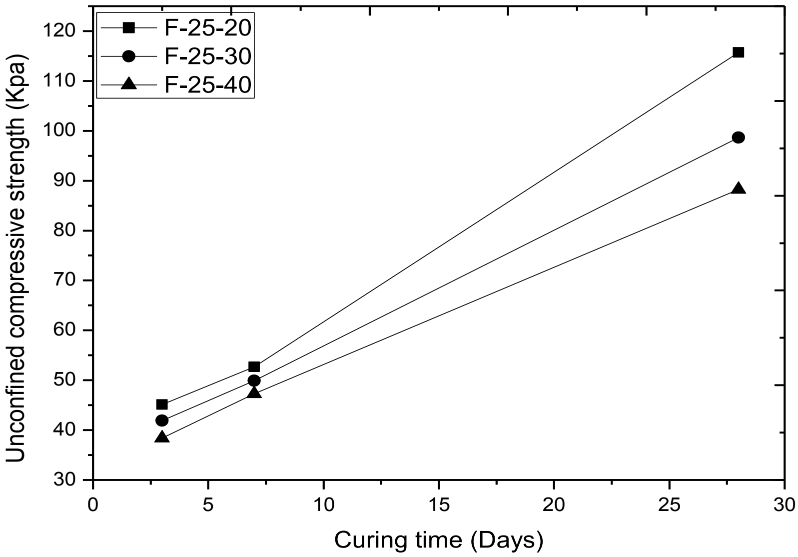

Figure 4.4 UCS results of F-25-20, F-25-30, F-25-40

Table 4.4 UCS results of all Fly ash Samples

Curing time (Days)	Unconfined compressive strength (kPa)								
	F-15-20	F-15-30	F-15-40	F-20-20	F-20-30	F-20-40	F-25-20	F-25-30	F-25-40
3	104.97	98.58	82.6	85.69	120.5	91.7	45.13	41.91	38.38
7	283.22	219.64	144.68	113.98	131.5	101.77	52.69	49.88	47.28
28	363.65	279.93	254.9	141.93	156.25	125.94	115.69	98.63	88.27

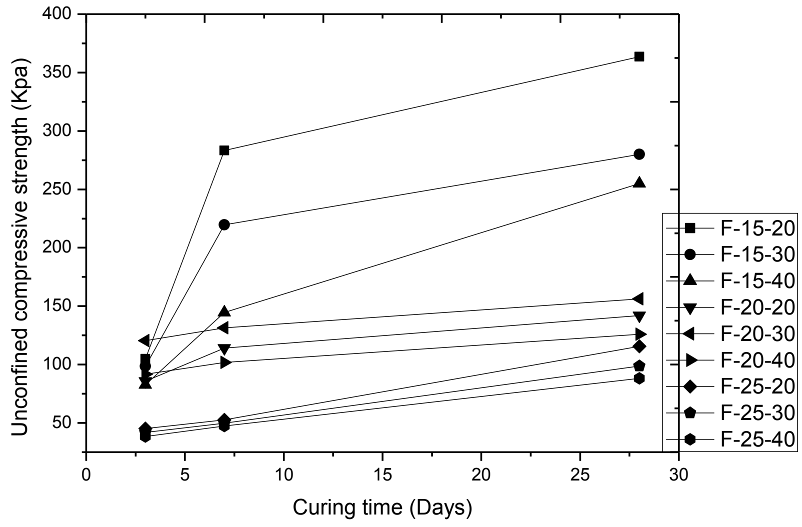

Figure 4.5 UCS results of all Fly ash Samples

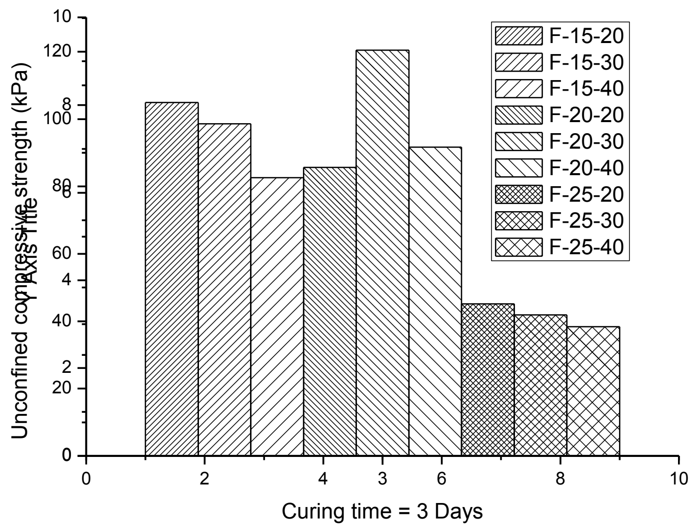

Figure 4.6 Bar chart showing the UCS results of Fly ash Samples after 3 days of curing

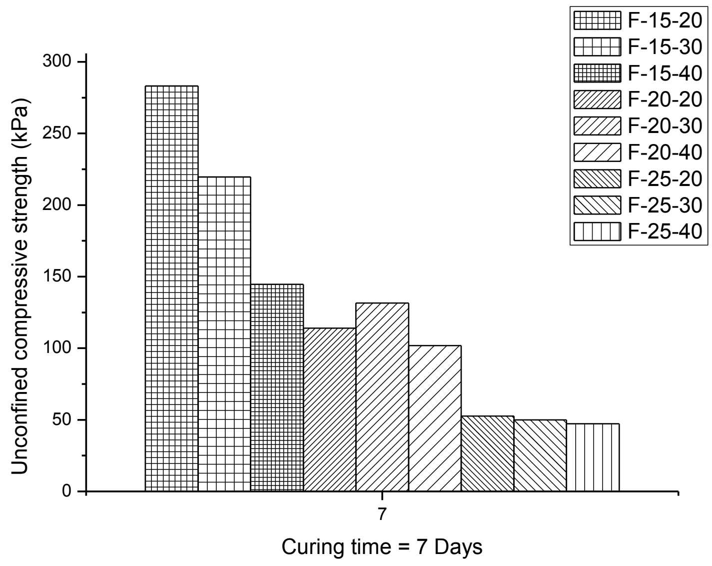

Figure 4.7 Bar chart showing the UCS results of Fly ash Samples after 7 days of curing

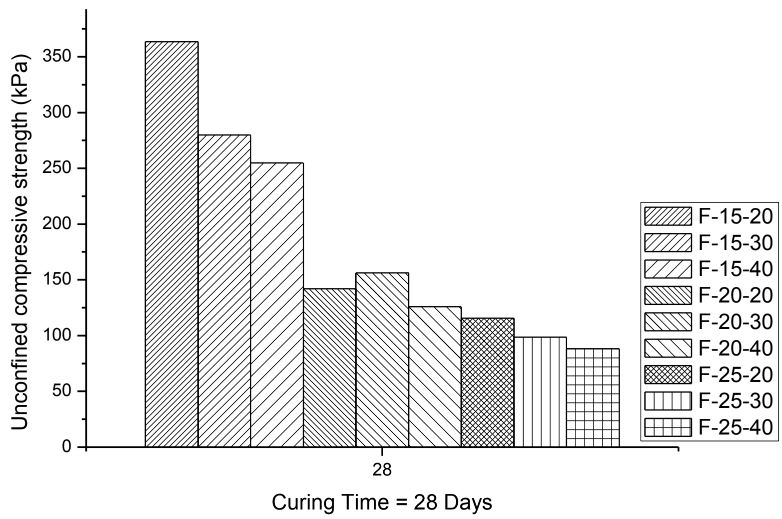

Figure 4.8 Bar chart showing the UCS results of Fly ash Samples after 28 days of curing

Table 4.4 shows the UCS values of all samples treated with fly ash, obtained after 3, 7 and 28 days curing. It is evident from the results depicted in table 4.4 that the mix F-20-30 is giving more 3 day strength as compared to other mixes. But the mix F-15-20 is giving more strength at 7 day and 28 day curing as compared to others. Strength of the mix F-25-40 obtained after 3, 7 and 28 days curing is the least among all others. The 3 day strength of F-20-30 is near about 2.2 times more than that of F-25-40. Similarly the strength obtained after 7 day and 28 day curing of the mix F-15-20 is about 5 times and 3 times more than that obtained from mix F-25-40. The variations of strength of the mix obtained with the days of curing are shown in a bar chart graph in figure 4.6, 4.7 and 4.8.

Chapter -5

Results on stabilization of expansive soils with activated fly ash

5.1 Introduction:

This chapter presents the results of stabilization of expansive black cotton soil, with alkli-activated fly ash. The increase in strength criteria is ascertained by conducting unconfined compression test on samples, at 3, 7 and 28 days curing. The samples, casted were of 50 mm diameter and 100 mm height, thereby ensuring L/D ratio as 2. These samples contains fly ash in 20, 30 and 40% by weight of dry mass and activator to total solid ratio is varied from 15, 20 and 25%. All the samples were covered with cling film, after casting and are kept in a air tight container for 48 hours. After 48 h, the samples were removed from the moulds and wrapped in cling film and left at ambient temperature and humidity conditions (50–60 % RH and 32-35° C). Immediately before testing, at the ages of 3, 7 and 28 days, the samples were trimmed to 100 mm long and tested for unconfined compressive strength (UCS) on an Aimil hydraulic testing machine at constant strain rate of 1.2 mm/min. Every single result obtained was the average of 3 tested samples.

5.2 Results

Table 5.1 UCS results of AF-100-20-15, AF-100-30-15, AF-100-40-15

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-100-20-15	AF-100-30-15	AF-100-40-15
3	195.46	175.95	140.51
7	253.32	179.24	131.41
28	436.63	195.23	128.9

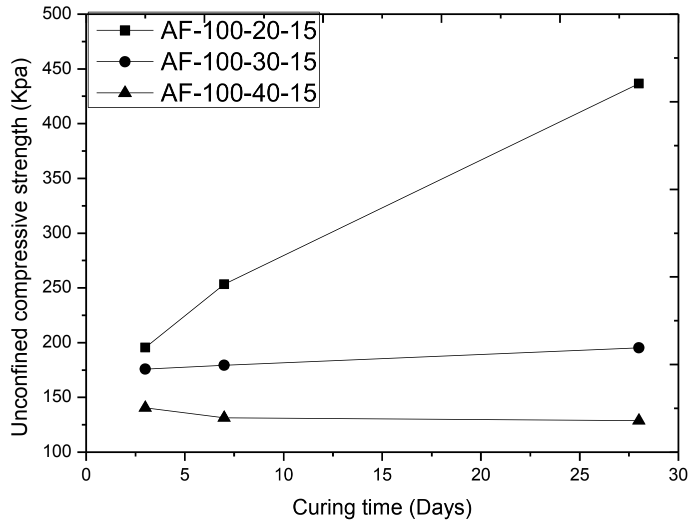

Figure 5.1 UCS results of AF-100-20-15, AF-100-30-15, AF-100-40-15

It is evident from the Table 5.1, that the mix AF-100-20-15, is giving more strength at 3, 7 and 28 days than the other two. The 3 day strength of AF-100-20-15 is 11 % more than that of AF-100-30-15 and 39 % more than that of AF-100-40-15. Similarly the 7 day strength of AF-100-20-15 is 41% more than that of AF-100-30-15 and is about 92 % more than that of AF-100-40-15. Moreover the 28 day strength of mix AF-100-20-15 is nearly 2.23 times than that of AF-100-30-15 and is 3.38 times more than that of AF-100-40-15. The variations of strength of the mixes are shown in Figure 5.1. and it can be stated as the strength of the mix is directly proportional to the curing period and is inversely proportional to the fly ash content in the mix. Thus it can be concluded that for a constant activator to total solid ratio, the strength increases with the curing period and also with the decreased fly ash content.

Table 5.2 UCS results of AF-100-20-20, AF-100-30-20, AF-100-40-20

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-100-20-20	AF-100-30-20	AF-100-40-20
3	311.58	392.7	322.8
7	350.83	462.64	546.88
28	407.7	580.62	810.02

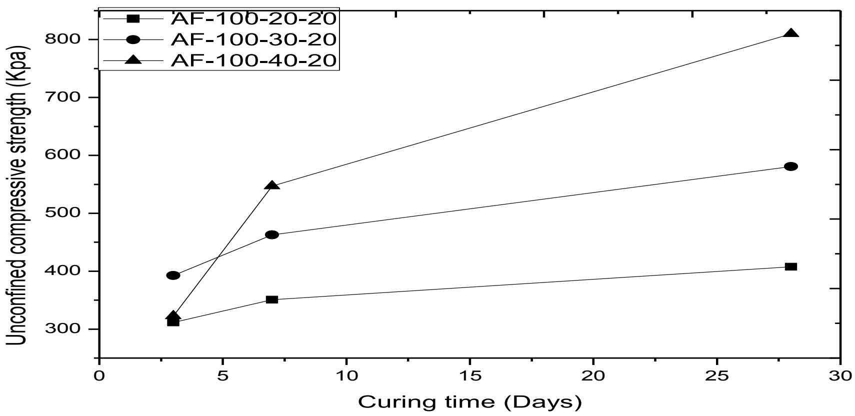

Figure 5.2 UCS results of AF-100-20-20, AF-100-30-20, AF-100-40-20

Table 5.2 shows the UCS values of the samples AF-100-20-20, AF-100-30-20, AF-100-40-20, obtained after 3, 7 and 28 days curing. It is evident from the results depicted in table 5.2 that the mix AF-100-30-20 is giving more strength after 3 days curing than the other two, while the strength after 7 and 28 days curing is more in case of mix AF-100-40-20. This can be probably related to necessary time period required for the nucleation phase to occur, during which the products resulting from the dissolution of the raw silica and alumina accumulate before precipitation. The variations of strength of the mixes are shown in Figure 5.2.

Table 5.3 UCS results of AF-100-20-25, AF-100-30-25, AF-100-40-25

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-100-20-25	AF-100-30-25	AF-100-40-25
3	103.97	94.71	85.42
7	130.13	146.92	112.03
28	238.77	215.77	232.77

Table 5.3 shows the UCS values of the samples AF-100-20-25, AF-100-30-25, AF-100-40-25, obtained after 3, 7 and 28 days curing. It is evident from the results depicted in table 5.3 that the mix AF-100-20-25 is giving more strength after 3 days and 28 days curing than the other two, while the strength after 7 days curing is more in case of mix AF-100-30-25 The variations of strength of the mixes are shown in Figure 5.3.

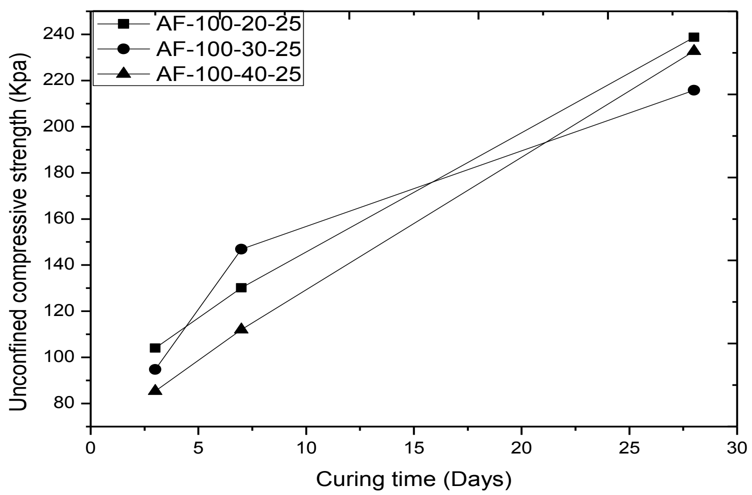

Figure 5.3 UCS results of AF-100-20-25, AF-100-30-25, AF-100-40-25

Table 5.4 UCS results of AF-125-20-15, AF-125-30-15, AF-125-40-15

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-125-20-15	AF-125-30-15	AF-125-40-15
3	114.59	158.87	187.08
7	220.1	152.8	250.27
28	364.32	221.54	399.24

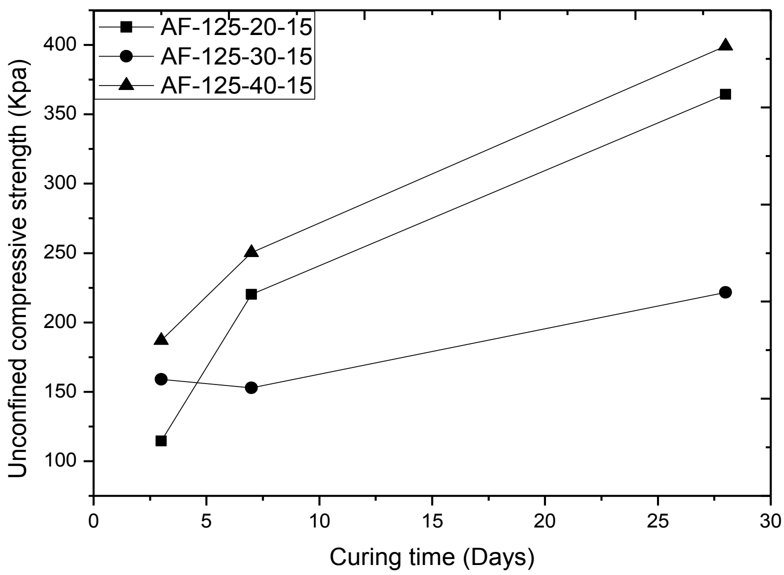

Figure 5.4 UCS results of AF-125-20-15, AF-125-30-15, AF-125-40-15

Table 5.4 shows the UCS values of the mixes, casted from 12.5 molal activator solution. From the table it is evident that the mix AF-125-40-15 is giving more strength than that of others, obtained after 3, 7 and 28 days curing. The variations of strength of the mixes are shown in Figure 5.4

Table 5.5 UCS results of AF-125-20-20, AF-125-30-20, AF-125-40-20

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-125-20-20	AF-125-30-20	AF-125-40-20
3	307.85	196.93	287.42
7	230.35	293.98	419.2
28	548.78	590.78	977.09

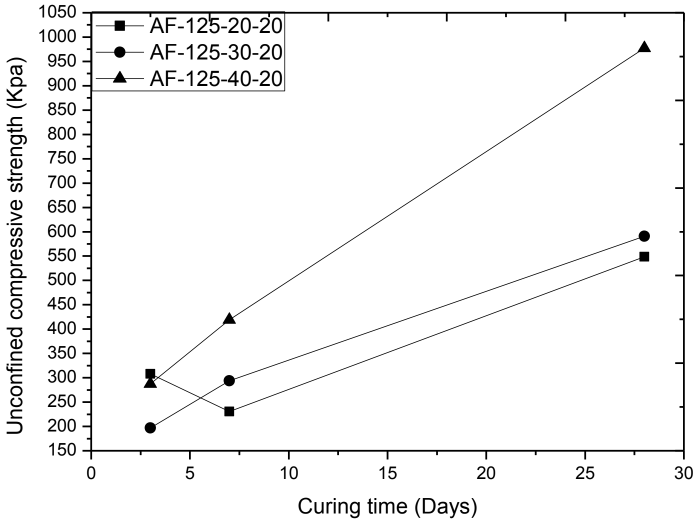

Figure 5.5. UCS results of AF-125-20-20, AF-125-30-20, AF-125-40-20

Similarly, Table 5.5 shows the UCS values of the mixes AF-125-20-20, AF-125-30-20, AF-125-40-20, casted from 15 molal activator solution. From the table it is evident that the mix AF-125-20-20 is giving more strength than that of others, obtained after 3days of curing, while mix AF-125-40-20, is giving more strength than the other two at 7 and 28 days curing. The variations of strength of the mixes are shown in Figure 5.5.

Table 5.6 UCS results of AF-125-20-25, AF-125-30-25, AF-125-40-25

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-125-20-25	AF-125-30-25	AF-125-40-25
3	128.77	114.93	113.76
7	154.83	179.89	192.29
28	317.55	555.47	852.17

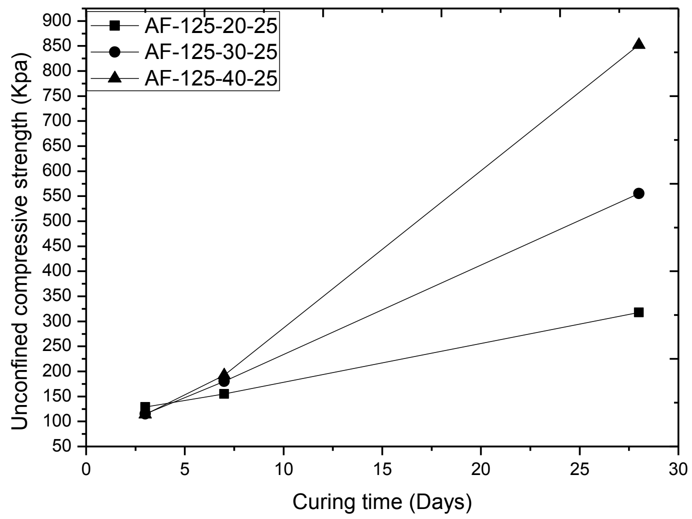

Figure 5.6 UCS results of AF-125-20-25, AF-125-30-25, AF-125-40-25

It is evident from the Table 5.6 that the 3 days strength of the mix AF-125-20-25, is more than the rest, while in case of 7 and 28 days strength the mix AF-125-40-25 is giving better results than the rest. The variations of strength of the mixes are shown in Figure 5.6.

Table 5.7 UCS results AF-150-20-15, AF-150-30-15, AF-150-40-15

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-150-20-15	AF-150-30-15	AF-150-40-15
3	288.17	247.41	160.75
7	339.7	428.28	503.98
28	579.28	603.32	643.86

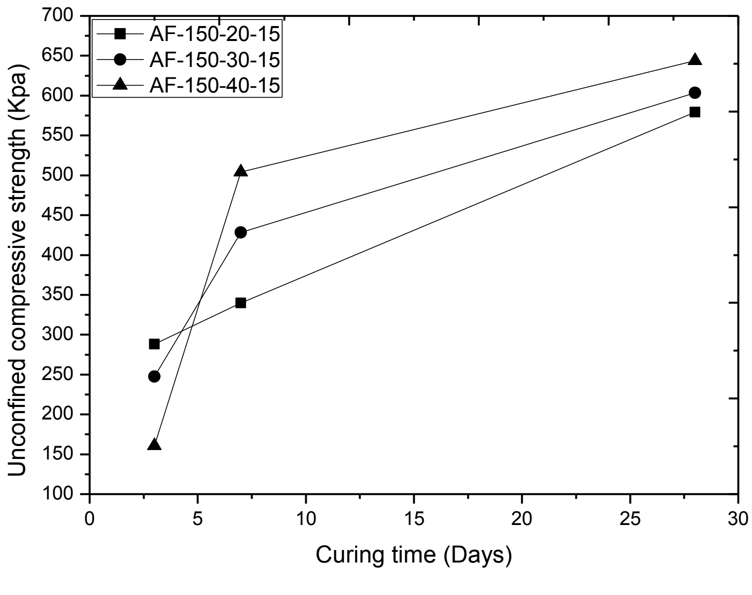

Figure 5.7 UCS results of AF-150-20-15, AF-150-30-15, AF-150-40-15

Table 5.7 shows the UCS values of the mixes, casted from 15 molal activator solution. From the Table 5.7, it can be concluded that the 3 days UCS is more in case of mix AF-150-20-15, whose magnitude is about 79 % more than that of mix AF-150-40-15. But in case of strength obtained after 7 and 28 days curing, AF-150-40-15 outperforms all. The variations of strength of the mixes obtained as are shown in Figure 5.7.

Table 5.7 UCS results AF-150-20-20, AF-150-30-20, AF-150-40-20

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-150-20-20	AF-150-30-20	AF-150-40-20
3	207.72	239.99	171.61
7	361.06	450.03	503.98
28	396.93	715.4	643.86

Similarly, Table 5.7 shows the UCS values of the mixes AF-150-20-20, AF-150-30-20, AF-150-40-20, casted from 15 molal activator solutions. From the table it is evident that the mix AF-150-30-20 outperforms all in the aspect of gaining more strength at 3, 7 and 28 days of curing. The variations of strength of the mixes are shown in Figure 5.7.

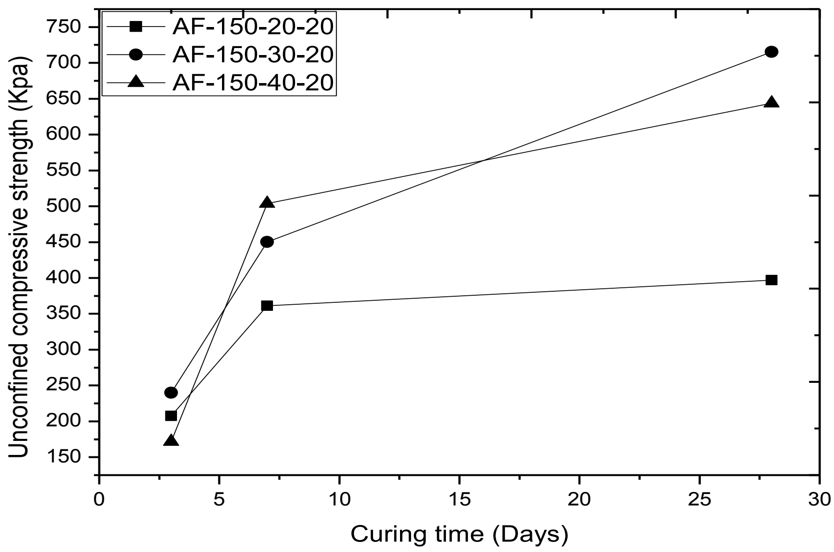

Figure 5.7 UCS results AF-150-20-20, AF-150-30-20, AF-150-40-20

Table 5.8. UCS results AF-150-20-25, AF-150-30-25, AF-150-40-25

Curing time (Days)	Unconfined compressive strength (kPa)		
	AF-150-20-25	AF-150-30-25	AF-150-40-25
3	111.24	98.43	75.63
7	138.52	181.89	256.55
28	182.15	465.24	296

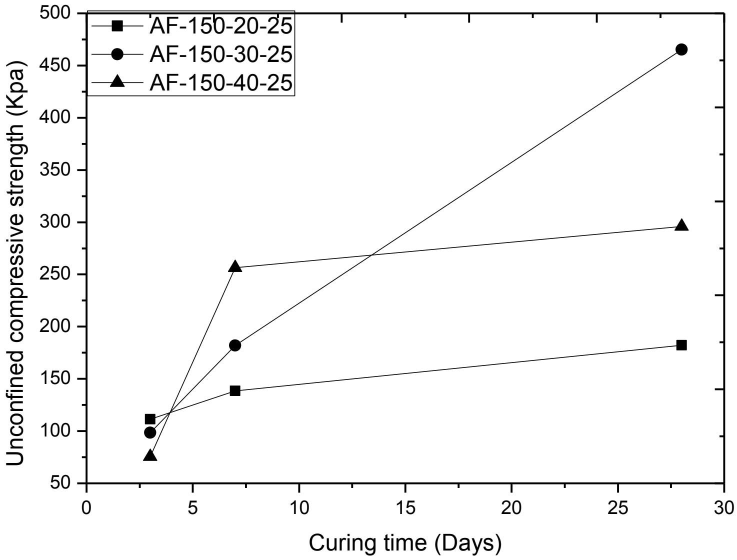

Figure 5.8. UCS results AF-150-20-25, AF-150-30-25, AF-150-40-25

Similarly, Table 5.8 shows the UCS values of the mixes AF-150-20-20, AF-150-30-20, AF-150-40-20, after 3, 7 and 28 days of curing. From the table it is evident that the mix AF-150-20-25 is giving more strength after 3 days of curing as compared to others, mix AF-150-40-25 is giving more strength after 7 days of curing as compared to mix AF-150-20-25 and mix AF-150-30-25. In case of 28 days strength mix AF-150-30-25, outperforms all. The variations of strength of the mixes are shown in Figure 5.8.

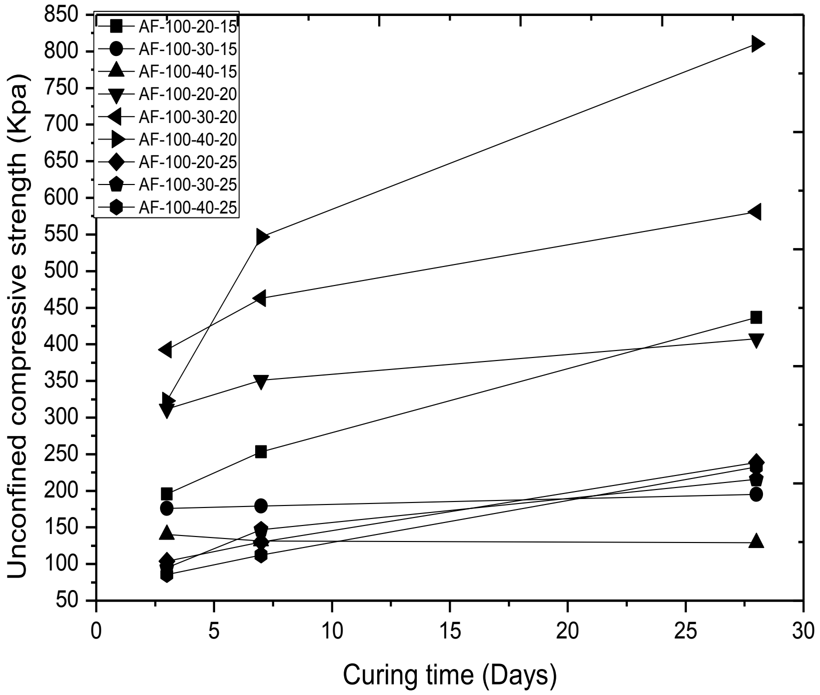

Figure 5.9. UCS results of all 10 molal sample

Table 5.9 shows the variation of strength obtained for 10 molal activator content and 20, 30 and 40% fly ash content mixed soil samples, after 3, 7 and 28 days curing periods. The variations are also shown in Figure 5.9. Figure 5.10, 5.11 and 5.12 shows the gain in strength of all 10 molal mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-100-30-20, while the 7 & and 28 days strength is more in case of mix AF-100-40-20. The least 3 and 7 days strength is exhibited by mix AF-100-40-25, while mix AF-100-30-25 exhibit least 28 days strength.

Table 5.9. UCS results of all 10 molal sample

Curing time (Days)	Unconfined compressive strength (kPa)								
	AF-100-20-15	AF-100-30-15	AF-100-40-15	AF-100-20-20	AF-100-30-20	AF-100-40-20	AF-100-20-25	AF-100-30-25	AF-100-40-25
3	195.46	175.95	140.51	311.58	392.7	322.8	103.97	94.71	85.42
7	253.32	179.24	131.41	350.83	462.64	546.88	130.13	146.92	112.03
28	436.63	195.23	128.9	407.7	580.62	810.02	238.77	215.77	232.77

Table 5.10. UCS results of all 12.5 molal sample

Curing time (Days)	Unconfined compressive strength (kPa)								
	AF-125-20-15	AF-125-30-15	AF-125-40-15	AF-125-20-20	AF-125-30-20	AF-125-40-20	AF-125-20-25	AF-125-30-25	AF-125-40-25
3	114.59	158.87	187.08	307.85	196.93	287.42	128.77	114.93	113.76
7	220.1	152.8	250.27	230.25	293.98	419.2	154.83	179.89	192.29
28	364.32	221.54	399.24	548.78	590.78	977.09	317.55	555.47	852.17

Table 5.11. UCS results of all 15 molal sample

Curing time (Days)	Unconfined compressive strength (kPa)								
	AF-150-20-15	AF-150-30-15	AF-150-40-15	AF-150-20-20	AF-150-30-20	AF-150-40-20	AF-150-20-25	AF-150-30-25	AF-150-40-25
3	288.17	247.41	160.75	207.72	239.99	171.61	111.24	98.43	75.63
7	339.7	428.28	503.98	361.06	450.03	503.98	138.52	181.89	256.65
28	579.28	603.32	643.86	396.93	715.4	643.86	182.15	465.24	296

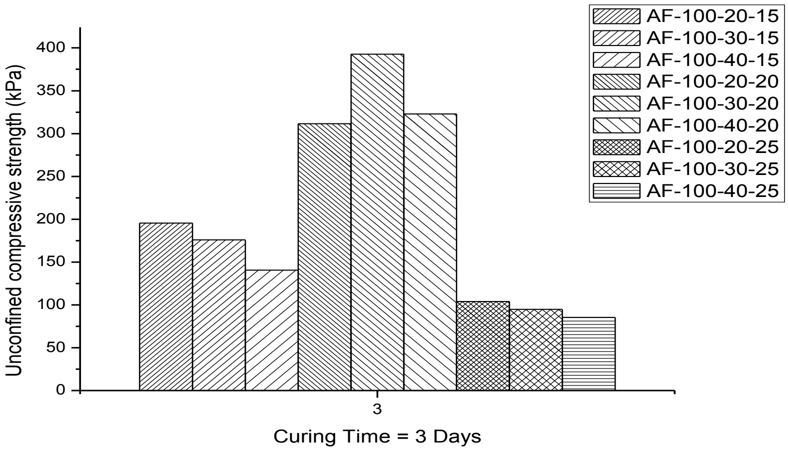

Figure 5.10. UCS results of 10 molal sample (3 Days curing)

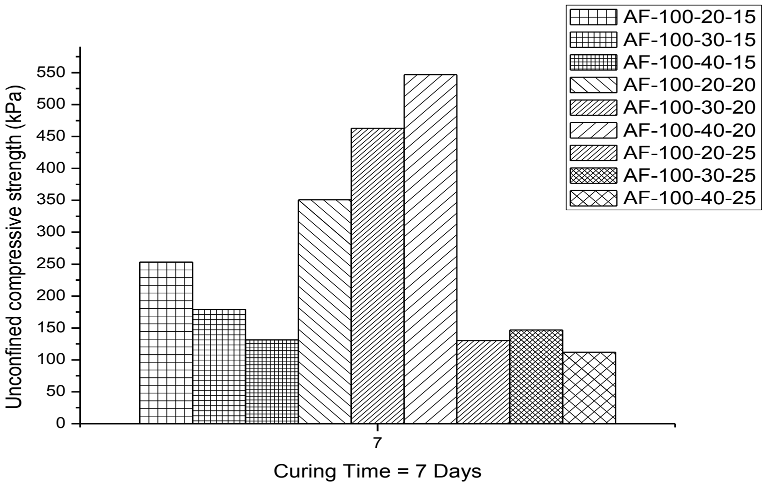

Figure 5.11. UCS results of 10 molal sample (7 Days curing)

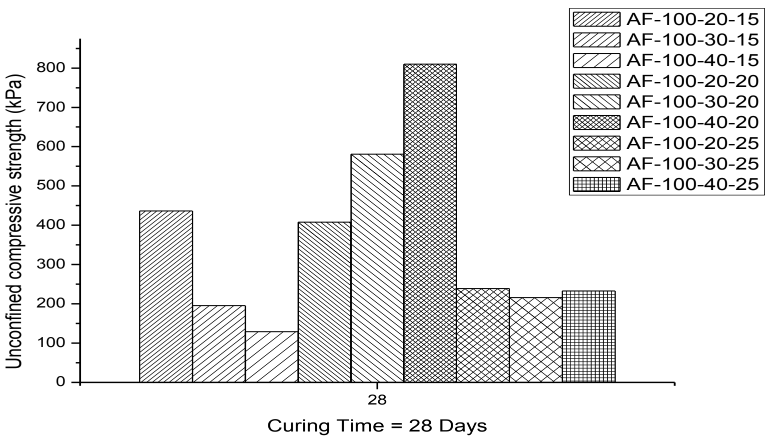

Figure 5.12. UCS results of 10 molal sample (28 days curing)

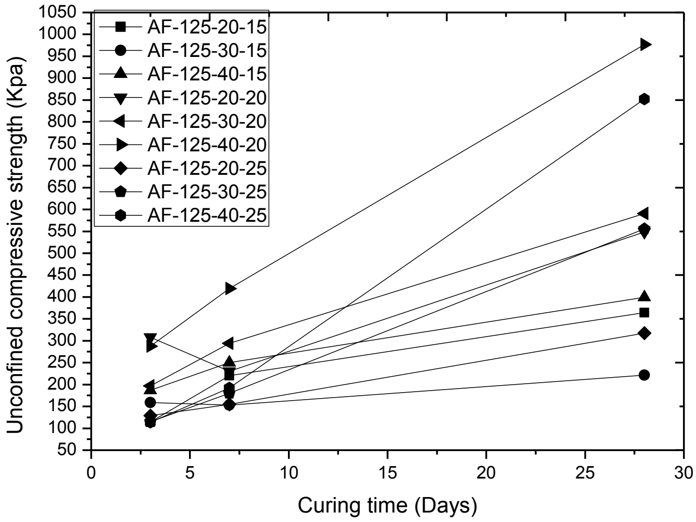

Figure 5.13. UCS results of all 12.5 molal sample

Table 5.10 shows the variation of strength obtained for 12.5 molal activator content and 20, 30 and 40% fly ash content mixed soil samples, after 3, 7 and 28 days curing periods. The variations are also shown in Figure 5.13. Figure 5.14, 5.15 and 5.16 shows the gain in strength of all 12.5 molal mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-125-20-20, while the 7 & and 28 days strength is more in case of mix AF-125-40-20. The least 3 days strength is exhibited by mix AF-125-40-25, while mix AF-125-30-15 exhibit least 7 days strength and mix AF-125-40-15 exhibit least strength after 28 days curing.

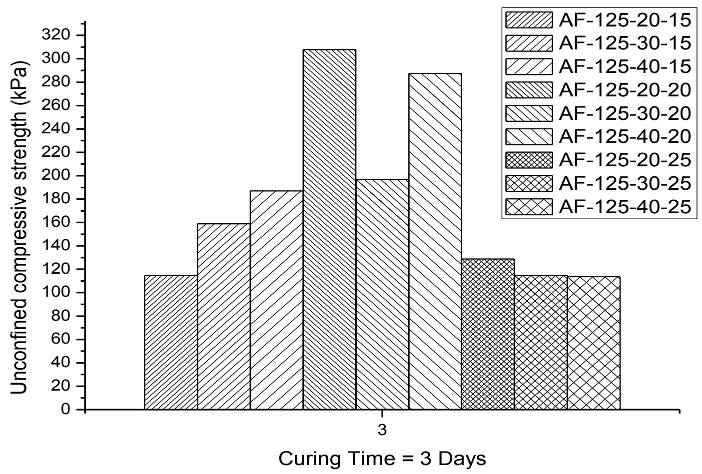

Figure 5.14. UCS results of 12.5 molal sample (3 Days curing)

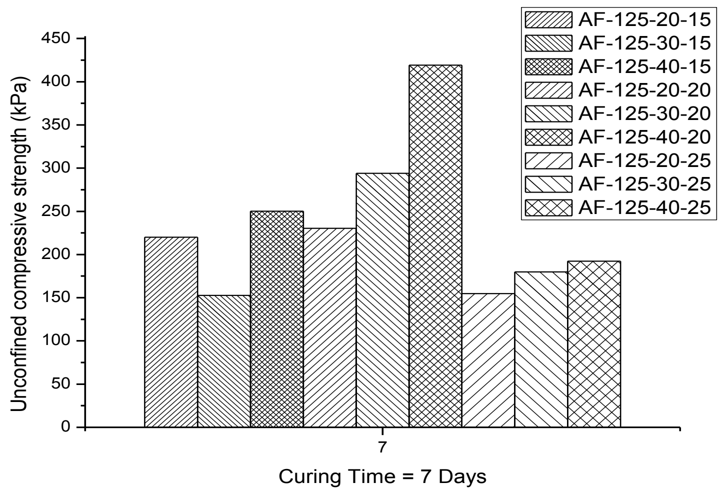

Figure 5.15. UCS results of 12.5 molal sample (7 Days curing)

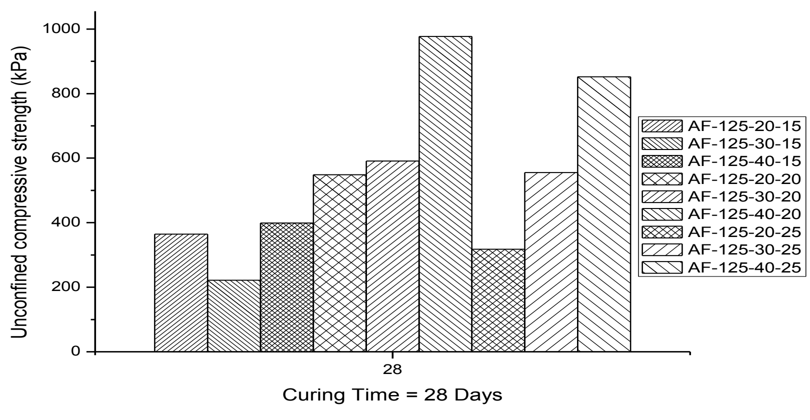

Figure 5.16. UCS results of 12.5 molal sample (28 Days curing)

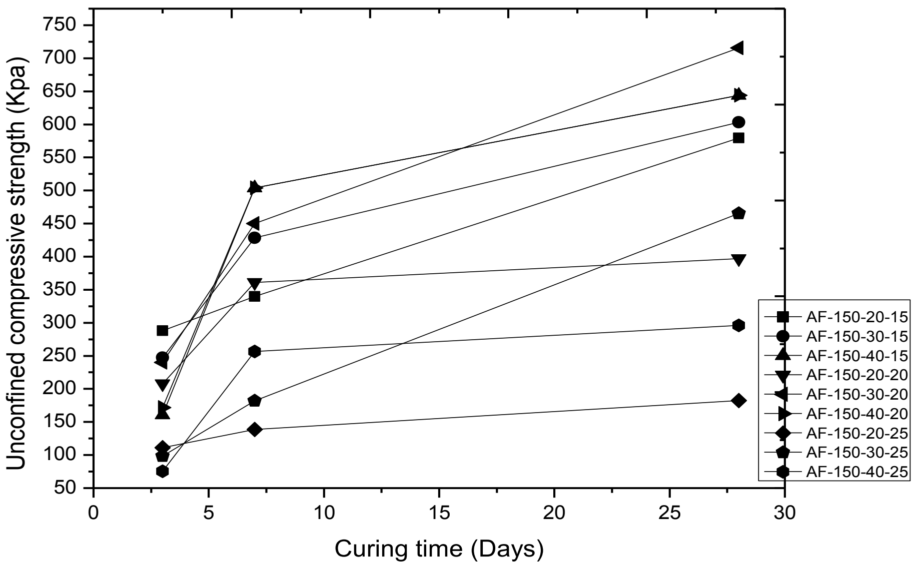

Figure 5.17 UCS results of all 15 molal Samples

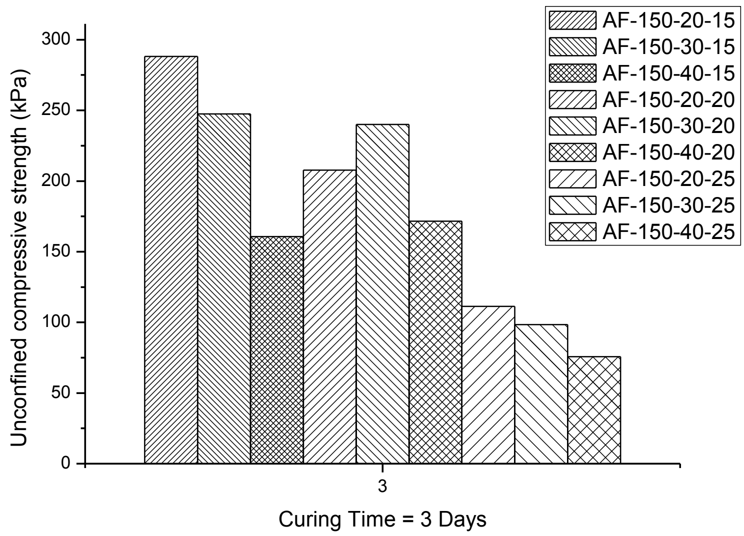

Figure 5.18. UCS results of 15 molal sample (3 Days curing)

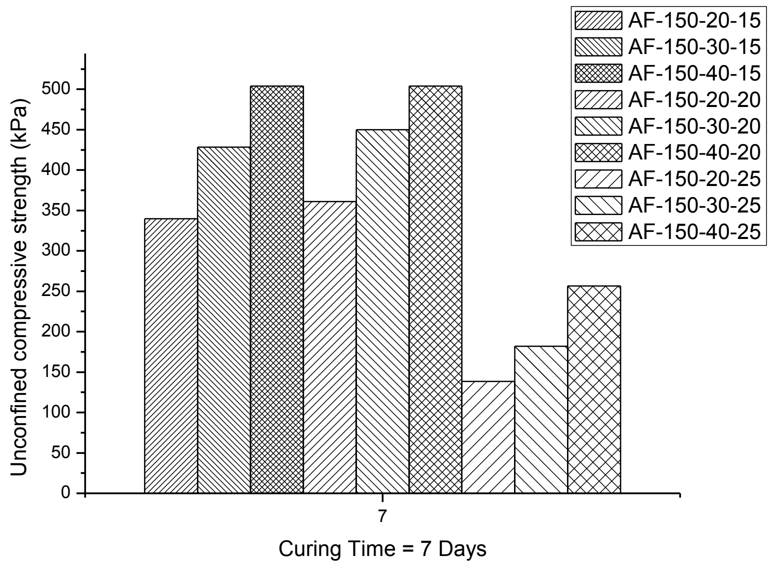

Figure 5.19. UCS results of 15 molal sample (7 Days curing)

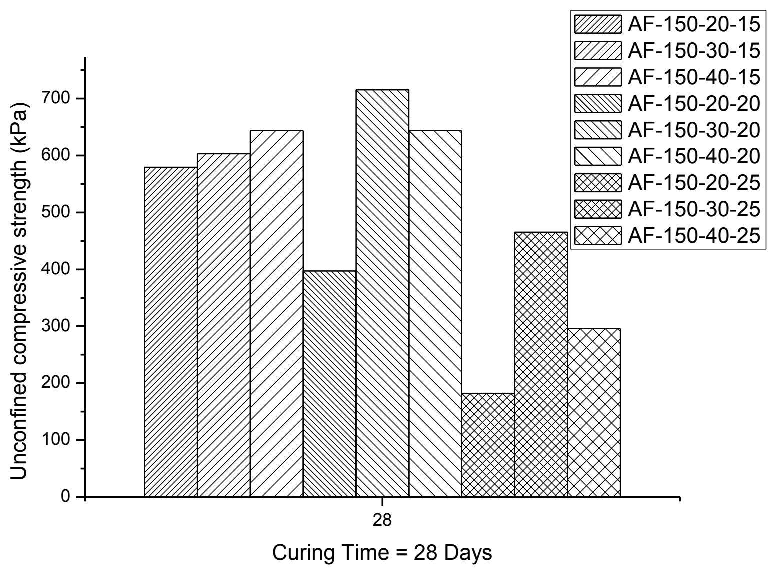

Figure 5.20. UCS results of 15 molal sample (28 Days curing).

Table 5.12 UCS results of all AAFA Samples

Name	Qu (kPa)	Name	Qu (kPa)	Name	Qu (kPa)
AF-100-20-15-3D	195.46	AF-100-20-15-7D	253.32	AF-100-20-15-28D	436.63
AF-100-30-15-3D	175.95	AF-100-30-15-7D	179.24	AF-100-30-15-28D	195.23
AF-100-40-15-3D	140.51	AF-100-40-15-7D	131.41	AF-100-40-15-28D	128.9
AF-100-20-20-3D	311.58	AF-100-20-20-7D	350.83	AF-100-20-20-28D	407.7
AF-100-30-20-3D	392.7	AF-100-30-20-7D	462.64	AF-100-30-20-28D	580.62
AF-100-40-20-3D	322.8	AF-100-40-20-7D	546.88	AF-100-40-20-28D	810.02
AF-100-20-25-3D	103.97	AF-100-20-25-7D	130.13	AF-100-20-25-28D	238.77
AF-100-30-25-3D	94.71	AF-100-30-25-7D	146.92	AF-100-30-25-28D	215.77
AF-100-40-25-3D	85.42	AF-100-40-25-7D	112.03	AF-100-40-25-28D	232.77
AF-125-20-15-3D	114.59	AF-125-20-15-7D	220.1	AF-125-20-15-28D	364.32
AF-125-30-15-3D	158.87	AF-125-30-15-7D	152.8	AF-125-30-15-28D	221.54
AF-125-40-15-3D	187.08	AF-125-40-15-7D	250.27	AF-125-40-15-28D	399.24
AF-125-20-20-3D	307.85	AF-125-20-20-7D	230.25	AF-125-20-20-28D	548.78
AF-125-30-20-3D	196.93	AF-125-30-20-7D	293.98	AF-125-30-20-28D	590.78
AF-125-40-20-3D	287.42	AF-125-40-20-7D	419.2	AF-125-40-20-28D	977.09
AF-125-20-25-3D	128.77	AF-125-20-25-7D	154.83	AF-125-20-25-28D	317.55
AF-125-30-25-3D	114.93	AF-125-30-25-7D	179.89	AF-125-30-25-28D	555.47
AF-125-40-25-3D	113.76	AF-125-40-25-7D	192.29	AF-125-40-25-28D	852.17
AF-150-20-15-3D	288.17	AF-150-20-15-7D	339.7	AF-150-20-15-28D	579.28
AF-150-30-15-3D	247.41	AF-150-30-15-7D	428.28	AF-150-30-15-28D	603.32
AF-150-40-15-3D	160.75	AF-150-40-15-7D	503.98	AF-150-40-15-28D	643.86
AF-150-20-20-3D	207.72	AF-150-20-20-7D	361.06	AF-150-20-20-28D	396.93
AF-150-30-20-3D	239.99	AF-150-30-20-7D	450.03	AF-150-30-20-28D	715.4
AF-150-40-20-3D	171.61	AF-150-40-20-7D	503.98	AF-150-40-20-28D	643.86
AF-150-20-25-3D	111.24	AF-150-20-25-7D	138.52	AF-150-20-25-28D	182.15
AF-150-30-25-3D	98.43	AF-150-30-25-7D	181.89	AF-150-30-25-28D	465.24
AF-150-40-25-3D	75.63	AF-150-40-25-7D	256.55	AF-150-40-25-28D	296

The variation of strength obtained for 15 molal activator content and 20, 30 and 40% fly ash content mixed soil samples, after 3, 7 and 28 days curing periods is shown in Table 5.11. The variations are also shown in Figure 5.17. Figure 5.18, 5.19 and 5.20 shows the gain in strength of all 15 molal mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-120-20-15, while the 7 & and 28 days strength is more in case of mix AF-150-40-15 and mix AF-150-40-20. The least 3 days strength is exhibited by mix AF-150-40-25, while mix AF-125-20-25 exhibit least strength after 7 and 28 days of curing.

Table 5.12 gives the details of the activated mix casted and their corresponding strengths attained after 3, 7 and 28 days of curing. Among all the highest strength obtained after 3 days of curing was attained by the mix AF-150-30-20-3D, while the strength attained by mix AF-150-40-20-7D after 7 days of curing is more than all others. The mix AF-150-40-20-28D outperforms all in respect of strength attained after 28 days of curing.

Chapter -6

Comparison of results

Table 6.1 Comparison of UCS results of 15% water and activator containing samples

Curing time (Days)	Unconfined compressive strength (kPa)											
	F-15-20	F-15-30	F-15-40	AF-100-20-15	AF-100-30-15	AF-100-40-15	AF-125-20-15	AF-125-30-15	AF-125-40-15	AF-150-20-15	AF-150-30-15	AF-150-40-15
3	104.97	98.58	82.6	195.46	175.95	140.51	114.59	158.87	187.08	288.17	247.41	160.75
7	283.22	219.64	144.68	253.32	179.24	131.41	220.1	152.8	250.27	339.7	428.28	503.98
28	363.65	279.93	254.9	436.63	195.23	128.9	364.32	221.54	399.24	579.28	603.32	643.86

Table 6.2 Comparison of UCS results of 20% water and activator containing samples

Curing time (Days)	Unconfined compressive strength (kPa)											
	F-20-20	F-20-30	F-20-40	AF-100-20-20	AF-100-30-20	AF-100-40-20	AF-125-20-20	AF-125-30-20	AF-125-40-20	AF-150-20-20	AF-150-30-20	AF-150-40-20
3	85.69	120.5	91.7	311.58	392.7	322.8	307.85	196.93	287.42	207.72	239.99	171.61
7	113.98	131.5	101.77	350.83	462.64	546.88	230.25	293.98	419.2	361.06	450.03	503.98
28	141.93	156.25	150.94	407.7	580.62	810.02	548.78	590.78	977.09	396.93	715.4	643.86

Table 6.3 Comparison of UCS results of 25% water and activator containing samples

Curing time (Days)	Unconfined compressive strength (kPa)											
	F-25-20	F-25-30	F-25-40	AF-100-20-25	AF-100-30-25	AF-100-40-25	AF-125-20-25	AF-125-30-25	AF-125-40-25	AF-150-20-25	AF-150-30-25	AF-150-40-25
3	45.13	41.91	38.38	103.97	94.71	85.42	128.77	114.93	113.76	111.24	98.43	75.63
7	52.69	49.88	47.28	130.13	146.92	112.03	154.83	179.89	192.29	138.52	181.89	256.65
28	115.69	98.63	88.27	238.77	215.77	232.77	317.55	555.47	852.17	182.15	465.24	296

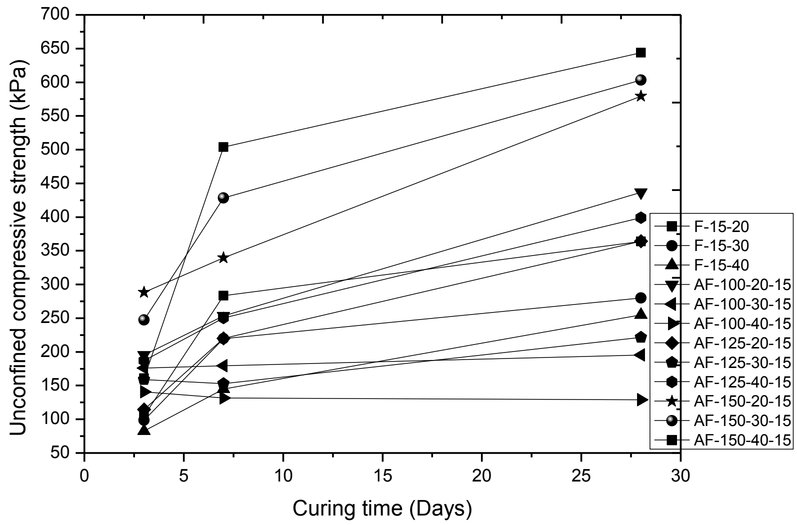

Figure 6.1 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 15% water or activator.

The variation of strength obtained for 10, 12.5 and 15 molal activator content, 20, 30 and 40% fly ash content and containing 15% fluid by weight of dry mass (water or activator) mixed soil samples, after 3, 7 and 28 days curing periods is shown in Table 6.1. The variations are also shown in Figure 6.1. Figure 6.2-6.4 shows the gain in strength of all mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-120-20-15, while the 7 and 28 days strength is more in case of mix AF-150-40-15. The least 3, 7 and 28 days strength is exhibited by mix F-15-40. The 3 days maximum strength of AAFA treated soil sample is 3.5 times higher than the minimum strength acquired by fly ash treated sample, while the 7 and 28 days maximum strength of AAFA treated soil sample are 3.5 and 2.5 times higher than the minimum strength acquired by fly ash treated sample respectively.

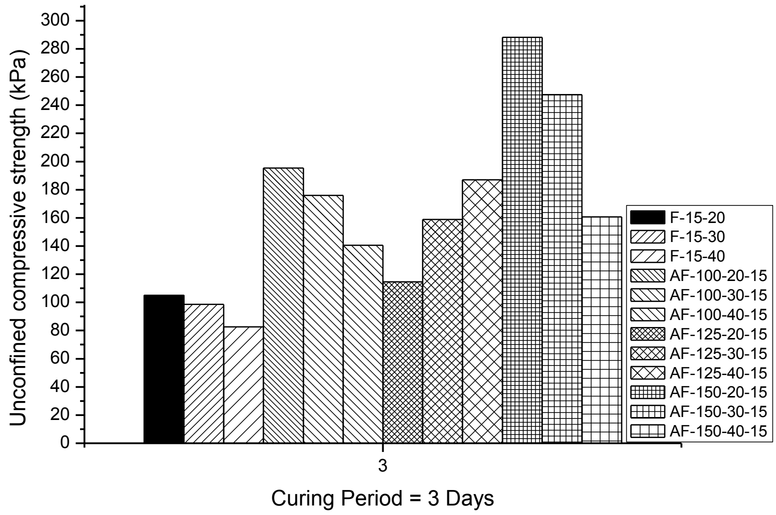

Figure 6.2 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 15% water or activator (3 Days Curing Period) .

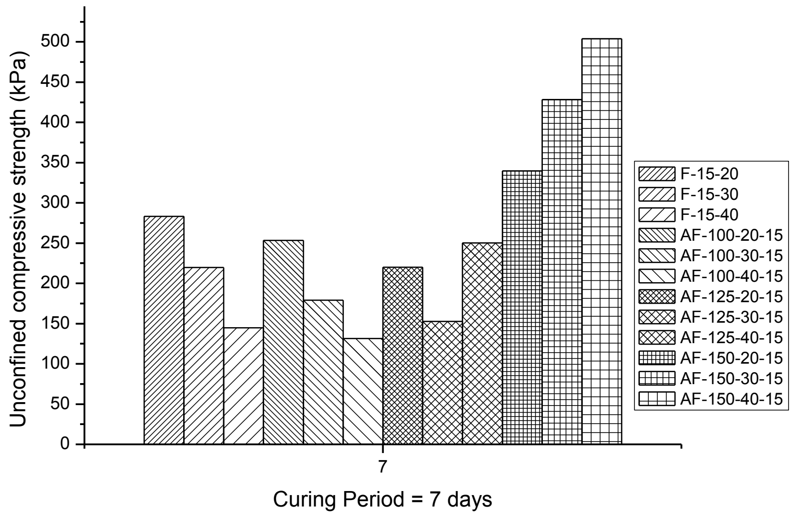

Figure 6.2 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 15% water or activator (3 Days Curing Period) .

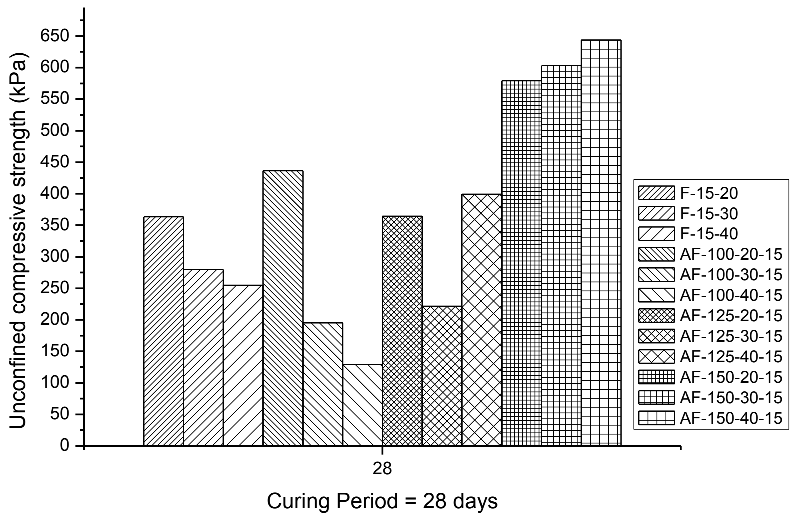

Figure 6.4 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 15% water or activator (28 Days Curing Period) .

The variation of strength obtained for 10, 12.5 and 15 molal activator content, 20, 30 and 40% fly ash content and containing 20% fluid by weight of dry mass (water or activator) mixed soil samples, after 3, 7 and 28 days curing periods is shown in Table 6.2. The variations are also shown in Figure 6.5. Figure 6.6-6.8 shows the gain in strength of all mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-100-20-20, while the 7 and 28 days strength is more in case of mix AF-100-40-20 and AF-125-40-20 respectively. The least 3, 7 and 28 days strength is exhibited by mix F-15-40, F-20-40 and F-20-20 respectively. The 3 days maximum strength of AAFA treated soil sample is 3.4 times higher than the minimum strength acquired by fly ash treated sample, while the 7 and 28 days maximum strength of AAFA treated soil sample are 5.3 and 5.7 times higher than the minimum strength acquired by fly ash treated sample respectively.

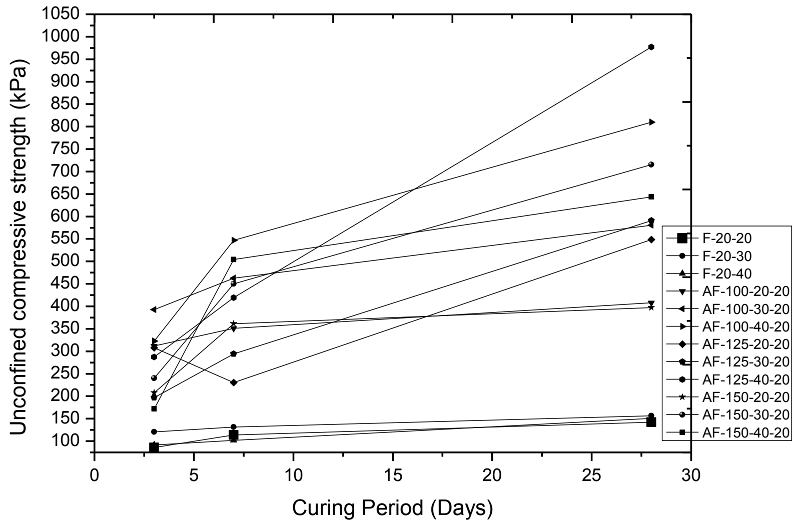

Figure 6.5 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 20% water or activator

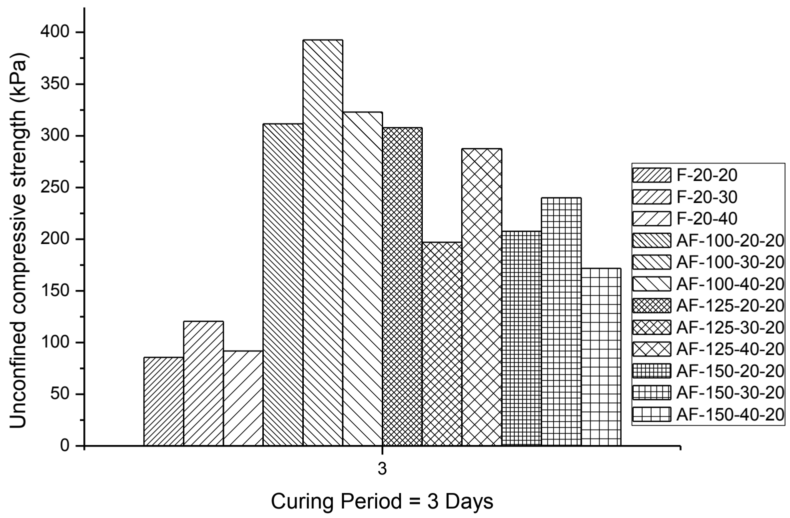

Figure 6.6 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 20% water or activator (3 Days Curing Period) .

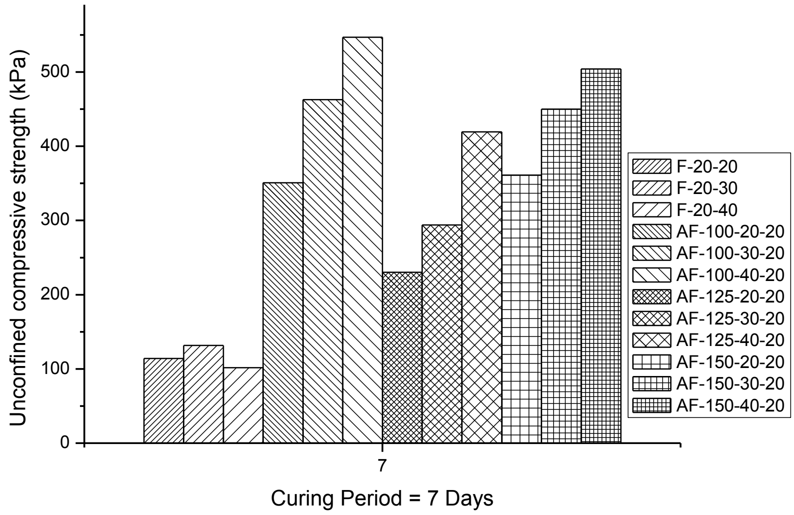

Figure 6.7 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 20% water or activator (7 Days Curing Period) .

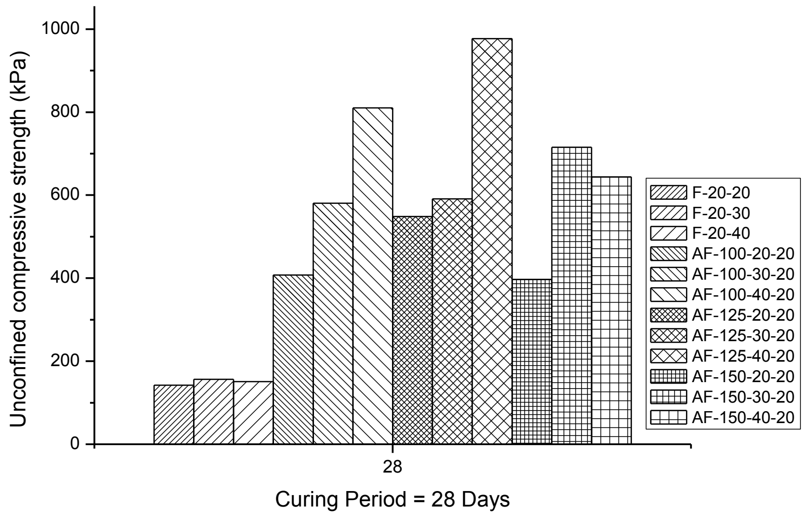

Figure 6.8 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 20% water or activator (28 Days Curing Period) .

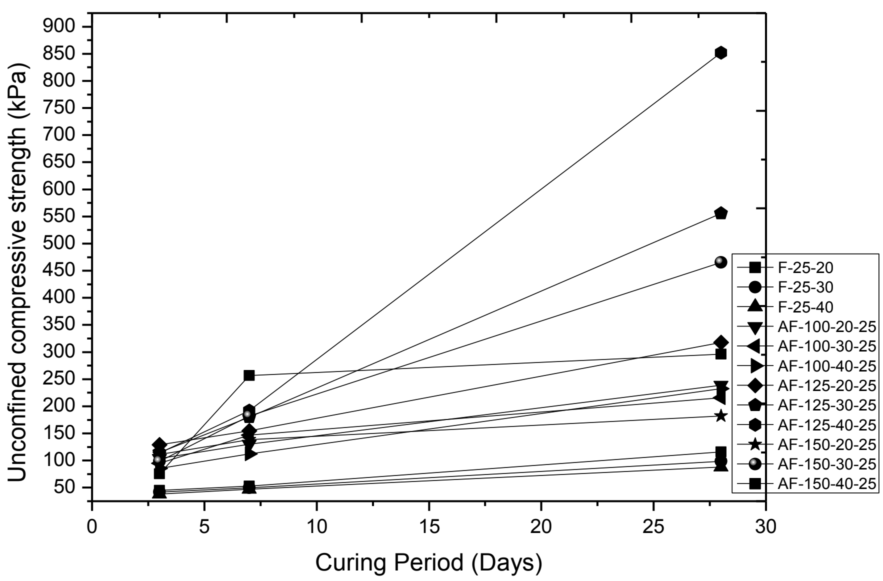

Figure 6.9 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 25% water or activator.

The variation of strength obtained for 10, 12.5 and 15 molal activator content, 20, 30 and 40% fly ash content and containing 20% fluid by weight of dry mass (water or activator) mixed soil samples, after 3, 7 and 28 days curing periods is shown in Table 6.3. The variations are also shown in Figure 6.9. Figure 6.10-6.12 shows the gain in strength of all mixes after 3, 7 and 28 days respectively in bar graph form. From the tables and graphs it is evident that the 3 days strength is more in case of mix AF-125-20-25, while the 7 and 28 days strength is more in case of mix AF-150-40-25 and AF-125-40-25 respectively. The least 3, 7 and 28 days strength is exhibited by mix F-25-40. The 3 days maximum strength of AAFA treated soil sample is 3.35 times higher than the minimum strength acquired by fly ash treated sample, while the 7 and 28 days maximum strength of AAFA treated soil sample are 5.4 and 9.65 times higher than the minimum strength acquired by fly ash treated sample respectively. Thus it can be concluded that AAFA treated soil samples exhibit more strengths than fly ash treated soil samples.

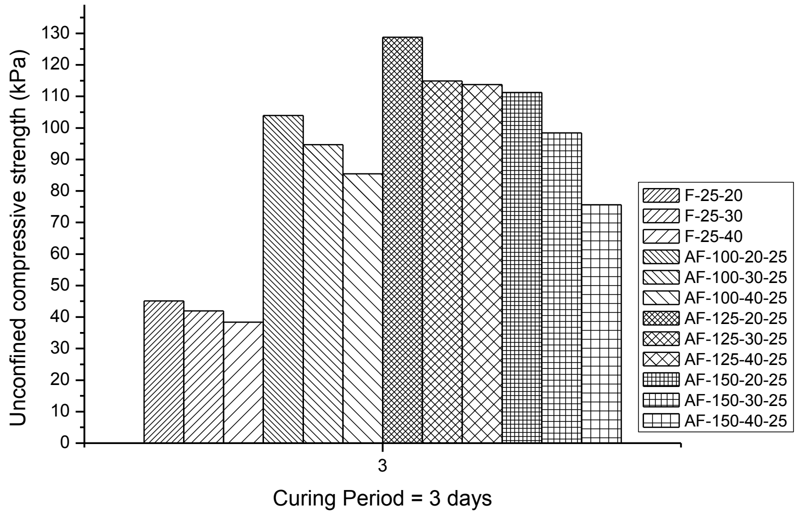

Figure 6.10 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 25% water or activator (3 Days Curing Period) .

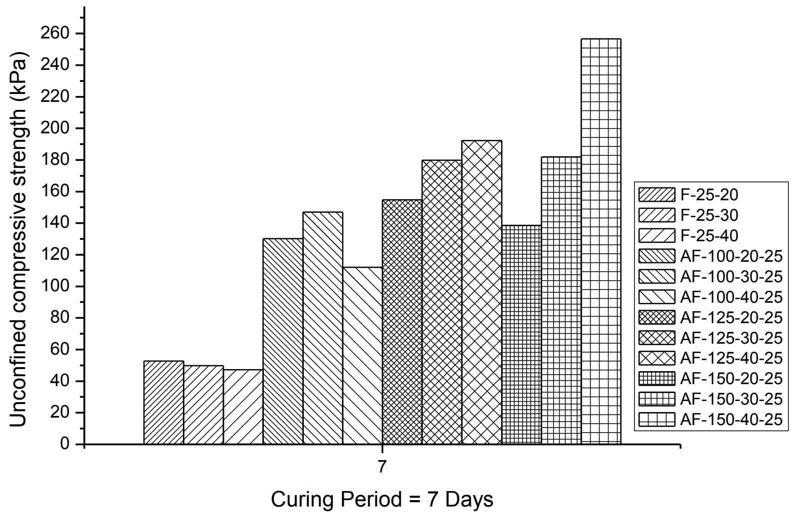

Figure 6.11 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 25% water or activator (7 Days Curing Period) .

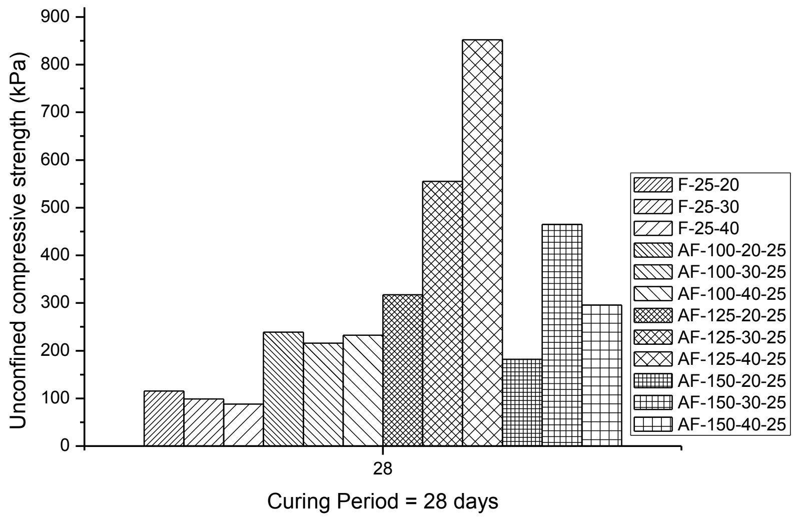

Figure 6.12 Comparison of UCS results of fly ash treated and AAFA treated soil samples, containing 25% water or activator (28 Days Curing Period).

Chapter - 7

Study of rheological properties of alkali activated fly ash

7.1 Setting time

This parameter was impossible to determine due to the very slow setting of the mixtures used, which is known to be significantly slower than the setting time of cement based grouts. During the tests it was possible to conclude that the setting process is not homogenous, since the upper layer of the grout mass was hardening at a significant higher rate than the remaining volume.

This was discovered when the Vicat's needle was able to puncture the upper layer of the grout, exposing the fresh material underneath. The puncture would allow the upper harden layer to mix with the fresh grout, which would result in the loss of the already achieved hardness. Therefore, this test does not seem to be the most appropriate to evaluate this parameter in activated fly ash grouts.

7.2 Viscosity

The results in Table 7.1 show that the viscosity of the alkaline grout is higher than that of the cement grout. The higher viscosity can be a factor in the grout/soil mixing levels, which can be overcome by increasing the water percentage in the activator. However, in so doing, the activator/ash ratio is increased, while the Na2O/ash ratio is kept constant, therefore justifying the study of the effects on strength.

Table 7.1 Density and Viscosity of cement and alkaline grouts

Binder	Density (gm/cm^3)	Marsh Funnel (S)
Cement grout	1.58	39
Alkaline grout, 10 m (activator/ash = 0.89)	1.64	80
Alkaline grout, 12.5 m (activator/ash = 0.89)	1.76	95
Alkaline grout, 15 m (activator/ash = 0.89)	1.88	150

Chapter - 8

Conclusions and Future Scope

8.1 Summary

The stabilization of expansive soil has drawn attention to avoid its disastrous effect on infrastructural components like road, building etc. In this work a new idea of stabilizing the expansive soil using alkali activated fly ash was discussed. The chemical sodium hydroxide and sodium silicate were used as a chemical activator for the fly ash. The method of sample preparation, proportion of chemical additive, curing of sample and changes in basic geotechnical properties of expansive soil is discussed.

8.2 Conclusions:

Based on the obtained results and discussion thereof following conclusions can be made.

- The unconfined compressive strength soil is found to vary with concentration of chemical in the activated fly ash and curing period.
- 10 molal samples are giving better 3 and 7 days strengths than 12.5 and 15 molal samples, which make it economical as compared to 12.5 and 15 molal samples.
- Long term strength is more in case of 12.5 molal samples.
- Maximum 3 day strength attained by activated sample is 392.7 kPa, which is 3.25 times more than that attained by fly ash treated samples.
- Maximum 7 day strength attained by activated sample is 546.88 kPa, which is 2 times more than that attained by fly ash treated samples.
- Maximum 28 day strength attained by activated sample is 977.09 kPa, which is 2.7 times more than that attained by fly ash treated samples.
- There is a strong dependency between the activator/ash ratio and mechanical strength. Results showed that it is advantageous to reduce this ratio since it has a positive effect on strength results, which has also a positive effect on final cost.

- Lowering the viscosity of the grout mixtures to similar values to that of cement grout can have a negative effect on final strength, since it demands an increase in the activator/ash ratio. Therefore, it is recommended that a compromise is made between an optimum viscosity level and the lowest activator/ash ratio possible, whenever the viscosity is a key issue for a particular application.
- Alkali-activated fly ash can be used effectively as a chemical stabiliser for stabilising expansive soils.

8.3 Scope for future study.

- Efforts should be made to reduce the cost of operation, by searching other natural alkaline materials.
- Field application of this method, by using suitable technology.
- Application of AAFA for stabilization of other low strength high compressible clay.
- Use of other alkalis like Potassium and Lithium, to study their effect on Fly ash.

References:-

- Escalante-Garcia JI, Espinoza-Perez LJ, Gorokhovsky A, Gomez-Zamorano LY. Coarse blast furnace slag as a cementitious material, comparative study as a partial replacement of Portland cement and as an alkali activated cement. Constr Build Mater 2009; 23: 2511–7.
- Romagnoli M, Leonelli C, Kamse E, Lassinantti Gualtieri M. Rheology of geopolymer by DOE approach. Constr Build Mater 2012;36:251–8.
- Essler R, Yoshida H. Jet grouting. In: Moseley MP, Kirsch K, editors. Ground Improvement. Spon Press; 2004. p. 160–96.
- Croce P, Flora A. Analysis of single-fluid jet grouting. In: Raison CA, editor Ground and soil improvement. Thomas Telford; 2004. p. 177–86.
- Hardjito D, Rangan BV. Development and properties of low-calcium fly ash based geopolymer concrete – research report GC 1. Perth; 2005.
- Criado M, Fernández-Jiménez A, De la Torre AG, Aranda MAG, Palomo A. An XRD study of the effect of the SiO_2/Na_2O ratio on the alkali activation of fly ash. Cem Concr Res 2007;37:671–9.
- Villa C, Pecina ET, Torres R, Gómez L. Geopolymer synthesis using alkaline activation of natural zeolite. Constr Build Mater 2010;24:2084–90.
- Winnefeld F, Leemann A, Lucuk M, Svoboda P, Neuroth M. Assessment of phase formation in alkali activated low and high calcium fly ashes in building materials. Constr Build Mater 2010;24:1086–93.
- Chindaprasirt P, Jaturapitakkul C, Chalee W, Rattanasak U (2009) Comparative study on the characteristics of fly ash and bottom ash geopolymers. Waste Manag (New York, NY) 29 (2):539–543.

- Chindaprasirt P, Chareerat T, Hatanaka S, Cao T (2011) Highstrength geopolymer using fine high-calcium fly ash. J Mater Civ Eng 23(3):264
- Gourly, C. S., Newill, D. and Schreiner, H. D. (1993). Expansive soils: TRL's research strategy. *Proc., 1st Int. Symp. on Engineering Characteristics of Arid Soils*.
- Chen, F. H. (1975). *Foundations on expansive soils*, Elsevier Science, Amsterdam, The Netherlands.
- Desai, I. D. and Oza, B. N. (1997). Influence of anhydrous calcium chloride on shear strength of clays. *Symp. on Expansive Soils*, Vol. 1, 17–25.
- Cokca, E. (2001). Use of class C fly ash for the stabilization of an expansive soil. *Jl. Of Geotech.andGeoenv. Engineering, ASCE*, 127 (**7**), 568–573.
- Phani Kumar, B. R., Naga Reddayya, S. and Sharma, R. S. (2001). Volume change behavior of fly ash-treated expansive soils. *Proc., 2nd Int. Conf. on Civil Engineering*, Indian Inst. of Science, Bangalore, India, Vol. 2, 689–695.
- Rollings, M. P. and Rollings, R. S. (1996). *Geotechnical materials in construction*, McGraw–Hill, New York.
- Sridharan, A., Pandian, N. S. and Rajasekhar, C. (1996). Geotechnical characterization of pond ash. *Proc., Conf. on Ash Ponds and Ash Disposal Systems*, Indian Inst. of Technology, New Delhi, India, 97–110.
- Edil, T. B., Berthoueux, P. M. and Vesperman, K. D. (1987). Fly ash as a potential waste liner. *Proc., Geotechnical Practice for Waste Disposal*, R. D. Woods, ed., ASCE, New York, 447–461.
- Palomo, A., Grutzeck, M.W. and Blanco M.T. (1999), Alkali-activated fly ashes A cement for the future, *Jl. of Cement and Concrete Research, Elsevier Science Ltd.*, 29, 1323-1329.

- Locat, J., Berube, M. A. and Choyuette, M. (1990), Laboratory Investigations on the Lime Stabilization of Sensitive Clay: Shear Strength Development, *Canadian Geotechnical Journal*, 27, 294–304.
- Chew, S. H., Kamaruzzaman, A. H. M. and Lee, F. H. (2004), Physicochemical and Engineering Behavior of Cement Treated Clays, *Jl of Geotech.andGeoenv. Engineering, ASCE*, 130 (7), 696–706.
- Holtz, W. G. and Gibbs, H. J. (1956). "Engineering properties of expansive clays." *Trans. Am. Soc. Civ. Eng.*, Vol 121**,** 641–677.