

EFFECT OF ADDITION OF GGBS & GLASS POWDER ON THE PROPERTIES OF GEOPOLYMER CONCRETE

*A dissertation submitted
in partial fulfillment of the requirements for
the award of degree of*

**MASTER OF ENGINEERING
IN
STRUCTURAL ENGINEERING**

Submitted by:

**HARSHAV SETHI
(ROLL NO. 801422014)**

UNDER THE SUPERVISION OF

Dr. PREM PAL BANSAL

*Associate Professor
Department of Civil Engineering*




**DEPARTMENT OF CIVIL ENGINEERING
THAPAR UNIVERSITY, PATIALA 147004
JULY 2016**

DECLARATION

I, Harshsav Sethi, hereby declare that this dissertation entitled "EFFECT OF ADDITION OF GGBS & GLASS POWDER ON PROPERTIES OF GEOPOLYMER CONCRETE" in fulfillment of the requirement for the award of the Degree of **Master of Engineering in Structural Engineering** and submitted in the Civil Engineering Department, Thapar University, Patiala is an authentic record of my work carried out during a period from January 2016 to July 2016 under the supervision of **Dr. Prem Pal Bansal, Associate Professor**, Department of Civil Engineering, Thapar University, Patiala.


This matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other University.

Date: 14/07/2016



HARSHSAV SETHI
Roll No. : 801422014

CERTIFICATE

This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge and belief.


Dr. PREM PAL BANSAL
Associate Professor
Department of Civil Engineering
Thapar University, Patiala

Countersigned by


Dr. NAVEEN KWATRA
Professor and Head
Department of Civil Engineering
Thapar University, Patiala


Dr. S.S. BHATIA
Dean of Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENT

Time has provided me the cherished opportunity to express my heartfelt gratitude to my guide Dr. Prem Pal Bansal, Associate Professor, CED ,Thapar University, Patiala, who permitted me to carry out research work under his able guidance. I shall ever remain indebted to him for his meticulous guidance, constructive criticism, clear thinking, keen interest, constant encouragement and forbearance right from the beginning of this research to its completion.

I wish to express my sincere thanks to Dr. Naveen Kwatra, Professor and Head, CED, Thapar University, Patiala, who has been a constant source of inspiration for me throughout this dissertation work.

The cheerful support of my friends and colleagues is sincerely appreciated. Special words of appreciation go to Sh. Ram Simran, Sh. Virender and other laboratory colleagues who helped me in my experimental work.

I am also thankful to all the staff members of Civil Engineering Department for their full cooperation and help.

Above all, I thank my parents, whose love and affectionate blessing have been a constant source of inspiration in making this manuscript a reality. I render my gratitude to the almighty who bestowed self confidence, ability and strength in me to complete this work.



(HARSHAV SETHI)

ABSTRACT

There is a growing interest in the development of new concrete type known as geopolymer in the recent years due to its lower global warming potential, higher durability, better serviceability and overall economy.

Geopolymer concrete represents a class of alkaline activation systems in which activation of the aluminosilicate source such as flyash is carried out by alkaline activators such as sodium silicate & sodium hydroxide respectively. The final end product of this whole reaction process is a three dimensional polymeric chain & ring structure containing Si – O – Al – O bonds. The system used in our dissertation work is a calcium-alumino-silicate system comprising of a combination of Flyash, GGBS & Glass Powder & activated using sodium hydroxide.

The present study aims at adopting ambient curing for developing geopolymer concrete so as to make this concrete feasible for mass applications. Keeping up with ambient curing the addition of GGBS in percentages of 15%,20%,25% & Glass Powder in percentages of 5%,10%,15% has been done so as to bypass the need for carrying out oven curing. In addition to this the study aims at gauging the effect of different molarities i.e 4M, 8M & 12M on the mixes prepared & in turn deciding the optimum molar concentration for preparation of the mixes.

To develop this geopolymer concrete according to our objectives some of the past literature has been reviewed to understand its reaction mechanism and accordingly select the proportion of materials for carrying out experimental work. To study the effectiveness of ambient curing over oven curing a total of 150 no samples have been prepared out of which 15 no comprise the control mix. The mix proportions of the geopolymer concrete samples prepared in this study have been adopted on a trial and error basis due to non availability of IS codes for design mix.

To carry out the dissertation work as per proposed objectives cubical specimens of size 150mm x 150mm x 150 mm, cylindrical specimens of size 300mm height x 150mm dia. & beam specimens of size 150mm x 150mm x 700mm have been prepared for finding out compressive, split tensile & flexural strength of concrete. Testing of these specimens have also been carried out according to IS 516-1959 & IS 5816-1999 respectively.

On testing the specimens for the properties mentioned above it has been found that the control mix containing only flyash has developed lesser strength as compared to all the other blended mixes. In addition to this it has been observed that samples with highest percentage of GGBS have developed highest strength. From the strength point of view the noticeable variation have been non observance of above mentioned pattern in 12M category samples & lesser flexural strength obtained for 28 days as compared to 7 days in the 12M category samples.

On the molarity front it has been seen that the maximum strength has been obtained for 4M category samples which is in variance with the trend observed in flyash based mixes. To study the effect of these variations comparison charts & tables have been made for each property studied. The possible reasons for each of these variations have been assigned on the basis of SEM-EDS test results and recommendations regarding further scope of work have been suggested.

TABLE OF CONTENTS

CONTENT	PAGE NO
DECLARATION	i
CERTIFICATE	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	xi
CHAPTER – 1 INTRODUCTION	
1.1 General	1
1.2 Definition of Geopolymer concrete	3
1.3 Classification of Geopolymer concrete	5
1.4 Reaction Mechanism of Geopolymer concrete	5
1.5 Advantages of Geopolymer Concrete	6
1.6 Applications of Geopolymer Concrete	7
1.7 Limitations of Geopolymer Concrete	8
1.8 Objective of the Dissertation	9
1.9 Orientation of the Dissertation	9
CHAPTER – 2 LITERATURE REVIEW	
2.1 General	10
2.2 Review of work done on Geopolymer Concrete	11
CHAPTER- 3 MATERIAL AND DESIGN METHODOLOGY	
3.1 General	44
3.2 Characteristics of Materials used	44
3.2.1 Flyash	44
3.2.2 Glass Powder	46

3.2.3	GGBS	47
3.2.4	Coarse Aggregates	49
3.2.5	Fine Aggregates	51
3.2.6	Water	52
3.2.7	Alkaline Activator	52
3.2.7.1	Properties of Sodium Hydroxide	53
3.3	Experimental Programme	
3.3.1	Test Data for materials	54
3.3.2	Scheme of samples prepared for study	55
3.3.3	Mix proportions used in the study	56
3.3.4	Casting procedure followed in the study	57
3.4	Test methods	
3.4.1	Specific gravity	
3.4.1.1	Definition & Purpose of Test	58
3.4.1.2	Calculations	59
3.4.2	Sieve analysis for coarse and fine aggregates as per IS 2386 (Part - 1) 1963	
3.4.2.1	Definition & Purpose of Test	59
3.4.2.2	Calculations	59
3.4.3	Compressive Strength	
3.4.3.1	Definition & Purpose of Test	60
3.4.3.2	Calculations	60
3.4.4	Flexural Strength	
3.4.4.1	Definition & Purpose of Test	61

3.4.4.2 Calculations	62
3.4.5 Split Tensile Strength	
3.4.5.1 Definition & Purpose of Test	62
3.4.5.2 Calculations	63
3.4.6 SEM & EDS Test	
3.4.6.1 Definition & Purpose of Test	63
3.5 Test Calculations	64
CHAPTER- 4 RESULTS AND DISCUSSION	
4.1 General	66
4.2 Compressive strength	66
4.3 Flexural strength	79
4.4 Split Tensile Strength	85
CHAPTER- 5 CONCLUSIONS	
5.1 General	91
5.2 Compressive strength	91
5.3 Flexural strength	91
5.4 Split Tensile Strength	92
5.5 Scope for further work	92
REFERENCES	

LIST OF FIGURES

FIGURE	TITLE	PAGE NO
1.1	Summary of CO ₂ -e for Grade 40 Concrete Mixtures with OPC and Geopolymer Binders(Turner & Collins(2013))	2
1.2	Pores in the Cross Section of Broken Geopolymer Concrete Specimen	4
1.3	Conceptual Mechanism of Geopolymerisation (Duxton et al., 2007).	6
2.1	Strength Development of Reactive Aggregate with Additional GLP. (Shayan & Xu, 2004)	13
2.2	Compressive Strength Development of IPCs with Age.(Wongpa et al., 2010).	14
2.3	The Occurring of Cracks in IPCs Illustrated from the Assumption (Wongpa et al., 2010).	15
2.4	Compressive Strength Variation of Geopolymer Concrete in Series A (Deb et al., 2014).	24
2.5	Compressive Strength Variation of Geopolymer Concrete with Different Slag Content and SS/SH ratio 2.5 of Series B. (Deb et al., 2014).	25
2.6	Change in Compressive Strength for Added Water in Geopolymer Concrete Mixtures. (Deb et al., 2014).	25
2.7	Heat Evolution of AA-Slag/Fly Ash Blends with Activator Modulus of 1.8 (Gao et al., 2015).	28
2.8	FTIR Spectra of Solid Raw Materials(Gao et al., 2015).	29
2.9	FTIR Spectra of Alkali Activated Slag/Fly Ash Blends(Gao et al., 2015)	30
2.10	Scanning Electron Microscopic Images of GP1 & FA .(Kamali & Ghahremaninezhad, 2015).	32
2.11	X-ray Diffraction Spectra of GP1, GP2, and FA. (Kamali & Ghahremaninezhad, 2015).	32
2.12	Compressive Strengths of Concretes at 7 days, 28 days, and 91 days of Curing. (Kamali & Ghahremaninezhad, 2015).	34

FIGURE	TITLE	PAGE NO
2.13	Flexural Strength of G series (Unreinforced) Specimens. (Nazari et al., 2015).	36
2.14	SEM Images of the Weakest Specimen .(Nazari et al., 2015).	37
2.15	SEM Images of the Medium Strength Specimen .(Nazari et al., 2015).	37
2.16	SEM Images of the High Strength Specimen .(Nazari et al., 2015).	38
2.17	Splitting Tensile Strength f_{ct} and Compressive Strength f_c of Alkali Activated FC and GGBFS Concrete Along with Proposed Models	41
3.1	Actual Photograph of Flyash	45
3.2	Actual Photograph of Glass Powder	47
3.3	Actual Photograph of GGBS	48
3.4	Actual Photograph of Sodium Hydroxide	53
3.5	Schematic Diagram Showing Casting Schedule	55
3.6	Mould Containing Vibrated Geopolymer Concrete	58
3.7	Compressive Strength Test Setup	60
3.8	Flexural Strength Test Setup	61
3.9	Split Tensile Test Setup	63
4.1	Effect of Concentration of NaOH solution as alkaline activator on 7 day Compressive Strength	68

FIGURE	TITLE	PAGE NO
4.2	Effect of Concentration of NaOH solution as alkaline activator on 28 day Compressive Strength	69
4.3	Compressive Strength Variation for Different Mixes at 7 days	70
4.4	Compressive Strength Variation for Different Mixes at 28 days	70
4.5	EDS Images of M1-4M ,M2-4M ,M3-4M	71
4.6	SEM Images of M1-12M ,M2-12M ,M3-12M	73
4.7	SEM Images of Control Sample,M1-4M,M1-8M,M1-12M	75
4.8	EDS Images of M-CO, M1-4M	77
4.9	SEM Images of M1-4M,M2-4M,M3-4M	78
4.10	Effect of Concentration of NaOH solution as alkaline activator on 7 day Flexural Strength	81
4.11	Effect of Concentration of NaOH solution as alkaline activator on 28 day Flexural Strength	82
4.12	Flexural Strength Variation for Different Mixes at 7 days	82
4.13	Flexural Strength Variation for Different Mixes at 28 days	83
4.14	SEM Images of M1-12M & M3-12M	84
4.15	Split Tensile Strength Variation for Different Mixes at 28 days	87

LIST OF TABLES

TABLE	TITLE	PAGE NO
2.1	Particle Size Range for Different Categories of Glass(Shayan & Xu, 2004).	11
2.2	Concrete Mixes for 25 MPa Concrete(Air Entrained)(Shayan & Xu, 2004).	12
2.3	Mix Proportions of Inorganic Polymer Concrete Mixtures (kg/m ³)(Wongp et al., 2010).	13
2.4	Trial Mix-1 (1:1.3:3.10)(Aleem & Arumairaj , 2012).	16
2.5	Trial Mix-2 (1:1.4:3.20) (Aleem & Arumairaj , 2012).	16
2.6	Trial Mix-3 (1:1.5:3.30) (Aleem & Arumairaj , 2012).	16
2.7	Trial Mix-4 (1:1.6:3.40) (Aleem & Arumairaj , 2012).	17
2.8	Compressive Strength (N/mm ²) in 7 days(Aleem & Arumairaj , 2012).	17
2.9	Compressive Strength (N/mm ²) in 28 days(Aleem & Arumairaj , 2012).	17
2.10	Mix Proportions (Naidu et al., 2012).	18
2.11	Compressive Strengths for Different Ages of Geopolymer Concrete (Naidu et al., 2012).	19
2.12	Flexural Strengths of Geopolymer Concrete at 28 days (Naidu et al., 2012).	19
2.13	Mix Proportions of Alkali-Activated Fly Ash/Slag Concrete (Lee & Lee , 2013).	20
2.14	Summary of Test Results (Lee & Lee , 2013).	21
2.15	Mix Design Parameters and Compressive Strength Results (Deb et al., 2014).	23

TABLE	TITLE	PAGE NO
2.16	Major Chemical Compositions of the Raw Materials (Gao et al., 2015).	26
2.17	Mix Proportions of AA-Slag/Fly Ash Pastes (Gao et al., 2015).	27
2.18	Chemical and Physical Properties of Glass powders and Fly Ash. (Kamali & Ghahremaninezhad, 2015).	31
2.19	Mixture Proportions of Unreinforced Geopolymer Pastes (Nazari et. al, 2015).	35
2.20	Summary of Compressive Strength(f_c')Tensile Strength (f_{ct}), Elastic Modulus & Poisson Ratio (μ)Results for All Mixtures(Thomas & Peethamparan ,2015)	40
2.21	Variation in Compressive Strength of Cubes in MPa For (FA+GP) (Mithanthaya & Rao, 2015).	43
2.22	Variation in Compressive Strength of Cubes in MPa For (FA+10%GP+GGBS)(Mithanthaya & Rao, 2015).	43
3.1	Physical Properties of Flyash	45
3.2	Chemical Properties of Flyash	46
3.3	Physical Properties of Glass Powder	47
3.4	Physical Properties of GGBS	48
3.5	Chemical Properties of GGBS	49
3.6	Properties of Coarse Aggregates	50
3.7	Sieve Analysis of Coarse Aggregates (20mm)	50
3.8	Sieve Analysis of Coarse Aggregates (10mm)	51

TABLE	TITLE	PAGE NO
3.9	Sieve Analysis of Fine Aggregates	52
3.10	Mix Proportion of Geopolymer Concrete Samples	56
4.1	Compressive Strength Test Results	67
4.2	Flexural Strength Test Results	80
4.3	Split Tensile Strength Test Results	85
4.4	Comparison of Measured Split Tensile Strength with Predicted Strength by Different Researchers	88
4.5	Comparison of Measured Split Tensile Strength with Predicted Strength by OPC Concrete Codal Provisions	89

1.1 GENERAL

With growing concern over environmental problems related to global warming, there have been many efforts in the construction field to reduce CO₂ emissions. On observation it has been found that about one ton of CO₂ is emitted for every ton of cement produced & this accounts for approximately 5–7% of global anthropogenic CO₂ emissions. The key causes of high CO₂ emissions arising from OPC manufacture have been attributed to calcination of limestone, one of the key ingredients, which leads to formation and release of CO₂ & high energy consumption during manufacturing, including heating raw materials within a rotating kiln at temperatures greater than 1400°C .

Alternative cements to OPC have been proposed to reduce greenhouse gas emissions such as blended cements, in which OPC has been partly substituted by supplementary cementitious materials (SCCs), to be used as binder for concrete. Common SCCs include fly ash, a fine waste residue that is collected from the emissions liberated by coal burning power stations, and ground granulated blast furnace slag, a waste by-product from steelmaking. Flower and Sanjayan (2007) have shown that blended cements reduce CO₂ emissions by 13–22%, although this estimate can vary depending on local conditions at the source of raw materials, binder quantity and amount of OPC replacement, type of manufacturing facilities, climate, energy sources, and transportation distances.

To carry out a complete overhaul of the OPC from construction activities an alternative cementitious binder, termed geopolymers, comprising of an alkali-activated fly ash, has been considered as a substitute for OPC. This new class of material known as geopolymers was developed in 1978 by a French scientist Joseph Davidovits. He defined geopolymers as a family of amorphous alkali or alkali-silicate activated aluminosilicate binders of composition $M_2O \cdot mAl_2O_3 \cdot nSiO_2$, usually with $m \approx 1$ and $2 \leq n \leq 6$ (M usually is Na or K). He defined that this process of geopolymerisation involved a chemical reaction between various alumino-silicate oxides with silicates under highly alkaline conditions, yielding polymeric Si – O – Al – O bonds.

Turner & Collins (2013) carried out a comparative study of the carbon footprint of OPC & geopolymer concrete with the help of term defined as CO₂-e emitted (kg CO₂-e/kg). They defined this term as the amount of energy utilized in activities necessary to construct 1m³ of concrete & the calculation of CO₂-e was based on the collective contributions of CO₂, CH₄, NO₂, and synthetic gases evolved during each activity, taking into account the energy content of the fuel, the global warming gas types produced, and the respective gas global warming potential (GWP), when the fuel is fully combusted. A comparison of the carbon footprint of OPC & geopolymer concrete is shown in Fig. 1.1.

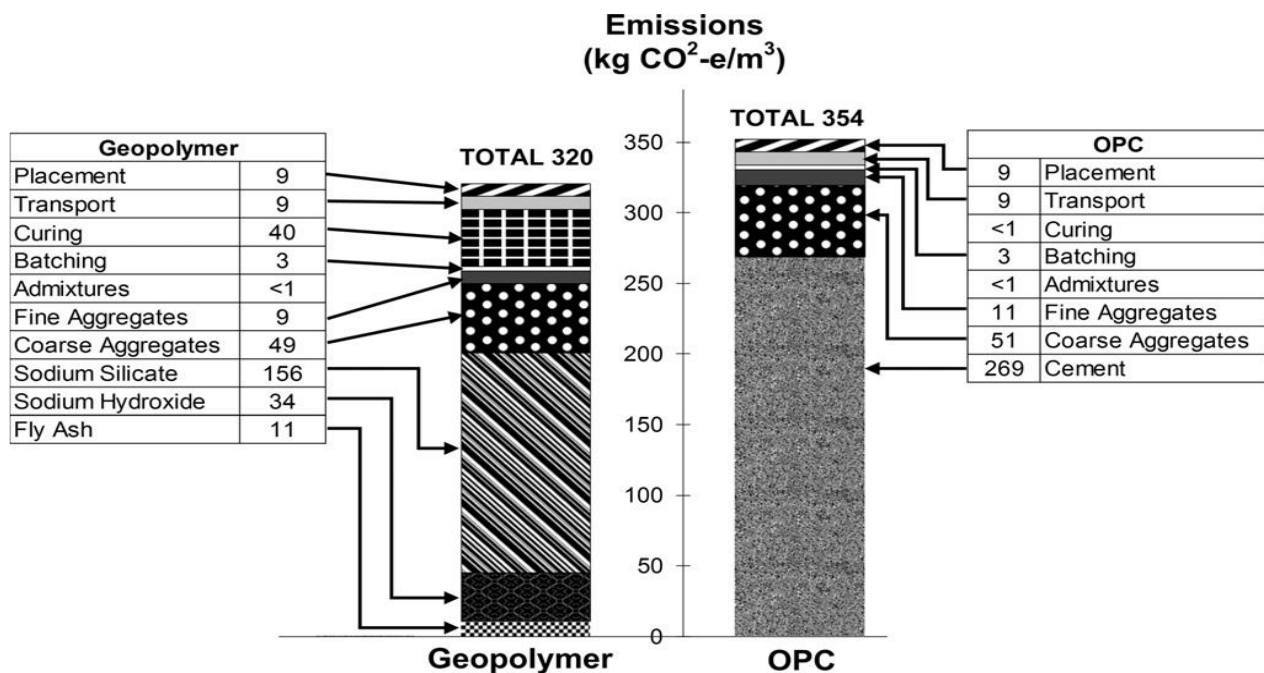


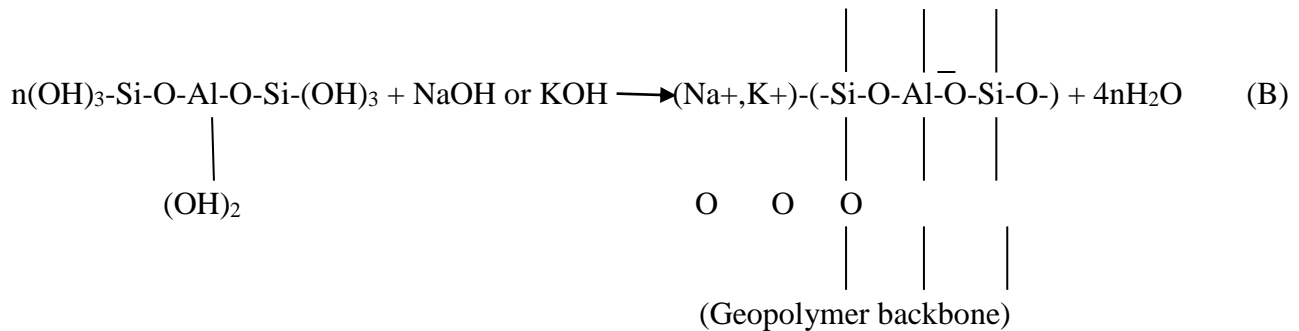
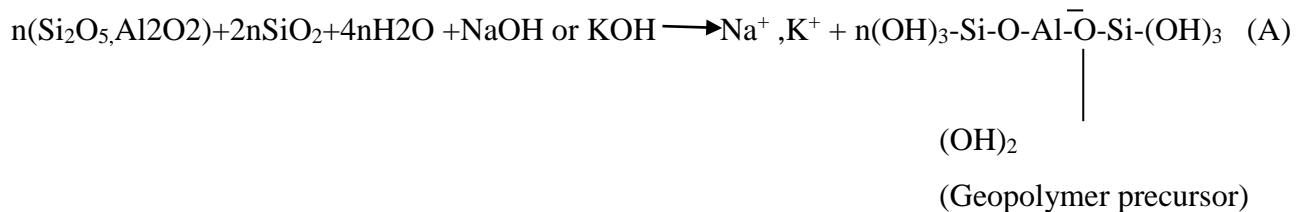
Fig. 1.1. Summary of CO₂-e for Grade 40 Concrete Mixtures with OPC and Geopolymer Binders(Turner & Collins,2013)

As shown in the Fig. 1.1 the carbon emissions involved in the formation of geopolymer concrete are approximately 9% lesser than that of OPC cement concrete. So considering this in mind a proposition was prepared to carry out dissertation work after removal of oven curing, sodium silicate & cement i.e major contributors to CO₂-e without compromising too much on the strength & durability front. This led to use of pozzolanic materials like flyash, glass powder and alccofine (GGBS) in varying proportions so that the desired strength & a comparatively lesser carbon footprint of the concrete can be achieved.

1.2 DEFINITION OF GEOPOLYMER CONCRETE (GPC)

Geopolymer concrete may be defined as amorphous three dimensional aluminosilicate material with ceramic-like properties having chemical composition similar to natural zeolitic material. The basic reaction involved in the formation of geopolymer concrete is a polymerization reaction in which aluminosilicates are rapidly dissolved in the presence of alkali hydroxide and silicate solution thereby releasing free SiO_4 and AlO_4 tetrahedral units in solution. These tetrahedral units are alternatively linked to polymeric precursors by sharing oxygen atoms thus forming amorphous geopolymers.

Geopolymer concrete basically involves a reaction of flyash with an aqueous solution containing NaOH & Na_2SiO_3 in their mass ratio thereby resulting in a material with 3D polymeric chain and ring structure. The polymeric chain & ring structure formed primarily consists of Si-O-Al-O bonds throughout the body of concrete. Due to formation of chain and ring polymers throughout the concrete geopolymers are also known as polysialates. The process involved in the formation of geopolymer concrete can be described by equation A & B as follows:



Geopolymer concrete differs from OPC concrete in the sense that the water added during mixing is expelled from the matrix of geopolymer concrete as shown in eqn B. Water added in the geopolymer concrete is used only for workability purpose & has no role in the chemical reaction unlike OPC concrete. The expulsion of water from the geopolymer matrix during curing & further drying periods leaves behind nano-pores in the matrix. as shown in Fig. 1.2.



Fig. 1.2. Pores in the Cross Section of Broken Geopolymer Concrete Specimen

The curing involved in the formation of geopolymer concrete is primarily of two types i.e heat curing & ambient(room temperature) curing. Heat curing is mostly adopted for flyash based geopolymer concrete mixtures because of low reactivity of flyash at lesser temperature. The heat curing is generally carried out in the form of oven curing or steam curing at a specified temperature. Ambient(Room Temperature) curing is mainly adopted for blended mixes containing a mix of flyash with other supplementary cementing materials.

Since heat curing in an oven or steam curing is practically not feasible at sites therefore ambient curing of the geopolymer concrete samples has been resorted to in our dissertation work. The main concern regarding gain of strength at ambient curing in our dissertation work has been addressed by addition of GGBS & Glass Powder.

1.3 CLASSIFICATION OF GEOPOLYMER CONCRETE (GPC)

Geopolymer concrete primarily comprises of two types of system which are as follows:

- 1) Calcium and Silica enriched (Ca + Si) system
- 2) Aluminosilicates dominated (Si + Al) system

1) Calcium and Silica enriched (Ca + Si) system

In this type of system the precursor for carrying out the reaction process of geopolymer concrete is ground granulated blast furnace slag (GGBS). In this type of system the reaction product obtained in process of formation of geopolymer concrete is a C-S-H (I) type gel with a lower Ca/Si ratio and a high Al incorporation.

2) Aluminosilicates dominated (Si + Al) system

In this type of system the precursor for carrying out the reaction process of geopolymer concrete is class F fly ash or metakaolin. In this type of system the reaction product obtained in process of formation of geopolymer concrete is a N-A-S-H type gel with three-dimensional network as the major product.

1.4 REACTION MECHANISM OF GEOPOLYMER CONCRETE (GPC)

The reaction mechanism involved in the formation of geopolymer concrete is different from the mechanism involved in formation of ordinary Portland cement concrete. The three main steps involved in the process of geopolymerisation are as follows:-

- Dissolution of any pozzolanic compound or source of silica and alumina that is readily dissolved in alkaline solution, with the formation of mobile precursors of aluminosilicate oxides through the complex action of hydroxide ions.
- Partial orientation of mobile precursors as well as the partial internal restructuring of the alkali polysialates.
- Re-precipitation of the particles from the initial solid phase where the whole system hardens to form an inorganic polymeric structure.

In this process reaction of alumina silicate resources occurs with alkali solution thereby leading to dissolution and precipitation of Al & Si complex. After dissolving alumina silicate particles from their surfaces, precipitation of gel begins & Al and Si complex penetrates in to gel phase. After that reorganization of the complex formed occurs followed by subsequent condensation of the complex formed. The conceptual mechanism for this whole process is shown in Fig. 1.3.

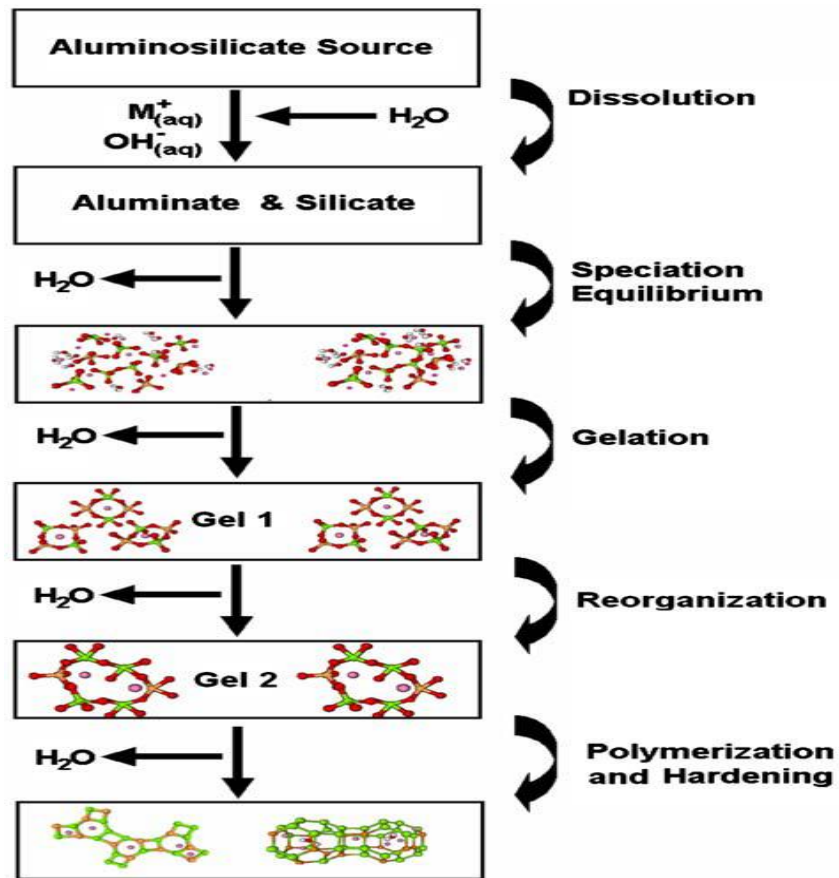


Fig. 1.3. Conceptual Mechanism of Geopolymerisation (Duxton et al., 2007).

1.5 ADVANTAGES OF GPC

Geopolymer concrete offers several advantages over portland cement concrete the list of which is as follows:-

- For a similar performance level, geopolymer concrete is cost effective against Portland cement concrete.
- Geopolymer concrete has low drying shrinkage as compared to Portland cement concrete.
- Geopolymer concrete has low creep as compared to Portland cement concrete.

- Geopolymer concrete has better resistance to sulphate attack as compared to Portland cement concrete.
- Geopolymer concrete has better acid resistance as compared to Portland cement concrete.
- Geopolymer concrete has better fire resistance as compared to Portland cement concrete.
- Geopolymer concrete provides an additional advantage of consumption of waste material such as Flyash, GGBS, RHA thereby reducing the problem associated with its disposal.
- Geopolymer concrete helps in saving the landfilling costs associated with the disposal of waste material such as Flyash, GGBS, RHA.
- Geopolymer concrete has 55% reduction in pore diameter as compared to Portland cement concrete thereby leading to reduced permeability.
- The global warming potential of Geopolymeric concrete is 70% lower than cement concrete.

1.6 APPLICATIONS OF GPC

Although use of geopolymer concrete at ground level is still at nascent stages but recently structures have been constructed using geopolymer concrete. Some of the interesting structures, where GPC has been successfully developed and used are discussed as below:-

- **Precast Industry**:- When geopolymer concrete is subjected to dry heat or steam cured it gives a high value of early age strength. This characteristic of high early age strength makes it useful for the precast industry & moreover facilities such as steam curing or heated bed curing can be carried out for components in precast industry. Some of the components prepared from geopolymer concrete are as follows:
 - Precast railway sleepers
 - Reinforced Box Culverts
 - Precast footway panels
- **Sewer systems**:- Geopolymer concrete has excellent resistance to acidic conditions & this characteristic of it makes it suitable for use in construction of sewer pipes.
- **Airport**:- Geopolymer concrete has been used in regional airport in southeast Queensland(Australia).In airport concrete pavements having thickness of 400-450 mm have been constructed from geopolymer concrete.

- **In-situ Concrete application**:- Geopolymer concrete has been used to make in-situ geopolymer concrete landscape retaining walls.
- **Structural Application**:-The Global Change Institute(GCI) situated inside University of Queensland's (Australia) has been constructed with the use of geopolymer concrete. It is a four storey high building for public use.

OTHER APPLICATIONS OF GEOPOLYMERS

Some of the applications of geopolymers apart from its usage in construction sector are listed as follows:-

- **Building Materials**:- Bricks, Blocks, pavers,Self glazed tiles, Acoustic Panels ,Pipes by Zazil in India
- **Fire Resistant material**:-Fire & heat resistant fiber composite material such as geopolymite & geopolytherm patented by Geopolymer Institute.
- **Refractory Application**:-Refractory moulds for metal casting
- **Immobilization of toxic materials**:-Encapsulation of domestic, hazardous & radioactive materials in a very impervious high strength material.
- **Archeology**:-Repairing & restoration of archeological monuments.
- **Base Liners**:-Construction of low permeability base liners in landfill

1.7 LIMITATIONS OF GPC

Geopolymer concrete inspite of its numerous advantages is still not very popular in construction sector for the reasons listed below:-

- Lack of IS design mix codes for GPC limits its economical usage as all the work carried out on GPC has been based on trial mixes prepared on the basis of past experience.
- Curing at elevated temperature is not possible at sites & if ambient curing has to be resorted to than that will also be dependent on the season & geographic location change.
- Preparation of the alkaline activator solution in large quantities requires skilled supervision.
- Working with alkaline activator solution requires proper safety equipment as its contact with the skin can lead to skin burns also.
- Proper procedure of mixing is to be adopted so as ensure that no case of unreacted alkali remains within the final product which will limit its strength & durability to a great extent.

1.8 OBJECTIVE OF THE DISSERTATION

On the basis of study done upto now the objectives for the dissertation work have been fixed and details of which are as follows:-

- To study the effect of addition of different percentages of GGBS i.e. 15%, 20%, & 25% on strength properties such as compressive strength, flexural strength and split tensile strength of geopolymer concrete.
- To study the effect of addition of different percentages of glass powder i.e. 5%, 10%, & 15% on strength properties such as compressive strength, flexural strength and split tensile strength, of geopolymer concrete.
- To study the effect of different molarities i.e. 4M, 8M & 12M of NaOH solution as alkaline activator on the mechanical properties studied & in turn deciding the optimum molar concentration for preparation of the mixes.
- To study the feasibility of geopolymer concrete for site applications by finding its gain of strength with age & understanding the ingredients responsible for strength gain at different ages.

1.9 ORIENTATION OF THE DISSERTATION

The dissertation report consists of five chapters:

Chapter 1:- Provides introduction & defines geopolymer concrete. This chapter enlists the advantages, limitations and applications of the geopolymer concrete. Furthermore reaction mechanism involved in the formation of geopolymer concrete has also been discussed.

Chapter 2:- Deals with the study of past research done on geopolymer concrete.

Chapter 3:- Details the scheme of experimentation, materials used and variables involved. Information about test methods & mixes used for geopolymer concrete have been discussed in this chapter.

Chapter 4:- Presents the results and the discussion of blended & control mixes for different concentrations of alkaline activator .

Chapter 5:- Summarizes and concludes the findings of the study. Few recommendations for further studies are also discussed

References are placed at the end.

2.1 GENERAL

Geopolymer was introduced to the world in the late 1970s. It was developed in 1978 by a French scientist Joseph Davidovits. The use of the material increased during the 1980s and 1990s for non structural applications. During this period, geopolymer became recognized for high thermal stability and good acid resistance. Keeping up with the pace it has been used for a no of non structural applications but on structural front it is largely confined to lab scale. Of late usage of geopolymer concrete for construction of building has been reported in Australia.

This chapter presents a review of literature highlighting the work done by various researchers with regards to the mechanical properties of GPC. The mechanical properties which have been primarily reviewed in the research papers are compressive strength, flexural strength & split tensile strength. To have a clear overview of our proposed work research papers using similar kind of materials & under similar testing condition have been mainly reviewed.

For the review of the papers presented all the details such as materials used, mix proportion, casting procedure, results & their discussion have been thoroughly presented. All the papers presented in the literature review have been discussed chronologically thereby indicating the advancement in the material up till date.

Furthermore, the significant developments regarding performance and applications of GPC that have taken place in the recent past have also been studied. Some of the papers covered in the literature review are Shayan & Xu (2004), Wongpa et al. (2010), Aleem & Arumairaj(2012), Naidu et al. (2012), Lee & Lee (2013), Deb et al. (2014), Gao et al. (2015), Kamali & Ghahremaninezhad (2015), Nazari et al. (2015), Thomas & Peethamparan (2015) & Mithanthaya & Rao (2015) respectively.

All the necessary information in the form of source of materials, mix proportions adopted, properties studied and their results in the form of graphs & tables have been incorporated in this literaturereview.

2.2 REVIEW OF WORK DONE ON GPC

Shayan & Xu (2004) studied the three aspects of glass utilisation in concrete. These included coarse glass aggregate, fine glass aggregate and GLP for use in concrete. The particle size range for each of these products is given below in Table 2.1.

Table 2.1

Particle Size Range for Different Categories of Glass (Shayan & Xu, 2004).

Product	Particle size range	Designation
Coarse Glass Aggregate	4.75-12 mm	CGA
Fine Glass Aggregate	0.15-4.75 mm	FGA
Glass powder	< 10 um	GLP

The coarse and fine glass particles were used as replacement for the corresponding size ranges of natural aggregate materials, whereas the GLP was used as a pozzolanic material, i.e., the same application as for fly ash. The natural materials used in this work were nonreactive, natural, victorian concrete sand and a crushed basalt coarse aggregate. A reactive greywacke coarse aggregate from NSW was used to assess the effectiveness of GLP in suppressing ASR expansion.

Glass, due to its silica-rich nature and amorphous structure, is susceptible to chemical attack under the high alkali conditions provided by the hydrated cement phase in the concrete. This chemical attack on glass leads to production of extensive formation of ASR gel, which is expansive and could cause premature cracking in the concrete, if appropriate precautions are not put in place in the formulation of the concrete mix.

Based on the criteria given in Australian Codes, it was found that use of up to 30% glass in the concrete may not cause deleterious effects, particularly if the alkali content of the concrete was low (below 3-kg Na₂O equivalent per cubic meter). At higher alkali contents of concrete, further expansion may occur. In addition to the glass content of mortar bars, the particle size also had an effect on the expansion. Therefore, it was concluded that the magnitude of expansion would depend on the interaction of glass content, particle size and alkali content of the concrete. These results showed that glass could react and produce ASR gel and that once the particle size was sufficiently reduced, it could act as a pozzolanic material.

As far as utilisation as fine and coarse aggregates was concerned, trial mixes were undertaken with the view of establishing how much fine and coarse glass could be used in concrete mixtures that would be suitable for some structural applications and for concrete pavements. The trials aimed at producing concrete appropriate as Vic Roads 32-MPa strength grade. This mixture contained a binder of 255-kg/m³ cement and 85-kg/m³ fly ash. The coarse aggregate and sand contents were 1080 and 780 kg/m³, respectively. After a number of trials & adjusting the properties of fresh and hardened concrete, the following concrete mixture formulations were found to be satisfactory, as detailed in table 2.2.

Table 2.2

Concrete Mixes for 25 MPa Concrete(Air entrained) (Shayan & Xu, 2004).

Mix no.	Binder(%)		Glass content(%)		w/b	Slump (mm)	Air(%)	Strength (MPa)		Super plasticiser
	Cement	Flyash	Coarse	Fine				7 days	28 days	
1	75	25	50	50	0.46	60	1	28.6	39.9	Yes
2	75	25	50	50	0.52	80	2	25.3	35.0	No

In the use of glass as pozzolanic material, replacement was done with cement & mortar cubes having aggregate/cement ratio of 2.25 & water/cement ratio of 0.47 were prepared. In the case of cement replacement, the reduction in the 28-day strength increased with the level of cement replacement and for samples containing up to 30% replacement it was concluded that reduction in the strength occurred mainly because in such short periods the pozzolanic effects were not fully operational. In addition to this, replacement of aggregates was also done with GLP & mortar cubes were prepared. On testing mortar cubes at 28 days it was found that the effect of replacement of aggregates by GLP was more pronounced as compared to the replacement of cement by GLP.

On studying about the long term strength development characteristics it was observed from the tests that the replacement of cement and aggregates by GLP was beneficial for strengths obtained at longer ages & it was probably due to improvement in the particle packing as well as the pozzolanic reaction becoming fully operational at longer ages. The result for this observation is shown by Fig. 2.1

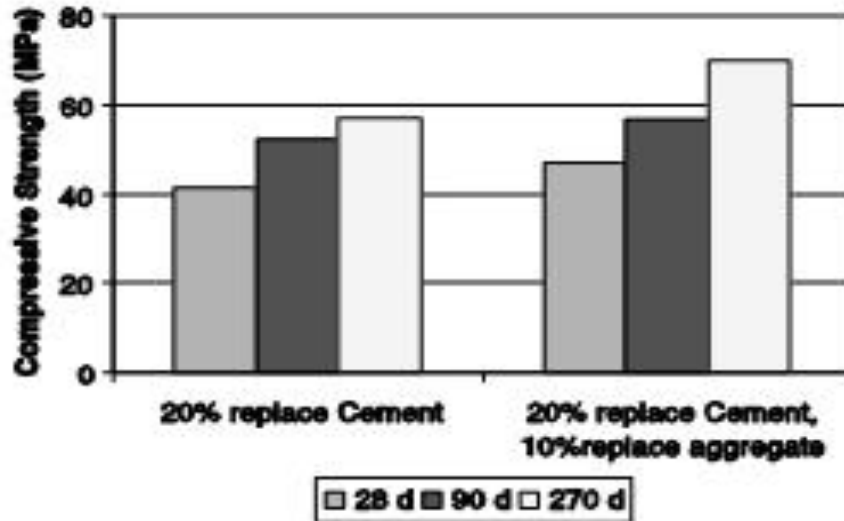


Fig. 2.1. Strength Development of Reactive Aggregate with Additional GLP. (Shayan & Xu, 2004

Wongpa et al. (2010) studied the effect of mix proportions on the properties of IPCs and compared it to that of conventional concrete. In order to keep the effect of chemical composition to a minimum, the ratio of FA to RHBA was fixed at 80:20 by weight and the ratio of sodium silicate solution to sodium hydroxide solution was fixed at 2.5 by weight for all mixtures. In total six different mixtures were used and the primary focus was laid on studying the effects of P/Agg ratio (paste content/aggregate content) and S/A ratio (solution content/ash content) on the compressive strength, modulus of elasticity, and water permeability of IPCs. The mix proportions of the six mixtures prepared are presented in Table 2.3.

Table 2.3

Mix Proportions of Inorganic Polymer Concrete Mixtures (kg/m³)(Wongpa et al., 2010).

Sample	FA	RHBA	WG	NaOH	C.Agg	F.Agg	P/A	S/A
P3-6	320	80	180	72	956	751	0.38	0.63
P3-7	280	70	181	72	990	778	0.34	0.72
P4-7	320	80	207	83	920	722	0.42	0.73
P4-8	320	80	23	93	884	694	0.46	0.82
P5-7	360	90	23	93	850	667	0.51	0.72
P6-7	400	10	26	106	746	617	0.64	0.74

An alkali activator comprising of sodium silicate solution or water glass (WG) and sodium hydroxide were used as the solution part of the mixture. Sodium silicate solution was used without any modification, whereas the sodium hydroxide was diluted to a concentration of 14 M before use. After that all the constituent materials were mixed together as per the proportions given in table & a uniform fresh mixture was obtained. The prepared mixture was then poured into $\varnothing 5 \times 10$ cm steel moulds & was left in room temperature for 24 h before de-molding. Subsequently hardened IPCs were cured under ambient conditions without any further treatment.

In this study compressive strength of the IPCs was examined at 3, 7, 14, 28, 60, and 90 days to observe the development of the compressive strength. The elastic modulus of each sample was investigated at 7, 28, and 90 days & water permeability was examined at 28 and 90 days. On testing of the specimens prepared it was found that compressive strength of all mixtures decreased after the age of 14 days or 28 days, depending on the mix proportions. In addition to this it was observed that P4-8 had the highest S/A ratio while P6-7 has the highest P/Agg ratio followed by P5-7. The results of the compressive strength developed for these mixtures are shown in Fig. 2.2

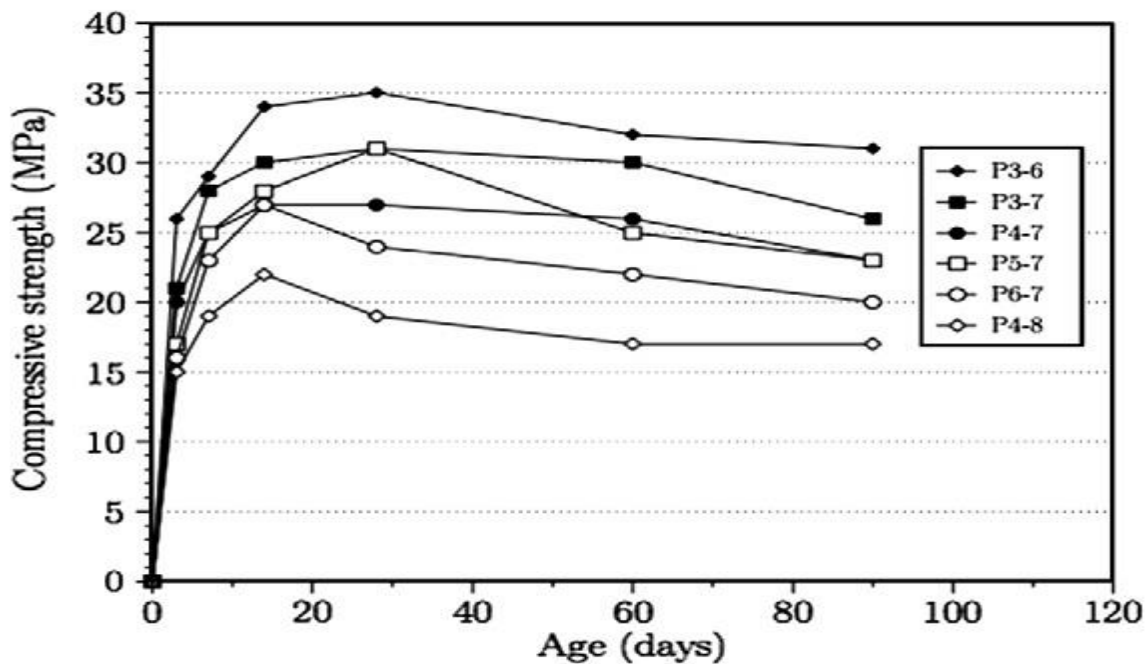
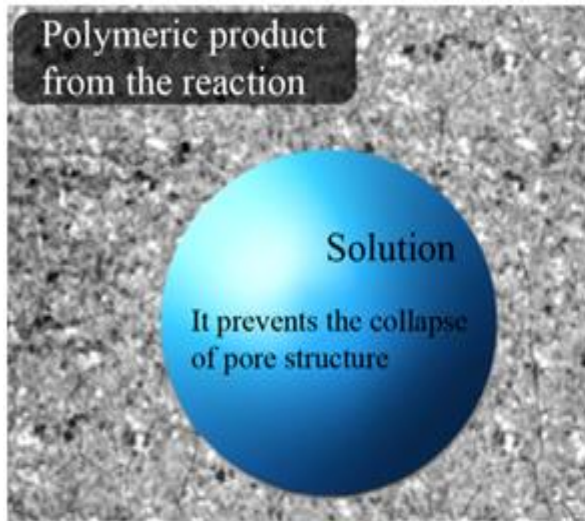
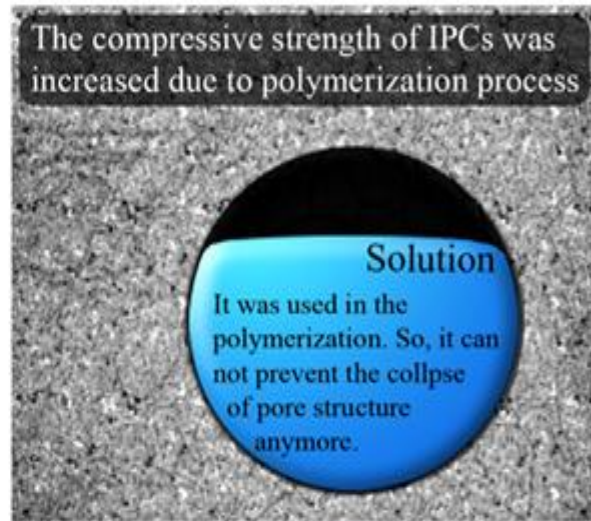


Fig. 2.2. Compressive Strength Development of IPCs with Age.(Wongpa et al., 2010).

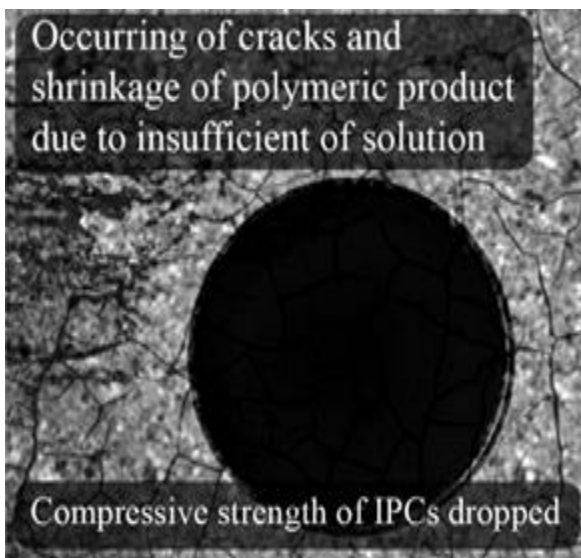
On observing the results it was concluded that decrease in compressive strength with age was due to occurrence of shrinkage cracks in the IPCs & the rate of shrinkage was dependent on P/Agg ratio and S/A ratio of the mixture. Fig.2.3 illustrates the process of occurrence of cracks in IPCs with time.



a) Solution in a void at early age of polymerization (less than 7 days)



b) Solution in void was used during polymerization process (7-28 days)



(c) Solution has been completely used in the polymerization process (over 28 days)



(d) A picture of cracks on the surface of an inorganic polymeric paste sample

Fig. 2.3. The Occurring of Cracks in IPCs Illustrated from the Assumption (Wongpa et al., 2010).

Aleem & Arumairaj(2012) conducted experiments to find out the optimum mix for the geopolymer concrete. For determination of the optimum mix proportion four trial mixes were prepared & compressive strength was found at 7 & 28 days. An alkaline activator solution comprising of sodium hydroxide(10 M solution) & sodium silicate was used in the ratio of sodium silicate solution to sodium hydroxide solution as 2.5.The various trial combinations tested are shown as follows in Table 2.4, 2.5, 2.6 & 2.7.

Table 2.4

Trial Mix-1 (1:1.3:3.10)(Aleem & Arumairaj, 2012).

Materials	Kg/m ³
Fly Ash (Class F)	408
Fine sand	530.40
Coarse aggregate(20 mm in size)	1264.80
Sodium silicate solution	103
Sodium Hydroxide solution(10 M)	41

Table 2.5

Trial Mix-2 (1:1.4:3.20)(Aleem & Arumairaj, 2012).

Materials	Kg/m ³
Fly Ash (Class F)	408
Fine sand	571.20
Coarse aggregate(20 mm in size)	1305.60
Sodium silicate solution	103
Sodium Hydroxide solution(10 M)	41

Table 2.6

Trial Mix-3 (1:1.5:3.30)(Aleem & Arumairaj, 2012).

Materials	Kg/m ³
Fly Ash (Class F)	408
Fine sand	612
Coarse aggregate(20 mm in size)	1346.40
Sodium silicate solution	103
Sodium Hydroxide solution(10 M)	41

Table 2.7**Trial Mix-4 (1:1.6:3.40) (Aleem & Arumairaj, 2012).**

Materials	Kg/m ³
Fly Ash (Class F)	408
Fine sand	652.80
Coarse aggregate(20 mm in size)	1387.20
Sodium silicate solution	103
Sodium Hydroxide solution(10 M)	41

To find out the compressive strength, cubes of size 150x150x150 mm were prepared & were kept in room temperature for a rest period of 2 days. After that the specimens were demoulded and placed in an autoclave for steam curing for 24 hours at a temperature of 60°C. On completion of the specified age the cube specimens were tested in a compressive testing machine having 2000kN capacity in accordance with the Bureau of Indian Standard test procedures. The compression test results are tabulated in Table 2.8 & 2.9.

Table 2.8**Compressive Strength (N/mm²) in 7 days(Aleem & Arumairaj , 2012).**

Trial Mix 1	Trial Mix 2	Trial Mix 3	Trial Mix 4
(1:1.3:3.10)	(1:1.4:3.20)	(1:1.5:3.30)	(1:1.6:3.40)
32.0	43.5	47.0	42.0
36.5	42.5	48.5	41.5
38.0	41.0	48.0	39.8

Table 2.9**Compressive Strength (N/mm²) in 28 days(Aleem & Arumairaj , 2012).**

Trial Mix 1	Trial Mix 2	Trial Mix 3	Trial Mix 4
(1:1.3:3.10)	(1:1.4:3.20)	(1:1.5:3.30)	(1:1.6:3.40)
37.33	47.11	51.55	48.88
39.11	48.0	53.33	49.33
42.66	47.55	52.44	48.0

Naidu et al. (2012). studied the strength properties of geopolymer concrete made by replacing low calcium flyash with slag in 5 different percentages. Sodium silicate (103 kg/m^3) and sodium hydroxide of 8 molarity (41 kg/m^3) solutions were used as alkalis in all 5 different mixes. The Flyash used in this experimental work was obtained from National Thermal Power Corporation (NTPC), Visakhapatnam & had a specific gravity, fineness modulus, specific surface area of 2.82, 1.375, $310 \text{ m}^2/\text{kg}$ and 1.4 kg/m^3 respectively. Ground granulated blast furnace slag of fineness modulus 0.16 was used in the work.. Potable water with pH value 7.15 was used for the geopolymer concrete.

In the mix design of geopolymer concrete mix, the total aggregates (fine and coarse) were taken as 77% of entire concrete mix by mass. Fine aggregate was taken as 30% of the total aggregates. From the available literature, it was observed that the average density of flyash-based geopolymer concrete was similar to that of OPC concrete (2400 kg/m^3) & taking the density of geopolymer concrete to be same as OPC the combined mass of alkaline liquid and flyash was worked out. The ratio of alkaline liquid to flyash was assumed to be 0.4 & from this mass of flyash and mass of alkaline liquid were found out. The ratio of sodium silicate solution to sodium hydroxide solution was fixed at 2.5 & this was used to obtain mass of sodium hydroxide and sodium silicate solutions. In the investigation, concentration of NaOH solution was taken as 8 M. The mix proportions of the geopolymer concrete are shown in Table 2.10 .

Table 2.10
Mix Proportions (Naidu et al., 2012).

Materials		Mix 1 (kg/m^3)	Mix 2 (kg/m^3)	Mix 3 (kg/m^3)	Mix 4 (kg/m^3)	Mix 5 (kg/m^3)
Coarse Aggregate	20 mm	277	277	277	277	277
	12.5 mm	370	370	370	370	370
	4.75 mm	647	647	647	647	647
Fine Aggregate		554	554	554	554	554
Flyash		408	370.091	340	313.85	291.43
Slag		0	37.091	68	94.15	116.57
Sodium hydroxide		41 (8M)	41 (8M)	41 (8M)	41 (8M)	41 (8M)
Sodium silicate		103	103	103	103	103
Extra added water		22.5	22.5	22.5	22.5	22.5

Compaction of fresh concrete in the cube moulds was achieved by compacting on a vibration table for ten seconds. After casting, the specimens were left undisturbed for 24 hours. Five different mixes were developed in this study, for each mix 12 cubes of 150mmx150mmx150mm, 12 cylinders of diameter of 150mm x height 300mm and 3 beams of 150mm x 150mm x 750mm were cast to study compressive, split and flexural strengths of each mix. The specimens were tested as per IS 516:1959 and strengths were calculated for 3, 7, 14 and 28 days and the compressive strength & flexural strength results are tabled as below in Table 2.11 & 2.12.

Table 2.11

Compressive Strengths for Different Ages of Geopolymer Concrete (Naidu et al., 2012).

Mix	Cube strengths(MPa)			
	3 Days	7 Days	14 Days	28 Days
Mix No 1	4.25	6.2	7.14	8.27
Mix No 2	9.48	17.89	19.55	24.29
Mix No 3	15.26	31.26	36	41.04
Mix No 4	25.55	39.17	40.63	45.76
Mix No 5	31.85	46.52	53.63	57.33

Table 2.12

Flexural Strengths of Geopolymer Concrete at 28 days (Naidu et al., 2012).

Mix	Flexural strength of beams(MPa)
	28 Days
Mix No 1	0.00
Mix No 2	1.00
Mix No 3	5.00
Mix No 4	5.77
Mix No 5	7.06

Lee & Lee (2013) investigated the properties of alkali-activated fly ash/slag blended concrete manufactured at room temperature through various experiments which assessed the flow, setting time, compressive strength, strength development with time, elastic modulus, splitting tensile strength and porosity. The degree to which the slag added to alkali-activated fly ash/slag concrete improved the mechanical properties was also investigated here.

In this study NaOH with a purity level of 98% and water glass (Korean Industrial Standards,KS 3-grade, SiO₂ (29%), Na₂O (10%), H₂O (61%), specific gravity 1.38 g/mL) were used as alkali activators. Distilled water was used to dissolve the NaOH solid, and the alkali activator was prepared by mixing NaOH solution with water glass. A solution of 85% phosphoric acid(H₃PO₄) was used as a set-retarding admixture to retard the setting time of the alkali-activated fly ash/slag concrete.

The mix proportion of the alkali-activated fly ash/slag concrete is provided in Table 2.13 and denoted with specific codes. The labels ‘S’ , ‘M’, and ‘H’ represented the slag, molarity of the NaOH solution and the phosphoric acid, respectively. The first number, ‘10’, ‘15’, ‘20’, ‘25’, or ‘30’, referred to the percentage of the slag replacement for the fly ash by weight. The second number, ‘4’, ‘6’, or ‘8’, referred to the molarity(mol/l) of the NaOH solution. The third number, ‘0.5’, ‘1.0’, and ‘1.5’, referred to the ratio of water glass to NaOH solution by weight. The fourth number, 0.5–2.5, referred to the ratio of phosphoric acid to total binder (fly ash + slag) weight expressed as a percentage.

The ratio of alkali activator to total binder (fly ash + slag) by weight was 0.38 for all specimens. The mass ratios of the water glass to NaOH solution were 0.5, 1.0, and 1.5. The percentages of the slag replacement for the fly ash by weight were 10%, 15%, 20%, 25% and 30%..

Table 2.13
Mix Proportions of Alkali-Activated Fly ash/Slag Concrete (Lee & Lee , 2013).

Specimens	Solution /binder	H ₂ O /binder	(M)	Water glass/ NaOH	Alkali Solution (Kg/m ³)	Binder (Kg/m ³)		Sand (Kg/m ³)
						FlyAsh	Slag	
S20-6M0.5	0.56	0.42	6	0.5	215	293	88	760
S20-6M1.0	0.56	0.40	6	1.0	215	293	88	760
S20-4M0.5	0.56	0.44	4	0.5	215	293	88	760
S20-4M1.0	0.56	0.42	4	1.0	215	293	88	760
S10-4M0.5	0.56	0.44	4	0.5	215	344	34	760
S15-4M0.5	0.56	0.44	4	0.5	215	316	63	760
S204M0.5-H2.25	0.56	0.44	4	0.5	215	293	88	760
S25-4M0.5-H2.25	0.56	0.44	4	0.5	215	272	108	760
S30-4M0.5-H2.25	0.56	0.44	4	0.5	215	253	126	760

The alkali-activated fly ash/slag concrete was cast into moulds of 100 mm x 200 mm cylinder for each mixture. Compressive strength tests were conducted using a universal testing machine according to ASTM C 39 at 3, 7, 14, 28 and 56 days.

The compressive strength of alkali-activated fly ash/slag concrete with time is shown in Table 2.14. In one of the cases it was observed that larger amounts of NaOH solid and water glass were added to the 6M 1.0 specimen compared to the other specimens but the compressive strength was lower than that of the 4M 0.5 and the 4M 1.0 specimens. In addition, the compressive strength of the 6M 1.0 specimen at 28 days (26.6 MPa) was lower than that at 14 days (27.4 MPa), while the compressive strengths of the 4M 0.5 and the 4M1.0 specimens at 28 days (29.9 MPa and 30.7 MPa) were equal to or higher than those at 14 days (29.9 MPa and 27.4 MPa). According to a previous study, geopolymer activated with NaOH solution alone showed a decrease in its compressive strength compared to geopolymer activated with sodium silicate. It was also found from microstructural observations that geopolymer activated with a silicate-based solution showed a more homogeneous microstructure than that activated with a NaOH-based solution. The reason for this reverse trend in strength is not clear, but the compressive strength may decrease due to the high shrinkage amount resulting from an increase in the alkali-activator content.

Table 2.14
Summary of Test Results (Lee & Lee , 2013).

Specimens	(M)	Waterglass/ NaOH	Slump (mm)	Compressive strength(MPa)				
				3 days	7 days	14 days	28 days	56 days
S20-6M0.5	6	0.5	200			34.6	37.4	
S20-6M1.0	6	1.0	250			27.4	26.6	
S20-4M0.5	4	0.5	205			29.9	29.9	
S20-4M1.0	4	1.0	200			27.5	30.7	
S10-4M0.5	4	0.5	220	2.2	10.4	13.1	15.5	18.4
S20-4M0.5- H2.25	4	0.5	200	3.4	10.8	27.6	30.6	29.5
S25-4M0.5	4	0.5	160	17.98	27.15	29.15	39.01	40.96
S25-4M0.5- H2.25	4	0.5	160	3.8	18.3	24.9	27.8	27.3
S30-4M0.5- H2.25	4	0.5	160	14.9	26.6	24.1	28.0	19.8

In this study the measured splitting tensile strengths were compared with the predicted splitting tensile strength of the OPC concrete according to the ACI 318-08 code and Eurocode 2. The relationship between the mean tensile strength f_{ctm} and the compressive strength f_c is as follows:

$$f_{ctm} = 0.30(f_c)^{2/3}, f_c \leq 50 \text{ MPa}$$

A relationship for finding tensile strength f_{ctm} from the measured splitting tensile strength $f_{ct,sp}$ is as follows:

$$f_{ctm} = 0.9f_{ct,sp} \text{ MPa}$$

The average splitting tensile strength f_{ct} could also be calculated as per (ACI 318, 2008) as follows:

$$f_{ct} = 0.56\sqrt{f_c} \text{ MPa}$$

It was observed in this study that most measured splitting tensile strengths were lower than the predictions made by the two codes. Based on these results, the following prediction equation for the splitting tensile strength of alkali-activated fly ash/slag concrete was proposed:

$$f_{ct} = 0.45\sqrt{f_c} \text{ MPa}$$

The results coming from use of this equation were found to be in close resemblance to results coming from eqn proposed by Sofi et al.

Deb et al. (2014) proposed an idea to evaluate the effect of different proportions of GGBFS and activator content on the workability and strength properties of fly ash based geopolymer concrete. In this study, GGBFS was added as 0%, 10% and 20% of the total binder with variable activator content (40% and 35%) and sodium silicate to sodium hydroxide ratio (1.5–2.5). The correlation of the splitting tensile strength with compressive strength of the ambient-cured geopolymer concrete was compared with those of heat-cured geopolymer concrete and traditional water-cured OPC concrete.

In this study alkaline activator used was a combination of sodium hydroxide and sodium silicate solutions. Sodium hydroxide solution of 14 M concentration was prepared by mixing 97–98% pure pellets with tap water. The mass ratio of SiO_2 to Na_2O of the sodium silicate solution was 2.61 ($\text{SiO}_2 = 30.0\%$, $\text{Na}_2\text{O} = 11.5\%$ and water = 58.5%). The final combined aggregate volume was a combination of 41% of 20 mm, 9% of 10 mm, 15% of 7 mm aggregates and 35% of sand. A naphthalene based superplasticiser conforming to ASTM: C494-13 as Class A and F admixture was used in this study.

In this study two series of geopolymer concrete mixtures with different amounts of alkaline activator were used . In series A, four geopolymer mixtures were prepared with the activator content of 40% and varying the SS/SH ratio and the percentage of GGBFS. The quantity of aggregates was kept constant for all four mixtures in series A. The geopolymer concrete mixtures were designated by their variable constituents in the mixture. For example, A35 S20 R1.5 represented a geopolymer concrete mixture having alkaline activator solution (A) as 35% of the binder, GGBFS (S) as 20% of fly ash-GGBFS blend and sodium silicate to sodium hydroxide ratio (R) of 1.5. Water and superplasticiser were added to improve workability of some geopolymer concrete mixtures, as shown. The OPC concrete mixtures were designed for two different strengths based on the guidelines of ACI 211.1-91.

Geopolymer and OPC concrete cylinder specimens of 100 mm diameter and 200 mm in height were cast & these specimens were used for compressive strength test. The geopolymer concrete specimens were cured in ambient condition at $20 \pm 2^\circ\text{C}$ and $70 \pm 10\%$ relative humidity and the OPC concrete specimens were cured in water at the same temperature. The mixture design parameters & compressive strength results of ten geopolymer and two OPC concretes studied are given in Table 2.15.

Table 2.15
Mix Design Parameters and Compressive Strength Results (Deb et al., 2014).

Mixtures		H ₂ O/Na ₂ O	Slump (mm)	Compressive strength(MPa)				
				7 Days	28 Days	56 Days	90 Days	180 Days
A(40%)	R2.5S10	11.745	250	27.0	40.0	45.0	47.0	49.0
	R2.5S20	11.758	195	31.0	47.0	50.0	54.0	59.0
	R1.5S10	10.628	210	25.0	43.0	50.0	52.0	54.0
	R1.5S20	10.639	180	29.0	54.0	63.0	68.0	70.0
	R2.5S00	11.656	245	11.0	25.0	30.0	33.0	35.0
B(35%)	R2.5S10	12.764	230	15.0	27.0	35.0	38.0	39.0
	R2.5S20	12.781	215	22.0	35.0	40.0	43.0	44.0
	R1.5S00	10.558	235	8.0	27.0	32.0	34.0	37.0
	R1.5S10	11.540	245	14.0	27.0	35.0	41.0	44.0
	R1.5S20	11.553	220	25.0	45.0	52.0	54.0	57.0
	OPC 1	-	105	36.0	48.0	56.0	62.0	65.0
	OPC 2	-	150	23.0	33.0	37.0	40.0	43.0

The compressive strength development of the geopolymer concrete mixtures of series A has been shown in Fig 2.4 . The graphs showed that the strength development of the geopolymer concrete mixtures slowed down after the age of 28 days and continued to increase at slower rates until 180 days of age. It was observed in Fig.2.4 that the compressive strength of series A increased with the increase of GGBFS content in the mixtures. It was seen that addition of more calcined source materials led to increase of compressive strength by improving the microstructure of geopolymer matrix.

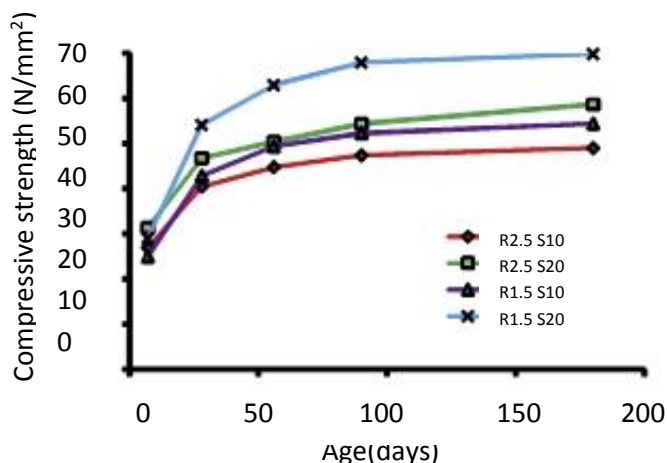


Fig. 2.4 Compressive Strength Variation of Geopolymer Concrete in Series A(Deb et al., 2014).

The strength development of the mixtures of series B with different slag contents and different SS/SH ratios have been plotted in Fig 2.5. In this series, the activator content was reduced to 35% as compared to 40% in series A. Superplasticiser and extra water were added to improve the workability of these mixtures. In series B, mixture R2.5S00 with no slag in the binder developed strength at a slow rate. When GGBFS was incorporated in the mixture as a part of the binder with constant alkaline activator of 35% and SS/SH ratio of 2.5, the strength increased significantly.

As shown in Fig 2.5, the compressive strength of geopolymer concrete increased from the early age of 7 days and continued to increase up to 180 days. At 28 days, mixtures R2.5S10 and R2.5S20 having 10% and 20% slag respectively, achieved higher strengths than the geopolymer concrete without slag (R2.5S00). The improvement of strength of slag blended fly ash based geopolymer concrete was due to the increase of calcium bearing compound in the dissolute binder which produced a reaction product from both slag and fly ash .

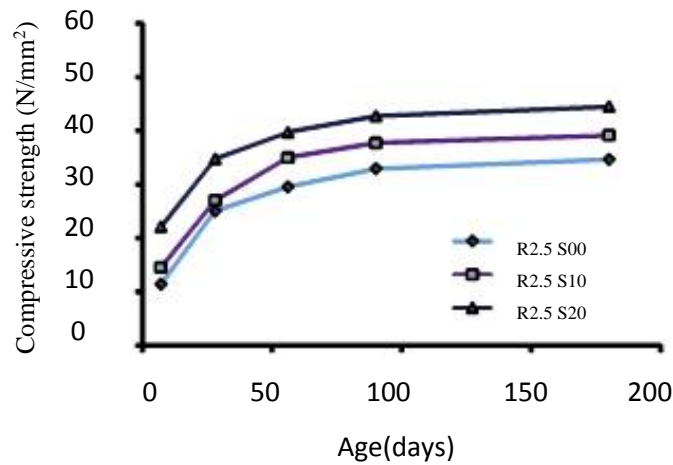


Fig. 2.5. Compressive Strength Variation of Geopolymer Concrete with Different Slag Content and SS/SH ratio 2.5 of Series B. (Deb et al., 2014).

It was also observed that the compressive strength of geopolymer concrete was significantly influenced by the amount of water in the mixture. Geopolymer concrete mixtures with extra water showed significant decrease in compressive strength for ambient cured geopolymer concrete. A comparison of the 28-day compressive strengths of the mixtures with and without water in series A and B is shown in Fig.2.6. A reduction of the activator liquid from 40% to 35% and addition of water to improve workability have increased the H_2O/Na_2O & the increase of this ratio eventually decreased the compressive strength of the mixtures of series B, as shown in

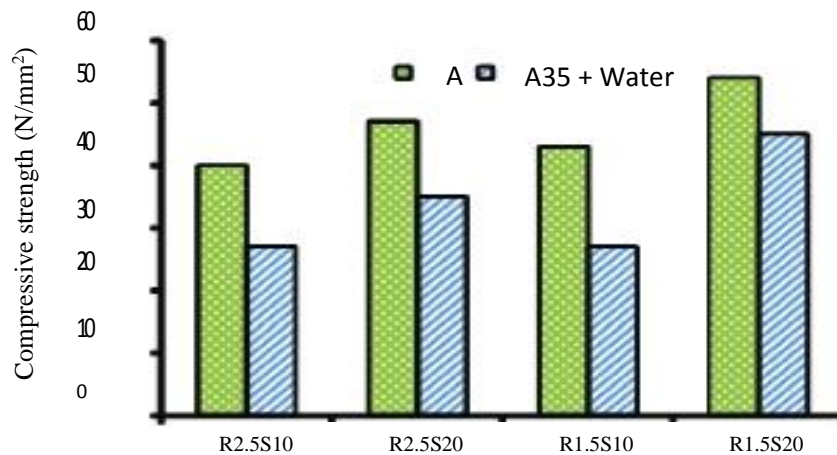


Fig. 2.6. Change in Compressive Strength for Added Water in Geopolymer Concrete Mixtures. (Deb et al., 2014).

Gao et al. (2015) studied the effects of two compositional factors i.e activator modulus having ($\text{SiO}_2/\text{Na}_2\text{O}$ from 1.0 to 1.8) and slag/fly ash mass ratios ranging (between 90/10 and 50/50) on reaction kinetics, gel characters and compressive strength of the resulting mix. He chose slag dominated mixes containing (at least 50% slag by mass) due to its superior mechanical properties under room temperature & different slag/fly ash ratios were used to give different starting $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ compositions. In addition to this different activator modulus were used to provide various levels of extra silica, and the total Na_2O content was kept constant to exclude its influence on total extra silicate content. The reaction kinetics and gel characters were investigated by isothermal calorimetry, Fourier transform infrared spectroscopy (FTIR) and thermogravimetry/differential scanning calorimetry (TG/DSC) analysis. The chemical compositions of slag and flyash were analyzed by X-ray fluorescence and the results are given in Table 2.16.

Table 2.16
Major Chemical Compositions of the Raw Materials (Gao et al., 2015).

Oxides(%)	FlyAsh	GGBS
SiO_2	54.6	35.5
Al_2O_3	24.36	13.6
CaO	4.44	38.6
MgO	1.43	10.2
Fe_2O_3	7.2	0.48
Na_2O	0.73	0.35
K_2O	1.75	0.48
SO_3	0.46	1.27
LOI	2.80	1.65

An alkali activator used was a mixture of sodium hydroxide pellets(analytical level) and sodium silicate solution which comprised of 27.69% SiO_2 , 8.39% Na_2O and 63.9% H_2O by mass. The desired activator modulus (M_s , $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio) were achieved by adding different amounts of sodium hydroxide pellets into sodium silicate solution & the solution after mixing was cooled down to ambient temperature prior to use. Distilled water was added in order to reach the desired water/binder ratio.

While carrying out the mix design, the equivalent sodium oxide (Na_2O) content was kept constant at 5.6% by mass of the binder in all samples, five levels of activator modulus ranging (M_s from 1.8 to 1.0) were used & assigned as A to E to provide different extra silicate contents from activator to the solid material. The fly ash/slag ratios of 90/10, 80/20, 70/30, 60/40 and 50/50

by mass were used & represented as 1 to 5. The water/binder ratio was kept constant at 0.35 & the total water consisted of the water added from distilled water and the water contained in the original sodium silicate solution. The fresh paste was poured into plastic moulds of 40 x 40 x 40 mm³ and vibrated for 1 min, then covered with a plastic film on the top surface for 24 h & finally all the specimens were demoulded and cured at 20°C and relative humidity of 95% until the testing age. The detailed information of mix proportions is shown in Table 2.17.

Table 2.17
Mix Proportions of AA-slag/Fly ash Pastes (Gao et al., 2015).

	Slag/Flyash	Na(%)	Activator Modulus					W/B
			A	B	C	D	E	
1	90/10	5.6	1.8	1.6	1.4	1.2	1.0	0.35
2	80/20	5.6	1.8	1.6	1.4	1.2	1.0	
3	70/30	5.6	1.8	1.6	1.4	1.2	1.0	
4	60/40	5.6	1.8	1.6	1.4	1.2	1.0	
5	50/50	5.6	1.8	1.6	1.4	1.2	1.0	

The compressive strength tests were carried out on 40x40x40 mm³ cubes and the test were performed at the ages of 7 and 28 days respectively. The isothermal calorimetry analysis was conducted under a constant temperature of 20° C for 72 h. Solid raw materials were firstly mixed with the activating solution for about 1 min & then the mixed paste was transferred into the ampoule and loaded into the calorimeter. Fourier Transform infrared spectroscopy(FTIR) measurement was performed in a Varian 3100 instrument with the wave numbers ranging from 4000 to 600 cm⁻¹ at a resolution of 1 cm⁻¹, and each sample was scanned for about 50 times. Thermogravimetry and differential scanning calorimetry(TG/DSC) analysis was conducted in a STA 449-F1 instrument. For this grinded powder samples were firstly heated to 105°C and held for 2 h, then up to 1000 °C, both at 5 °C/min with nitrogen as the carrier gas. Both FTIR and TG/DSC analysis of the samples were carried out at the age of 28 days.

The isothermal calorimetric analysis was conducted on the samples with the activator modulus of 1.8, 1.4, 1.0 (assigned as A,C, E) and slag/fly ash mass ratios of 90/10,70/30, 50/50 (represented by 1, 3 and 5). The heat evolution curves within the first 72 h are shown in Fig. 2.7 & it showed the heat flow of samples with an activator modulus of 1.8 and slag/fly ash mass ratios of 90/10, 70/30 and 50/50 (A1, A3 and A5).

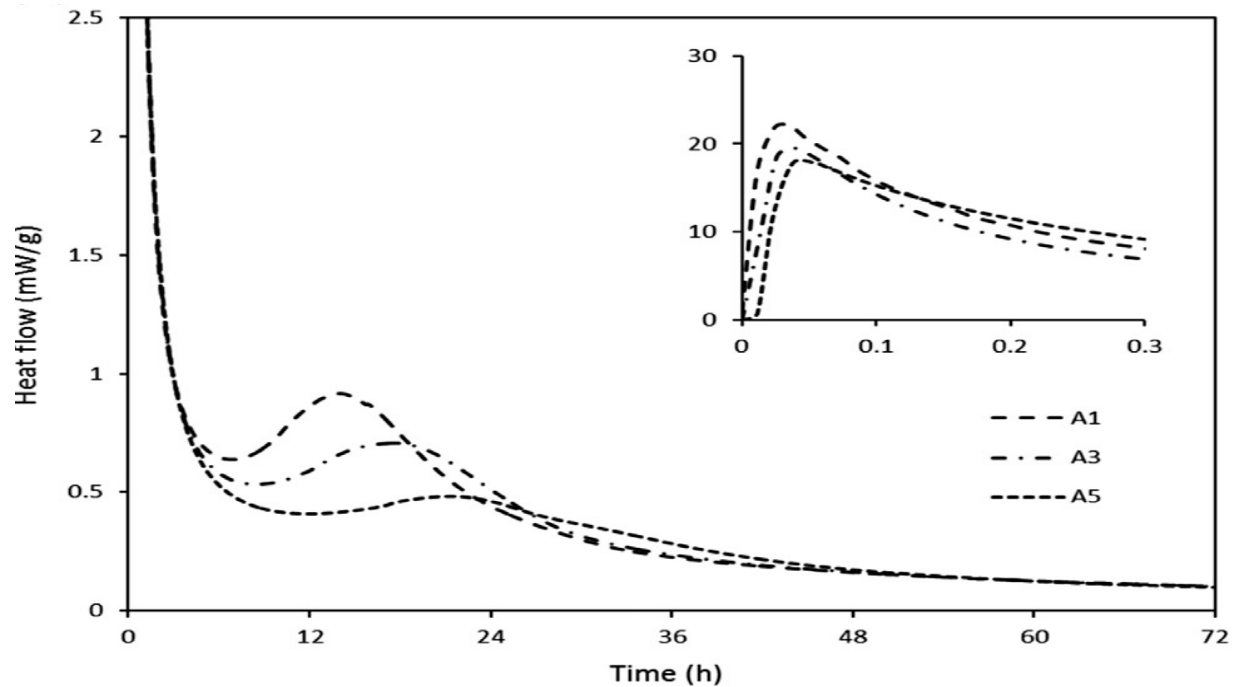


Fig. 2.7. Heat Evolution of AA-Slag/Fly Ash Blends with Activator Modulus of 1.8 (Gao et al., 2015).

They described that the entire reaction processes could be divided into four stages, namely initial dissolution, induction, acceleration/deceleration and stable period. Two calorimetric peaks were observed in all samples i.e an initial peak with significant high heat flow during the first few minutes and an acceleration peak with relatively low intensity at around 6 to 24 h. They observed that the occurrence of two typical peaks was in agreement with the heat evolution curves of silicate activated slag or its blends observed in previous studies. The first peak of heat flow indicated to the initial wetting, dissolution of raw materials (primarily the breakdown of MeAO and TAO bonds of slag) within the first few minutes after mixing , also partly due to the formation of the initial reaction products from the dissolved units such as Si, Ca and Na in the solution. The presence of the early peak is generally regarded as a physical rather than a chemical progress. The acceleration peak(i.e., the second peak) observed at over 6 h was considered to be the massive formation of reaction products.

They found out that the the initial dissolution peak appeared at around 3–4 mins and samples with a higher slag content resulted in a higher dissolution heat flow, which demonstrated that slag was easier to dissolve than fly ash in alkali solutions under ambient temperature. After the initial dissolution stage, all mixes exhibited an induction period that lasted to about 4 to 10 h

before the second heat evolution peak. The dissolution of solid precursors in alkali solution led to the dissolution of the glassy structure of slag and the release of Ca, Si and Al units. The newly formed reaction products from those released units grew rapidly and formed a layer on the surface of unreacted slag particles, which limited the amount of available alkalis for slag dissolution and reduced the heat evolution. Because of the continuous alkali supply of sodium silicate and the penetration of alkalis through the newly formed layer, further reaction continued and the second peak of heat flow appeared. Samples with a higher fly ash content presented a considerably longer induction time & this was probably due to the low reactivity of fly ash.

The influence of activator modulus and slag/fly ash mass ratio on gel character was investigated by FTIR. Fig. 2.8 shows the infrared spectra of the unreacted slag and fly ash. The main vibration band for slag was at around 900 cm^{-1} and about 1020 cm^{-1} for fly ash, which was associated with the asymmetric stretching vibration of Si-O-T bonds (where T represented tetrahedral Si or Al units). The difference in the main band wavenumber was attributed to the different glassy phase structure of raw materials. A small band at around 1450 cm^{-1} was also observed in slag, this band corresponded to the asymmetric stretching vibration of O-C-O bonds, which indicated that a slight degree of carbonation had already taken place in the raw material. For the fly ash, absorption bands located at around 1080 , and 600 to 800 cm^{-1} indicated the presence of small amount of quartz.

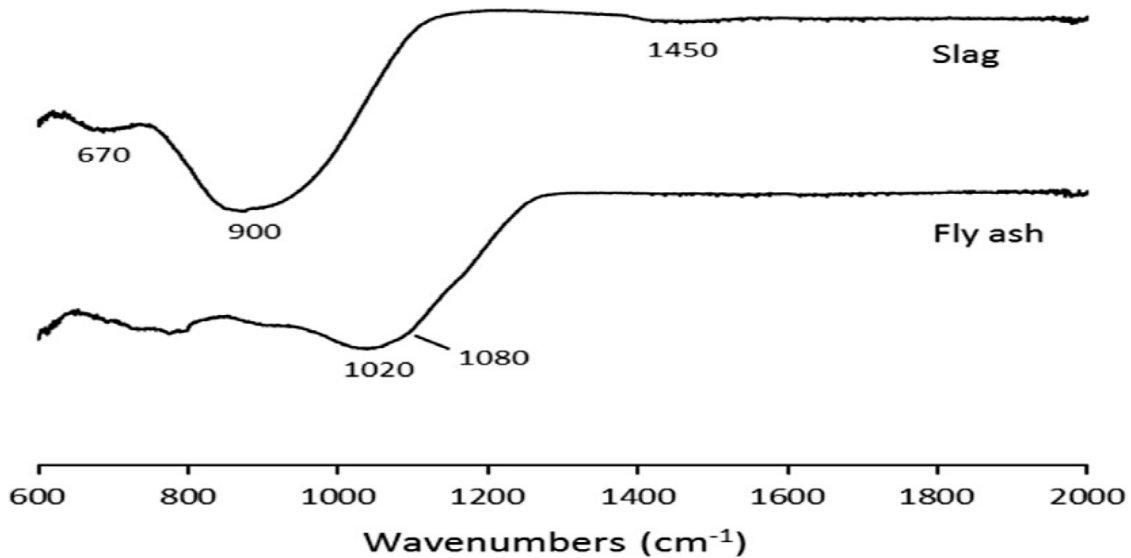


Fig. 2.8. FTIR Spectra of Solid Raw Materials(Gao et al., 2015).

Fig.2.9 showed the infrared spectra of samples with the activator modulus of 1.8, 1.4, 1.0 (represented by A, C, E) and slag/fly ash mass ratios of 90/10, 70/30, 50/50 (represented as 1, 3, 5 respectively) after alkali activation. It was seen that, regardless of the activator modulus and raw materials' relative content, all specimens exhibited similar location of absorption bands in general. Specifically, all samples showed OH groups at 1640 cm^{-1} and around 3200 cm^{-1} which indicated the presence of chemically bound water within the hydration products. The absorption band at around 1420 cm^{-1} in all mixes corresponded to the stretching vibrations of O-C-O in carbonates, and this band was more significant than that in the raw material, which revealed the occurrence of carbonation during the reaction or curing process.

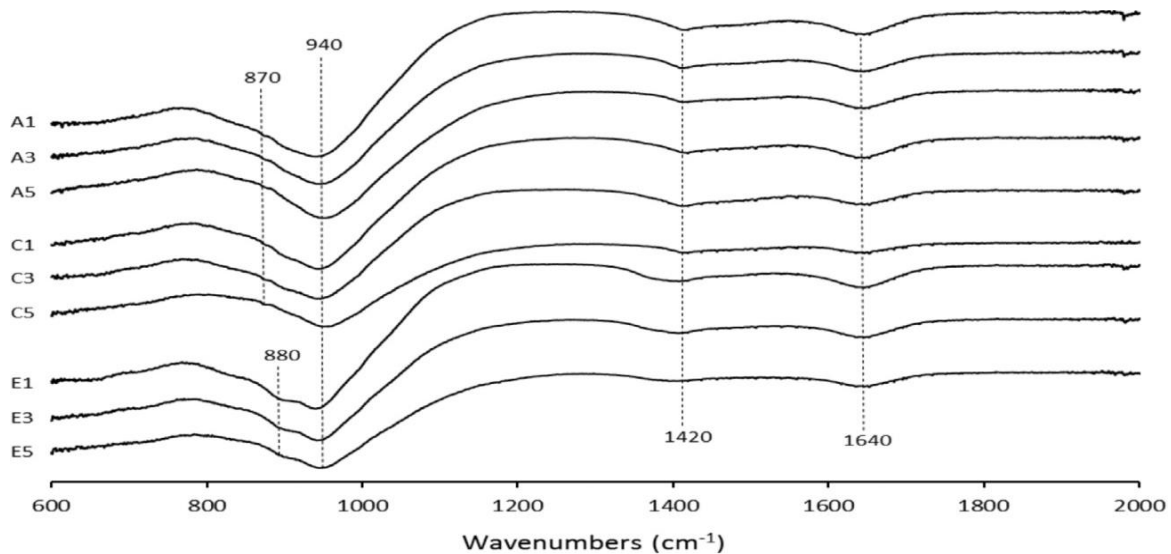


Fig. 2.9. FTIR Spectra of Alkali Activated Slag/Fly Ash Blends(Gao et al., 2015).

The compressive strength of samples with different starting material compositions and activator parameters after 7 days' curing is shown in Fig. 2.9. It was seen in Fig. 2.9 that all samples exhibited satisfying compressive strength (between 56.24 MPa and 82.18 MPa) after 7 days curing under ambient temperature. The compressive strength decreased when increasing the fly ash content in general. On the basis of test results of 7 & 28 days it was concluded that the glassy phases of slag were more vulnerable to alkaline attack than the aluminosilicates enriched ones from fly ash under room temperature, and the slag generally had a higher content of reactive phase than fly ash, thus a higher amount of Si and Ca got dissolved and more hydrated gels were formed than fly ash, which explained the decrease in compressive strength at both 7 and 28 days when the fly ash content was increased.

Kamali & Ghahremaninezhad (2015) examined the mechanical strength and durability behavior of cementitious materials modified with two types of glass powders and a class F fly ash at various levels of cement replacement. Mechanical strengths were evaluated via compressive strength and flexural strength tests, and durability characteristics studied included alkali-silica-reactivity, electrical resistivity, chloride permeability and porosity.

In this study the materials used included type I/II Portland cement, limestone coarse aggregate, silica sand, glass powders (GP) and a class F fly ash (FA). Two glass powders designated as GP1 and GP2 were used in this study. GP1 was a post-industrial by-product derived from waste glass fiber and GP2 was a post-consumer by-product derived from recycled glass. The chemical and physical properties of glass powders and fly ash are given in Table 2.18 The scanning electron microscopic images of GP1 and FA showing the morphology and size distribution of GP1 and FA are shown in Fig. 2.10 respectively. The X-ray diffraction spectra of GP1, GP2, and FA are depicted in Fig. 2.11.

It was seen from the X-ray diffraction spectra that GP1 and GP2 possessed an amorphous structure as indicated from the absence of detectable peaks in their spectrum. The presence of peaks in the FA spectrum indicated that some crystalline phases were present in the microstructure of FA as shown in the figure. It has been pointed out that pozzolanic reactivity increases with increasing amorphous phases in supplementary cementitious materials.

Table 2.18
Chemical and Physical Properties of Glass powders and Fly ash. (Kamali & Ghahremaninezhad, 2015).

Composition % by mass	GP1	GP2	FA
Silica (SiO ₂)	50-55	50-80	54
Alumina (Al ₂ O ₃)	15-20	1-10	28
Iron oxide (Fe ₂ O ₃)	<1	<1	7
Calcium oxide (CaO)	20-25	5-15	1.4
Magnesium oxide (MgO)	<1	<1.5	1
Potassium oxide (K ₂ O)	<0.2	<1	2.4
Sulfur trioxide (SO ₃)	<0.1		0.1
Titanium dioxide (TiO ₂)	<1	<0.1	
Loss on ignition (%)	<0.5	<1	3.4
Specific gravity	2.6	2.5	2.31
Median particle size (µm)	8.4	8.4	13.1

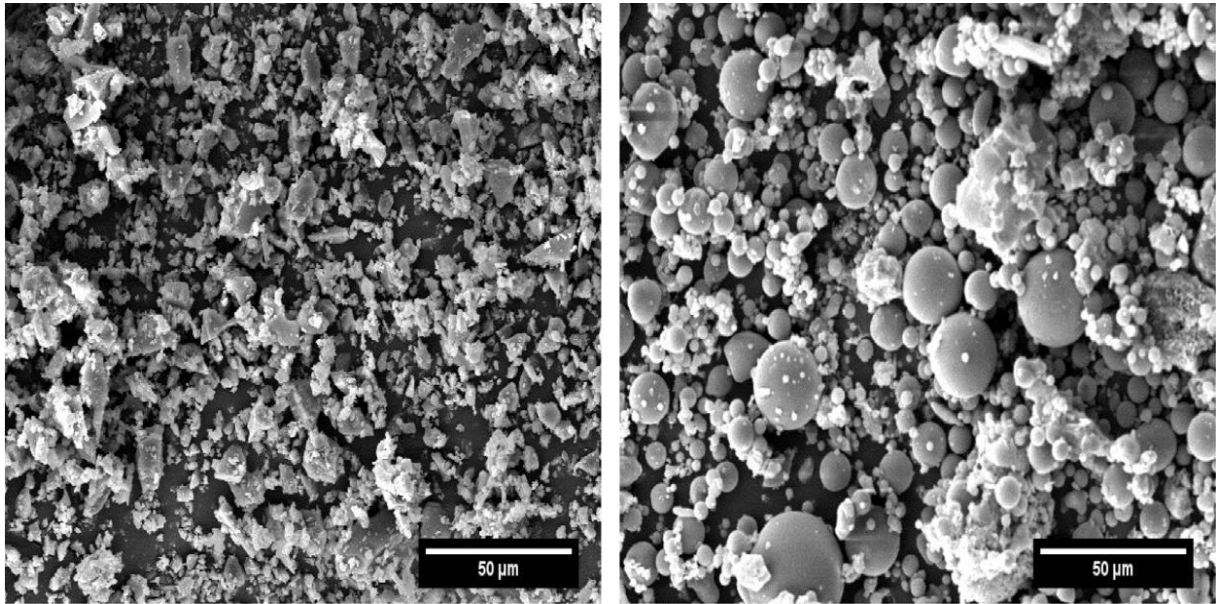


Fig. 2.10 Scanning Electron Microscopic Images of GP1 & FA .(Kamali & Ghahremaninezhad, 2015).

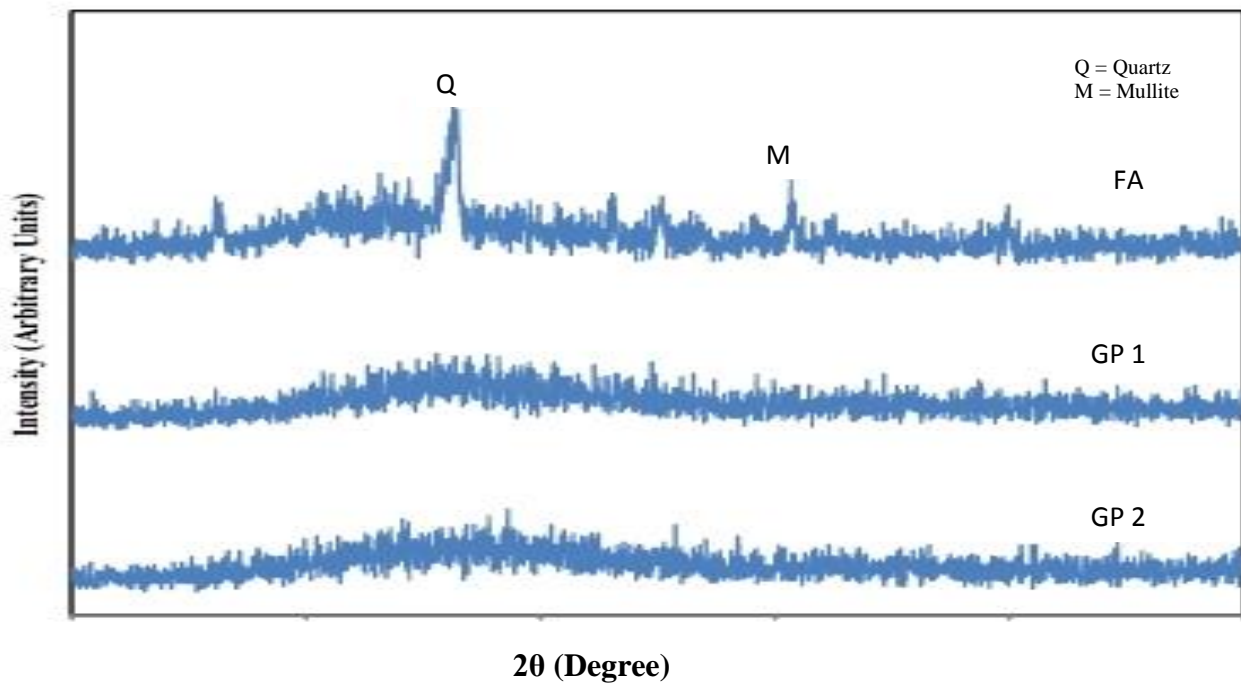


Fig. 2.11. X-ray diffraction spectra of GP1, GP2, and FA. (Kamali & Ghahremaninezhad, 2015).

In this study glass powder was replaced with cement in percentages of 5%, 10%, 15%, and 20% and fly ash was replaced with cement in percentage of 20%. Water-reducing and air-entraining admixtures in the amount of 1651.7 mL and 3.9 mL, respectively, per cubic meter of concrete

were added to the mixes. The water/binder ratio of the mix designs was specified at 0.5. Concrete cylinders of dimensions 100 mm (diameter) x 200 mm (height) were prepared in accordance with ASTM C192. The compressive strength test of cylindrical specimens of concrete was performed at 7 days, 28 days, and 91 days of curing. The compressive strength of mortars using portions of prisms used in the flexural test was evaluated as per ASTM C349.

For finding the flexural strength mortar prisms of dimensions of 40 mm x 40 mm x 160 mm having the same water/binder and sand/binder ratios as concrete mix designs with only 20% replacement of cement with glass powders and fly ash were cast following ASTM C348. The test specimens were cured for 24 h in the moist room at more than 95% relative humidity and at a temperature of 23 ± 2 °C for 24 h. After 24 h, the mortar prisms were demoulded and stored in a saturated lime solution until testing time. The flexural strength test was carried out using mortar prisms (ASTM C348) with only 20% glass powder and fly ash at 28 days and 91 days of curing.

To assess the alkali-silica reactivity (ASR) of mortars modified with glass powders and fly ash accelerated mortar bar tests were conducted. It was seen that the control mortar without any modification experienced a large expansion over the testing period. Modified mortars with glass powders and fly ash showed a reduction in ASR expansions with mortars modified at 20% replacement being most effective in reducing ASR reaction. A slight improvement in ASR behavior of mortars with GP1 with respect to mortars with GP2 was observed from the results. It was observed that the primary mechanism by which supplementary cementitious materials suppress ASR reaction in concrete is by reduction of alkalis and hydroxide concentration in pore solution as a result of pozzolanic reaction and alkalis dilution due to partial replacement of cement.

The low calcium C-S-H gels produced as a result of pozzolanic reaction bind to alkalis in the pore solution reducing available alkalis to participate in alkali silica reaction. The reduction in the ASR reactivity of mortars modified with glass powders was attributed to the pozzolanic property of glass powders resulting in microstructure densification with lower alkalis mobility as well as a reduction in available alkalis in the pore solution of the modified mortars.

The compressive strength test results of concretes at various curing ages are shown in Fig 2.12. It was seen that concretes with GP1 at various replacement levels showed an increased strength compared to the control concrete at all ages. The increase in the compressive strength of concrete

with GP1 was seen to improve with curing age & it was observed that the compressive strengths of concrete increased with increasing replacement levels of cement with GP1 at later ages with concrete containing 20% replacement of cement with GP1 indicating the highest compressive strength among all concrete mixtures. The increase in compressive strength with increasing replacement level of cement with GP1 may be attributed to the pozzolanic property of GP1, which leads to a more densified microstructure and improved interfacial bonding between aggregates and cement paste matrix in concrete. It could be seen from Fig 2.12 that concrete with 20% FA showed higher compressive strength than the control concrete at 91 days and its compressive strength is comparable with that of concrete with 20%

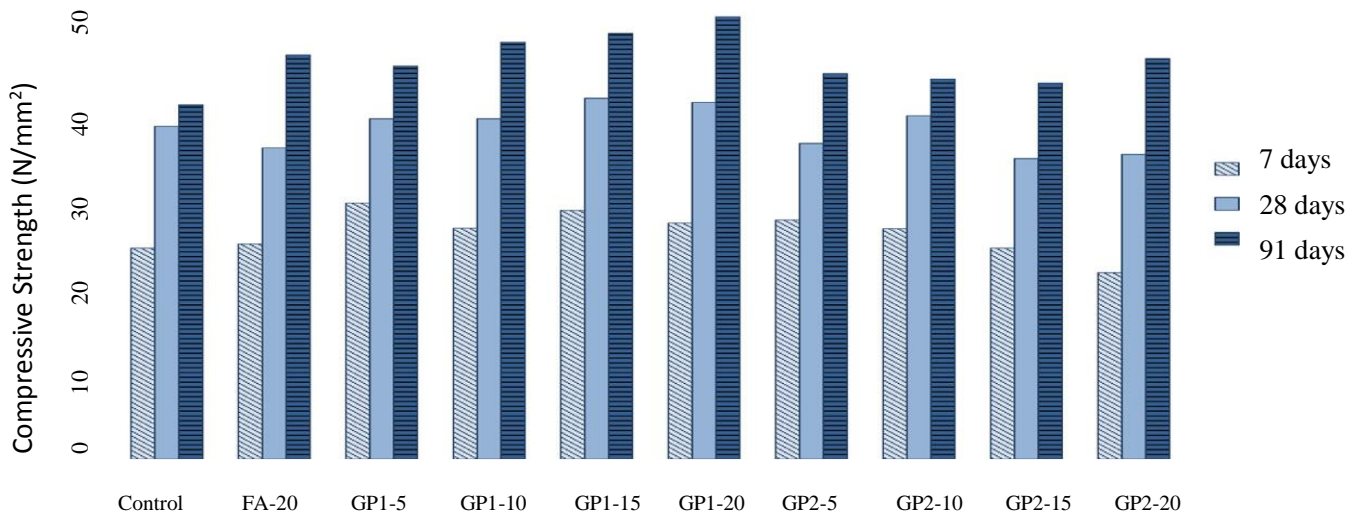


Fig. 2.12 Compressive Strengths of Concretes at 7 days, 28 days, and 91 days of Curing. (Kamali & Ghahremaninezhad, 2015).

Nazari et al. (2015) conducted experimental investigations for finding flexural strength of plain and fibre-reinforced boroaluminosilicate geopolymers. In this study alkali activation of fly ash was performed by mixtures of anhydrous borax and sodium hydroxide. Flexural strength of the specimens in unreinforced and reinforced conditions was measured by three-point bending & reinforced specimens were prepared by using 2, 3 and 5 wt.% of steel fibres, with length and diameter of 30 and 0.5 mm respectively.

In this study for production of unreinforced and steel fibre-reinforced boroaluminosilicate geopolymer pastes, class F fly ash, sodium hydroxide solution (NaOH), anhydrous borax ($\text{Na}_2\text{B}_4\text{O}_7$) and steel fibres were used. NaOH solution with a concentration of 8 M was prepared

by dissolving NaOH flakes in distilled water & anhydrous borax was prepared by a two stage heating of borax decahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$).

In the first stage heating was done at 150 °C for 30 min to dry some of the water content and to achieve borax pentahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$) & subsequently heating was performed at 300 °C for 15 h to remove the remaining intermolecular water. After mixing NaOH solution and anhydrous borax, the mixtures were left in room temperature for 2 h to cool down and then, were used for alkali activation of flyash.

In total, two kinds of specimens namely G series (unreinforced) and RG series (reinforced) specimens were prepared in which G series specimens comprised of nine different mixtures of only fly ash and alkali activator. Table 2.19 illustrates mixture proportions of these series of specimens. RG series specimens were those reinforced by steel fibres in percentages of 2, 3 and 5 & this led to a total of 27 series of RG mixtures.

Table 2.19
Mixture Proportions of Unreinforced Geopolymer Pastes (Nazari et. al, 2015).

Sample	Borax/NaOH solution weight ratio	NaOH/flyash	Flyash (kg/m^3)	Borax (Kg/m^3)	NaOH Flakes (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
G1	0.593	0.75	1312	366	198	416	4.20
G2	0.593	0.80	1276	380	205	431	4.35
G3	0.593	0.90	1208	405	219	459	4.64
G4	0.700	0.75	1312	405	185	390	3.94
G5	0.700	0.80	1276	420	192	404	4.08
G6	0.700	0.90	1208	448	205	431	4.35
G7	0.912	0.75	1312	469	165	347	3.5
G8	0.912	0.85	1241	503	177	371	3.75
G9	0.912	0.90	1208	519	182	383	3.87

Flexural strength of specimens was acquired in accordance to the ASTM C293-10 standard by using samples with 20 cm length, 4 cm width and 4 cm thickness. Fig.2.13 illustrates flexural strength of unreinforced geopolymeric pastes with minimum flexural strength of 5 ± 0.1 MPa for the specimen with borax to NaOH solution weight ratio of 0.700 and alkali activator to fly ash weight ratio of 0.75. The maximum flexural strength was observed as 9.5 ± 0.4 MPa for the said

specimen with borax to NaOH solution weight ratio of 0.912 and alkali activator to fly ash weight ratio of 0.9.

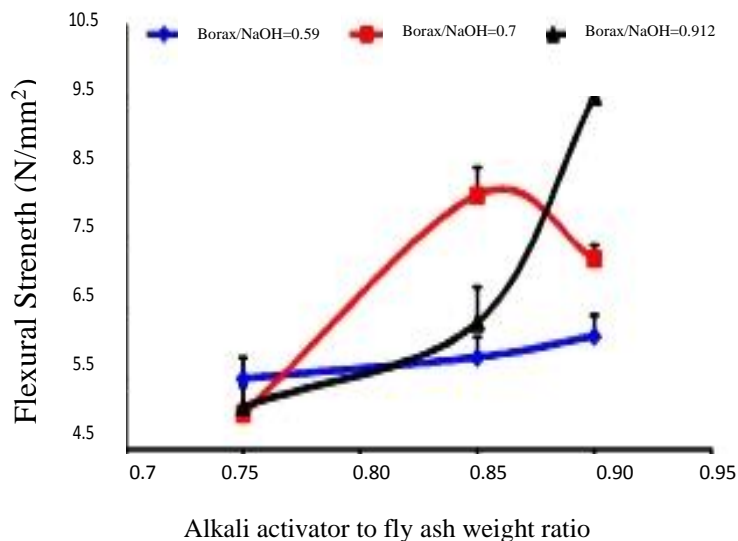


Fig. 2.13. Flexural Strength of G Series (Unreinforced) Specimens. (Nazari et al., 2015).

In addition to flexural strength, fracture surface of unreinforced specimens and adhesion of steel fibres to geopolymeric paste was studied through scanning electron microscopy (SEM). Fig. 2.14 illustrates fracture surface of the weakest specimen in which a brittle fracture occurred and large crystals appeared after fracture. Propagation of cracks along the weak paste appeared to be the reason of low flexural strength. Fig 2.15 represents the fracture surface of a medium strength specimen. Although flexural strength of this specimen was not much higher than the previous one but a few needle-like crystals were observed which were suggestive of the reason of strength gain in borosilicate geopolymers.

Fig. 2.16 shows the availability of large number of visible needle-like crystals which were responsible for high strength of the specimen. From the SEM results it was observed that in high strength specimens the required energy for crack propagation was divided between many fine needle-like crystals, hence a lot of energy was needed for causing fracture in the specimens. These needle-like crystals were the characteristic feature of fracture surface of borosilicate geopolymers, which were formed during successful syndissertation of these pastes, and were not observed in traditional aluminosilicate geopolymeric binders.

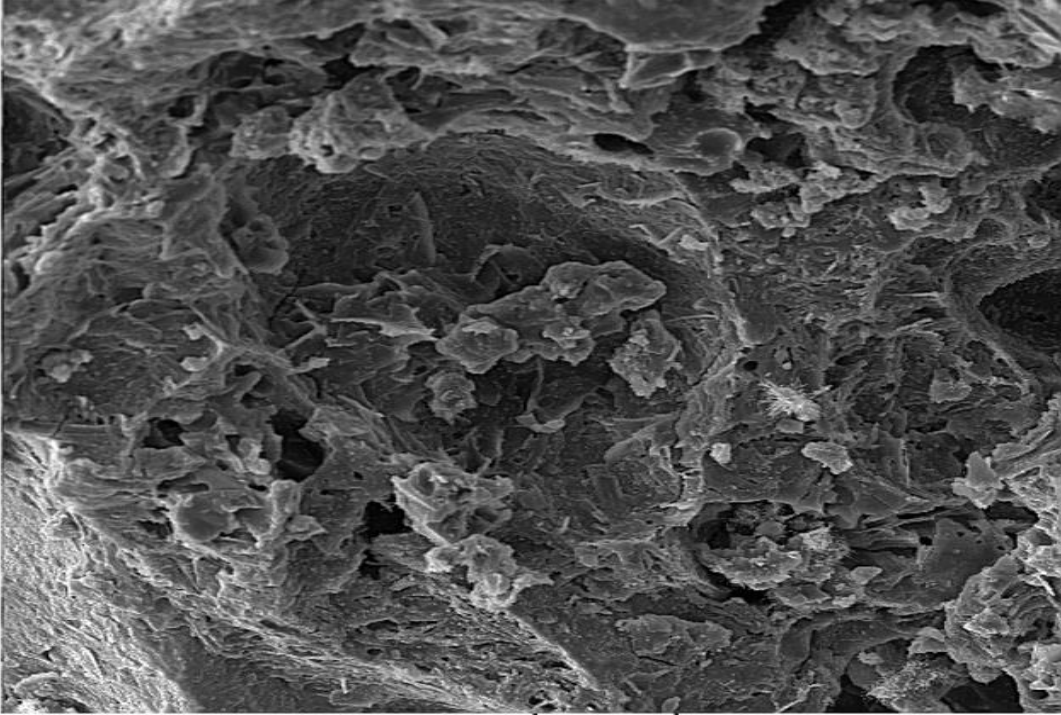


Fig. 2.14. SEM Images of the Weakest Specimen .(Nazari et al., 2015).

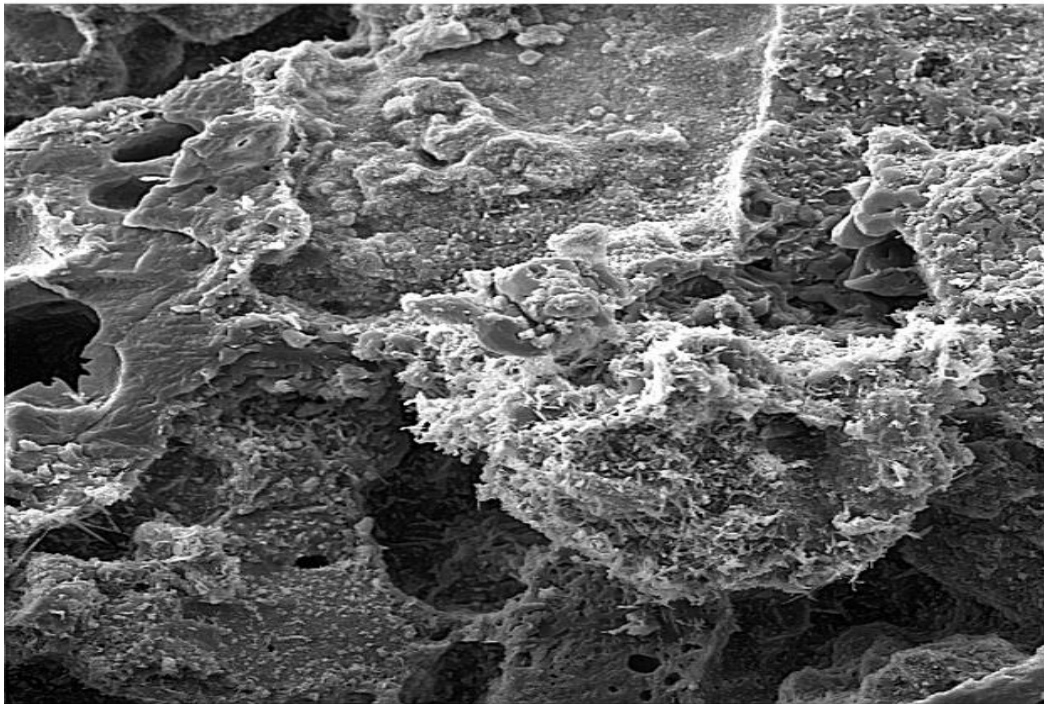


Fig. 2.15. SEM Images of the Medium Strength Specimen .(Nazari et al., 2015)

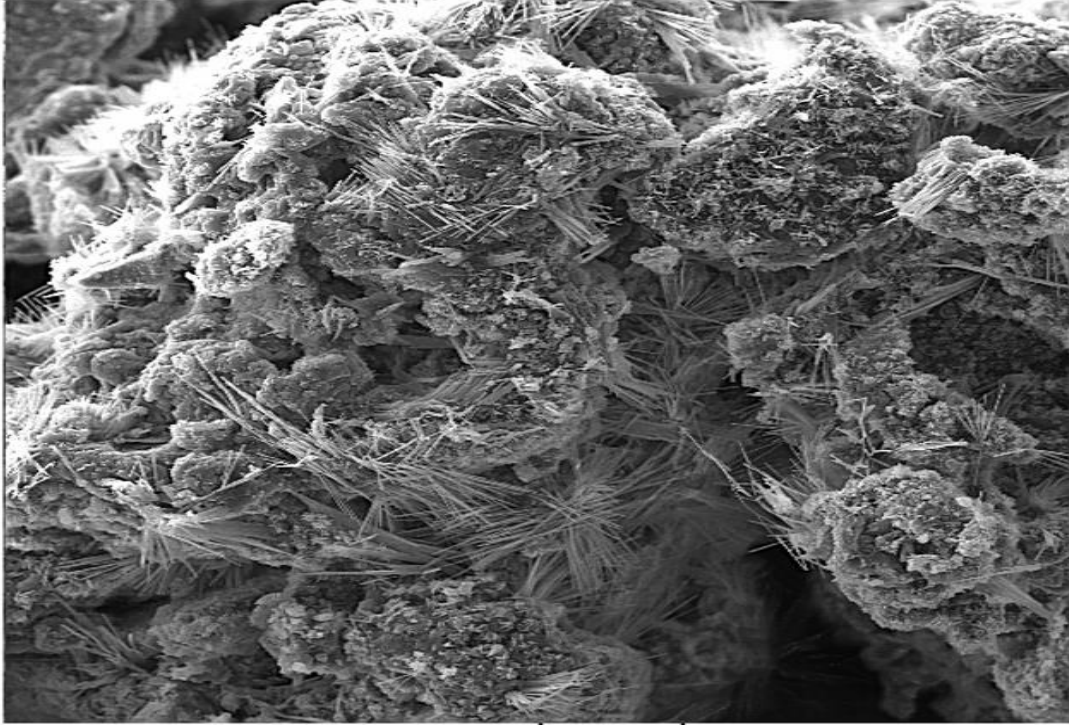


Fig. 2.16. SEM images of the High Strength Specimen . (Nazari et al., 2015).

Thomas & Peethamparan (2015) investigated the tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain relationships of alkali-activated portland-cement-free concrete made with fly ash or ground granulated blast furnace slag (GGBFS) as the sole binder. Specifically, this study evaluated the compressive strength, splitting tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain response for alkali-activated class-C fly ash (FC) and GGBFS concrete & the results from this study were compared to the typical behavior of portland cement concrete (PCC).

In this study the binder materials used comprised of high-calcium ASTM C618 Class C coal fly ash (FC) and ASTM C989 Grade 100 granulated blast furnace slag (GGBFS). The activator was a mixed solution of sodium silicate ($\text{Na}_2\text{O} + m \cdot \text{SiO}_2$) and sodium hydroxide (NaOH). The Na_2O equivalent of the activator has been reported relative to binder mass ($\% \text{Na}_2\text{O}$, by mass of binder), and the relative concentration of silica to sodium oxide equivalent has been reported as the silica modulus. Saturated surface-dry (SSD) natural fine aggregate with fineness modulus of 2.42 and specific gravity of 2.65 was used for all mixtures. Alkali-activated FC and GGBFS mixtures included 0.1% dosage of rosin-based air-entraining agent for the purpose of workability

improvement. ASTM C150 Type I/II ordinary portland cement concrete (PCC) control mixtures were selected to produce similar compressive strengths as expected for the selected alkali-activated FC and GGBFS mixtures.

In this study 24 cylindrical concrete specimens measuring 150 mm in length and 75 mm in diameter were cast in accordance with the specifications of ASTM C192 for each mixture proportion. Specimens were cured at elevated temperature (48 ± 0.25 h @ $50 \pm 0.1^\circ\text{C}$) and the other half were cured at ambient temperature (28 ± 0.5 days @ 22 ± 1 °C and $>95\%$ RH). All specimens remained sealed for the duration of curing to prevent moisture loss. After curing, specimens were de-molded and test faces were ground flat and plane using a wet silicon carbide grinding belt.

Compressive strength was determined in accordance with the specifications of ASTM C39 using a stress application rate of 15 MPa/min. The static chord modulus of elasticity and Poisson's ratio were determined in general agreement with the specifications of ASTM C469, except for that the testing was performed under closed-loop displacement control. This modification in test procedure was made in order to allow evaluation of the post-failure strain response. Specimens were loaded in pure uniaxial compression at a constant displacement rate of 0.1 mm/min and were instrumented with an axial and radial extensometer. Post-failure strain measurements were also desired, and because failure typically causes the mounted gauges to slip, two LVDT were also deployed in diametrically opposed positions in the axial direction.

Ambient-temperature-cured (28 d @ 22°C) activated fly ash concrete exhibited very low compressive strength compared to identical specimens cured at elevated temperature (48 h @ 50°C). No such effect was observed in compressive strength results for alkali-activated GGBFS concrete. For both binders, increased binder content resulted in reduced compressive strength as indicated by the strength reduction between FC formulations FC3 and FC4 and GGBFS formulations GGBFS2 and GGBFS4. Improved strength with increased binder content was observed in PCC. It was likely that this micro cracking, combined with increased volume fraction of the paste phase, led to the reduction in strength of alkali-activated concrete with increased binder content. The compressive strength, tensile strength, elastic modulus & Poisson ratio results for all mixtures are presented in Table 2.20.

Table 2.20

Summary of Compressive Strength(f_c') Tensile Strength (f_{ct}), Elastic Modulus(E) & Poisson Ratio (μ) Results for all Mixtures(Thomas & Peethamparan , 2015).

ID	Curing Condition	f_c' (MPa)	f_{ct} (MPa)	E(GPa)	μ
PCC 1	28 d @ 22° C	39.5	5.9	33.1	0.184
PCC 2	28 d @ 22° C	40.9	6.2	32.7	0.175
FC 1	28 d @ 22° C	16.2	2.9	17.7	0.126
	48 h @ 50° C	31.5	6.1	28.8	0.128
FC 2	28 d @ 22° C	28.9	6.7	21.5	0.128
	48 h @ 50° C	47.7	7.6	26.0	0.124
FC 3	28 d @ 22° C	22.9	3.8	22.6	0.127
	48 h @ 50° C	50.3	7.5	35.5	0.124
FC 4	28 d @ 22° C	21.3	4.1	10.5	0.127
	48 h @ 50° C	40.9	6.5	30.9	0.126
GGBFS1	28 d @ 22° C	33.7	6.8	34.2	0.129
	48 h @ 50° C	29.5	6.1	31.7	0.125
GGBFS2	28 d @ 22° C	44.7	7.2	26.2	0.130
	48 h @ 50° C	44.0	7.4	28.2	0.126
GGBFS3	28 d @ 22° C	46.7	6.3	27.0	0.127
	48 h @ 50° C	45.6	7.7	25.4	0.124
GGBFS4	28 d @ 22° C	35.0	6.3	27.9	0.134
	48 h @ 50° C	37.7	6.2	28.9	0.129
GGBFS5	28 d @ 22° C	45.7	8.3	22.4	0.125
	48 h @ 50° C	48.7	7.4	22.9	0.128
GGBFS6	28 d @ 22° C	52.6	8.4	33.5	0.127
	48 h @ 50° C	50.8	7.7	33.5	0.126

The average tensile strength of PCC control specimens was found to be $14.1 \pm 0.6\%$ of the corresponding compressive strength & was within the expected range of 10–15%. The tensile strengths of alkali-activated FC and GGBFS concrete observed in this study was marginally higher than those of PCC control mixtures. The average splitting tensile strength of alkali-activated GGBFS concrete was found to be $17.0 \pm 2.1\%$ of the corresponding compressive strength & was significantly higher than value observed for PCC mixtures in a similar strength range.

On further investigation it was found that the sensitivity of the splitting tensile strength of activated fly ash concrete to the compressive strength appeared to be affected by the curing condition i.e when it was cured at ambient temperature, the average splitting tensile strength was $19.4 \pm 2.8\%$ of the corresponding compressive strength, while the ratio was $16.5 \pm 1.9\%$ when cured at elevated temperature. The splitting tensile strength and corresponding compressive strength of activated fly ash and GGBFS concrete are plotted in Fig. 2.17.

Based on the experimental results obtained two prediction models were proposed to relate the splitting tensile strength to the compressive strength. The first, Eq. (12), was of the general form of Eq. (1) and fitted the data quite well ($R^2 = 0.86$). A second proposed equation was also given, following the common convention of limiting the power B in Eq. (1) to 1/2 .

$$f_{ct} = A(f_c)^B \dots\dots\dots(1)$$

$$f_{ct} = 2/5(f_c)^{7/9} \dots\dots\dots(12)$$

$$f_{ct} = 1.08(f_c)^{1/2} \dots\dots\dots (13)$$

In addition to the proposed models Eqs. (12) and (13), several previously proposed models for splitting tensile strength of concrete were also included for comparison on Fig. 2.17. These comprised of the model proposed by Sofi et al. for high-strength inorganic polymer concrete, the ACI 318 model for normal strength PCC, and a model proposed by Carrasquilio and Nilson for high strength PCC.

The splitting tensile strength observed in this study for alkali-activated FC and GGBFS concretes far exceeded the predictions for both portland cement concrete and for alkali-activated and geopolymer concrete by a factor of nearly two.

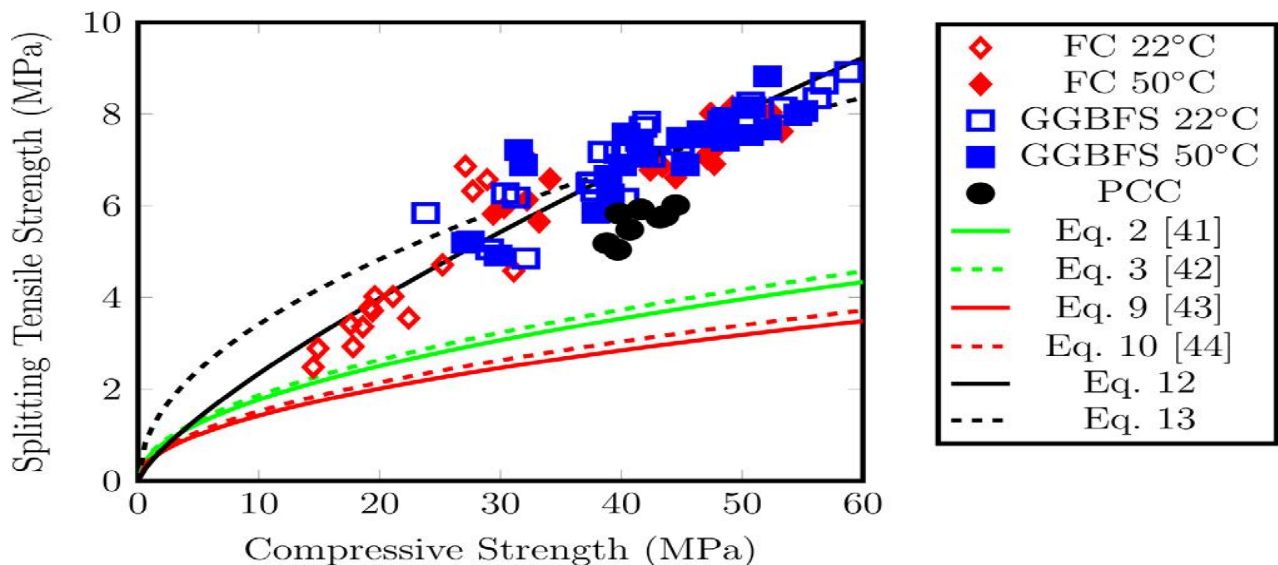


Fig. 2.17. Splitting Tensile Strength f_{ct} and Compressive Strength f_c of Alkali Activated FC and GGBFS Concrete Along with Proposed Models Eq. (12) and (13) and Existing Models Proposed by Lee and Lee , Sofi et al. , ACI 318 ,Carrasquilio and Nilson . (Thomas & Peethamparan , 2015).

Mithanthaya & Rao (2015) studied the effect of glass powder (GP) and ground granulated blast furnace slag (GGBS) on the compressive strength of Fly ash based geopolymer concrete. In this study the mass ratio of fine aggregate (fA) to coarse aggregate (CA) was maintained constant. NaOH flakes were dissolved in water to prepare activating liquid and the resulting activating solution along with other ingredients was mixed with fly ash (FA) to produce geopolymer concrete. The ranges of investigation parameters included GP/FA from 0% to 20%, and GGBS/ FA from 0% to 20% with constant amount of GP. All the samples were air cured inside laboratory under room temperature .

In order to make geopolymer concrete feasible for construction purposes at site & to provide additional source of reactive silica & alumina a combination of Flyash, GGBS & Glass Powder was selected. Fly-ash was obtained from a nearby thermal plant whereas glass powder was obtained by crushing available waste glass pieces using a crusher. GGBS powder sieved using 600 micron IS sieve and having a specific gravity of 2.88 was used for the experiment. Based on the information available in literature the mass ratios of certain parameters were selected & details are as follows:

- CA/fA is 0.522
- NaOH/FA or NaOH/(FA+GP) or NaOH/(FA+GP+GGBS) was taken as 7.50%
- W/FA or W/(FA+GP) or W/(FA+GP+GGBS) was taken as 0.3

The mass ratio for different batches of concrete, $(CA+fA)/FA$, $(CA+fA)/(FA+GP)$, $(CA+fA)/(FA+GP+GGBS)$ was maintained as 3.5 & variables considered are as follows:

- GP/ FA 0%, 5%, 10% 15% and 20%
- GGBS/FA 0%, 5%, 10%, 15%, 20%, with GP/FA as 10%

Considering all the parameters & different ratios a total of nine different mixes were formed and totally 54 cubes were cast.

To prepare activating solution sodium hydroxide flakes weighing 0.75kg were dissolved in 2.978 litre of water to form an alkaline solution & selected amount of FA or (FA + GP) or (FA+GP+GGBS) as per the case was added to NaOH solution and mixed properly. In order to increase the workability, an additional quantity of 0.9 litre water was added and mixed properly.. The whole process of sample formation was carried out in three stages in which the first stage comprised of formation of paste by mixing FA and NaOH solution and in the second stage mix

of FA and different % of GP was used to mix with NaOH solution to prepare the paste. In the third stage, mixture of FA, 10% GP and different % of GGBS was used to mix with NaOH solution to prepare the paste.

At 7 days of curing when the cubes were tested , the strength obtained for concrete having FA and 10% GP was found to be the highest so they decided to prepare concrete having FA, 10% GP and different percentages of GGBS to study the effect of GGBS on the strength of geopolymer concrete. The results of 7 & 28 day compressive strength are given in table 2.21 & 2.22 as follows:

Table 2.21

Variation in Compressive Strength of Cubes in MPa For (FA+GP) (Mithanthaya & Rao, 2015).

Replacement of FA by GP	0%	5%	10%	15%	20%
7 day compressive strength	4.22	5.45	6.67	4.89	5.34
28 day compressive strength	13.11	14.32	15.56	16.67	20.89

Table 2.22

Variation in Compressive Strength of Cubes in MPa For (FA+10%GP+GGBS) (Mithanthaya & Rao, 2015).

Replacement of FA by GGBS	0%	5%	10%	15%	20%
7 day compressive strength	6.67	8.33	12.45	16.67	17.33
28 day compressive strength	15.56	20.00	25.22	32.44	32.89

3.1 GENERAL

The present chapter deals with the material properties and the mix proportion adopted for the development of Geopolymer Concrete specimens. In order to achieve the objectives of the present study, an experiment was performed to determine the compressive strength, flexural strength & split tensile strength of the geopolymer concrete specimens made by using flyash, glass powder and GGBS along with the NaOH solution as alkaline activator.

3.2 CHARACTERISTICS OF MATERIALS USED

The properties of various materials used for making GPC concrete mixes were determined in laboratory as per relevant IS codes of practice. The materials used in the present experimental study undertaken for the development of GPC were flyash, coarse aggregates, fine aggregates, and NaOH solution, in addition to glass powder and alccofine(GGBS) in varying proportions. The importance of study of the various properties of material is used to check the acceptance of materials with the codal provision requirements and to enable an engineer to design a concrete mix for a particular strength. The description of various materials along with their investigated properties which were used in this study are detailed in the following sub-sections:

3.2.1 Fly Ash

Flyash may be defined as an aluminosilicate source which represents the majority component of geopolymer concrete quantity wise and has the least unit cost of all the cementing materials used in the mix. Flyash plays the important role of reducing brittleness in geopolymer concrete to a considerable extent so that it can withstand more tensile stress without addition of reinforcing steel. The fly ash particles are dominantly spherical in shape and range in diameter from 1 to 200 μm . Some of the fly ash particles are even hollow shaped. It contains both crystalline phases like quartz, mullite, hematite, etc. and also amorphous phases.

Fly ash, as the solid by-product of the combustion of coal, is generally extracted from the combustion flue gases emanating from coal-fired power plant through the process of electrostatic precipitation. The Flyash used in the dissertation work was procured from a coal based thermal

power plant located in Nalash village near Rajpura town in Patiala district of Punjab. The plant consists of 2x700 MW units & is being operated by Larsen & Toubro. The flyash procured was Class F flyash & photograph of it is shown in Fig. 3.1.



Fig. 3.1. Actual Photograph of Flyash

According to ASTM C 618-93 flyash is classified into 3 categories namely Class N, Class F & Class C depending upon the source from which it is produced. In this Class N flyash is obtained from natural sources & consists of raw or calcined natural pozzolans such as laterite shale, Class F flyash produced from burning anthracite & Class C flyash produced from burning lignite or sub-bituminous coal. The specification for the flyash of any type is given by the IS 3812: 2013. The physical properties & chemical properties of the flyash are presented in Table 3.1 & Table 3.2 respectively.

**Table 3.1
Physical Properties of Flyash.(Provided by Supplier).**

Characteristics	Value
Blaine fineness	265 m ² /Kg
Specific Gravity	2.35
Particle Size	8 to 14 μm

Table 3.2
Chemical Properties of Flyash.(Provided by Supplier)

S.N.O	Tests	Result(%)	Requirements in % (As per IS:3812:2013)
1	SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , % by mass	92.78	70(Min)
2	Silicon dioxide as SiO ₂ , % by mass	62.55	35(Min)
3	Magnesium Oxide as MgO, % by mass	0.13	5(Max)
4	Total Sulphur as SO ₃ , % by mass	0.22	3(Max)
5	Available Alkali as Na ₂ O % by mass	0.20	1.5(Max)
6	Total Chlorides as Cl,% by mass	0.024	0.05(Max)
7	Loss on Ignition,% by mass	0.52	5(Max)

3.2.2 Glass Powder

Glass powder may be defined as primarily a silicate source which provides the necessary cations to be acted upon by alkaline activator thereby leading to creation of additional cementing by products. Its main use in the geopolymer concrete is associated with strength gain at longer ages & improvement of durability properties of the resulting geopolymer concrete.

They may also be defined as non-crystalline silicates containing other oxides. In glass powder silicon atoms together with other elements (e.g. Al, Zr, B) readily form bridging bonds with oxygen atoms to provide the highly cross-linked glass network.

The Glass powder used in the study belonged to the family of post consumer glass. Scraps of Glass pieces were collected & were ground by manual means to obtain glass powder passing through 600 micron IS sieve. The photograph of the glass powder used in the dissertation work is shown in Fig.3.2 & its properties presented in Table 3.3 respectively.

There are mainly three types of glass powders that can be used for formation of geopolymer concrete: Post industrial by-product derived from waste glass fiber, Post industrial by-product obtained from recycling of glass & Post consumer glass powder obtained by grounding scraps of the glass pieces obtained from human consumption.



Fig. 3.2. Actual Photograph of Glass Powder

Table 3.3

Physical Properties of Glass Powder(Found out in Lab)

Characteristics	Value
Blaine fineness	175 m ² /Kg
Specific Gravity	2.294
Particle Size	<10 μm

3.2.3 Ground Granulated Blast Furnace Slag (GGBS)

GGBS may be defined as a calcium-silicate source which provides the necessary cations to be acted upon by alkaline activator. The use of GGBS in geopolymer concrete provides an additional source of alumina which on reaction with alkaline activator leads to creation of additional cementing by products. The role of GGBS is mainly concerned with early strength gain as majority of the GGBS present reacts within first 7 days.

Ground-granulated blast-furnace slag (GGBS or GGBFS) is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. The Ground Granulated Blast Furnace Slag(GGBS) used in the dissertation was procured from a subsidiary of Ambuja Cement Group. The product was named Alccofine 1203 & is shown in Fig. 3.3

There are mainly three types of blast furnace slag: air cooled slag, granulated slag and expanded slag. The basic difference in all these slags is the process of formation of these slags. The slag used in our dissertation work is granulated slag which is formed by quickly quenching molten slag with water thereby leading to creation of glassy sand like material. The physical properties & chemical properties of the GGBS are presented below in Table 3.4 & Table 3.5 respectively



Fig. 3.3. Actual Photograph of GGBS

Table. 3.4

Physical Properties of GGBS(Provided by Manufacturer)

Characteristics	Value
Blaine fineness	4490 cm ² /gm
Specific Gravity	2.9
Particle Size	< 2.5 μm-10%
	< 6 μm -50%
	< 12 μm- 90%

Table. 3.5
Chemical Properties of GGBS(Provided by Manufacturer)

S.N.O	Composition	Values in (%)
1	SiO ₂	29.96
2	Al ₂ O ₃	12.25
3	CaO	45.45
4	SO ₃	3.62
5	Na ₂ O	0.31
6	LOI	2.39

3.2.4 Coarse Aggregates

The aggregate which is retained over IS sieve 4.75 mm is termed as coarse aggregate. The basic function performed by these aggregates in geopolymer concrete is to increase the robustness of geopolymer concrete & thus help in making a solid and hard mass of geopolymer concrete. In addition to this it helps to reduce the cost of geopolymer concrete mix prepared by occupying the major volume of the concrete.

The coarse aggregates used in the present study were a mixture of two locally available crushed stones of 20mm and 10 mm nominal sizes. Coarse aggregates belonging to Anandpur Sahib area were used for this dissertation work.

According to IS 383:1970 coarse aggregates are of following types: Crushed gravel, stone obtained by crushing of gravel & hard stone, Uncrushed gravels, stones resulting from the natural disintegration of rocks & partially crushed gravel or stone which is obtained as a product of blending of above two types.

The specific gravity and other physical properties of coarse aggregates tested in the laboratory are given in Table 3.6. The sieve analysis of coarse aggregate was done in the laboratory and the values obtained are shown in the Table 3.7 for the 20mm aggregate and Table 3.8 for the 10mm aggregate.

Table 3.6
Properties of Coarse Aggregates

Characteristics	Value	
Shape	Angular	
Nominal size	20mm	10mm
Specific Gravity	2.71	2.75
Water Absorption	0.3%	0.5%

Table 3.7
Sieve Analysis of Coarse Aggregates (20mm)

S.N.O	IS-Sieve(mm)	Wt. Retained(gm)	%age Passing	%age retained	Cumulative % retained
1	80	0.00	0.00	100.00	0.00
2	40	0.00	0.00	100.00	0.00
3	20	28	0.93	99.07	0.93
4	10	2876	95.87	3.20	96.8
5	4.75	75	3.20	0	99.3
6	2.36	0	0	0	100
7	1.18	0	0	0	100
8	600	0	0	0	100
9	300	0	0	0	100
10	150	0	0	0	100
11	Pan	21	0.7		
Total		3000		SUM	697.03
				FM = 6.97	

Table 3.8
Sieve Analysis of Coarse Aggregates (10mm)

S.N.O	IS-Sieve(mm)	Wt. Retained(gm)	%age passing	%age retained	Cumulative % retained
1	80	0.00	0.00	100.00	0.00
2	40	0.00	0.00	100.00	0.00
3	20	447	22.35	77.65	22.35
4	10	415	20.75	56.90	43.10
5	4.75	1055	52.75	4.15	95.85
6	2.36	80	4	0.15	99.85
7	1.18	0	0	0	100
8	600	0	0	0	100
9	300	0	0	0	100
10	150	0	0	0	100
11	Pan	3	0.15	SUM	661
Total		2000		FM = 6.61	

3.2.5 Fine Aggregates

The aggregates most of which pass through 4.75mm IS sieve are termed as fine aggregates. The basic function performed by these aggregates in geopolymer concrete is to fill the voids in the concrete so as to make it a homogeneous mix. In addition to this it fills the voids existing in the coarse aggregate and reduces shrinkage and cracking of geopolymer concrete.

In our dissertation work fine aggregates belonging to Anandpur Sahib area & conforming to grading zone II as per IS 383:1970 were collected from a local supplier & used in the formation of geopolymer concrete samples.

According to IS 383:1970, fine aggregates are of following types: Natural sand i.e. the fine aggregate resulting from natural disintegration of rocks, Crushed stone sand i.e. the fine

aggregate produced by crushing hard stone & Crushed gravel sand i.e. the fine aggregate produced by crushing natural gravel.

In order to have an idea about the grading of the fine aggregate being used for preparation of geopolymer concrete a test known as sieve analysis of fine aggregate was performed & the results of which are given in table 3.9 as below.

Table 3.9
Sieve Analysis of Fine Aggregate

S.N.O	IS-Sieve(mm)	Wt. Retained (gm)	%age Retained	%age passing	Cumulative % Retained
1	4.75	5	0.5	99.5	0.5
2	2.36	59	5.9	93.6	6.4
3	1.18	136	13.6	80	20
4	600 μ	243	24.30	55.7	44.3
5	300 μ	415	41.5	14.2	85.8
6	150 μ	122	12.2	2.0	98.0
7	Pan	20	2.0		
Total		1000		SUM	255
ZONE II					FM= 2.55

3.2.6 Water

The water used in making geopolymer concrete can be defined as an ingredient primarily required for workability purpose & has no involvement in reaction process of geopolymer concrete. In our dissertation work potable water was used for mixing of geopolymer concrete.

3.2.7 Alkaline Activator

Alkaline activator in geopolymer concrete can be basically defined as an ingredient responsible for dissolution of any pozzolanic compound or source of silica and alumina leading to the formation of mobile precursors of alumino-silicate oxides through the complex action of hydroxide ions.

The reaction of hydroxide ions with alumino silicate oxides and silicates leads to formation of polymeric Si-O-Al-O bonds described by formula:-



Where M is a cation such as potassium, sodium or calcium, and n is a degree of polycondensation

The alkaline activator used in the dissertation work was prepared by dissolving sodium hydroxide pellets in water. To prepare a solution of say 12M concentration 480 grams (Molarity

x Molecular weight) of sodium hydroxide pellets were dissolved in water so as to make resulting one litre solution. The activator solution was prepared 24 hours prior to use so that excess heat generated due to exothermic reaction of water & sodium hydroxide flakes is dissipated by the time solution is to be used. The density of the final activator solution produced was found to be 1112 Kg/m³ for 4M, 1265 Kg/m³ for 8M & 1348 Kg/m³ for 12M NaOH solution respectively. Sodium hydroxide is also known as Caustic Soda in local parlance & is shown in Fig. 3.4.



Fig. 3.4. Actual Photograph of Sodium Hydroxide

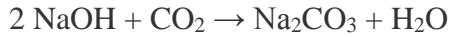
The two most commonly adopted systems for alkaline activation of geopolymer concrete are a combination of sodium silicate & sodium hydroxide in the ratio of 2.5:1 and the other one being sodium hydroxide alone. In our dissertation work to achieve our objective of lesser carbon footprint sodium hydroxide alone has been used as alkaline activator.

3.2.7.1 Properties Of Sodium Hydroxide

Some of the salient features of sodium hydroxide used are as follows:

- Shape of pellets:- Semi spherical.
- Nature :- Hygroscopic (i.e will absorb water from the air when exposed).
- Molecular Weight of Sodium Hydroxide is 40
- Is a caustic substance and skin contact should be avoided.

- Chemical Reaction with air:-



NaOH (sodium hydroxide), when exposed to the air, reacts with the carbon dioxide in air, to form sodium carbonate. This implies that sodium hydroxide as a solid or in solution will lose its strength with time and degree of exposure.

- Chemical Reaction with water:-

Sodium hydroxide (NaOH) ionises in water as shown by the following equation -



This equation shows that in solution NaOH will release hydroxide ions (OH⁻). The excess of OH⁻ ions in solution causes that solution to be basic or alkaline and caustic.

3.3 EXPERIMENTAL PROGRAMME

3.3.1 Test Data for Materials

The detail of the materials described in the previous section along with its properties have been taken to find out the right mixture combination for preparation of geopolymer concrete samples.

The detail of all the necessary ingredients to be used in this dissertation work are as follows:-

➤ Flyash	Class F
➤ Specific Gravity of Flyash	2.35
➤ Specific Gravity of GGBS	2.9
➤ Specific Gravity of Glass Powder	2.29
➤ Specific Gravity of Coarse Aggregate (20 mm)	2.71
➤ Specific Gravity of Coarse Aggregate (10 mm)	2.75
➤ Specific gravity of Fine Aggregate	2.60
➤ Free Surface Moisture of Coarse Aggregate (20mm & 10mm)	Nil
➤ Sieve Analysis of Coarse Aggregate	Conforming to Table 4 (IS: 383-1970)
➤ Sieve Analysis of Fine Aggregate	Conforming to Zone II (IS: 383-1970)
➤ Alkaline Solution	4M, 8M, 12M

3.3.2 Scheme of Samples Prepared for Study

For carrying out this dissertation work a total of 150 no samples were prepared. These samples comprised of control mix & blended mix samples with control mix contributing 15 no to the total quantity & the rest contributed by blended mixes. The details along with the scheme followed for preparation of samples used in this dissertation work is shown in Fig. 3.5.

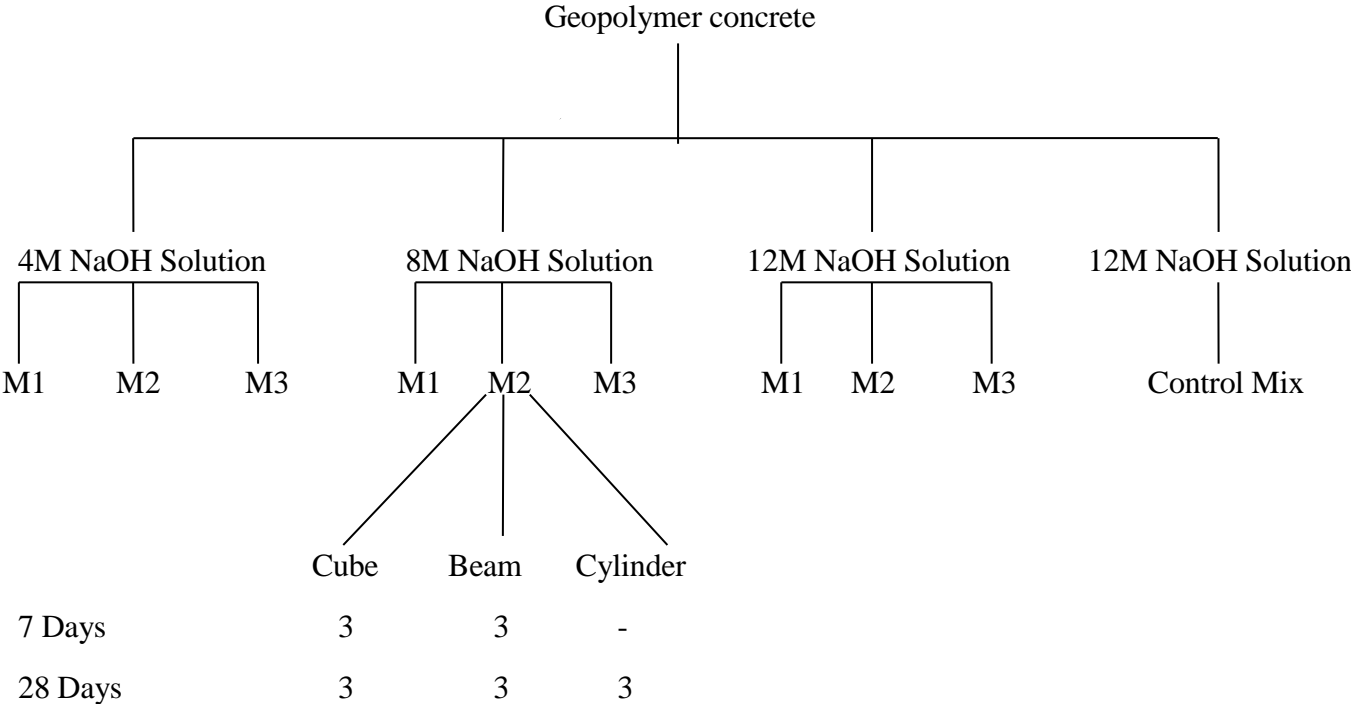


Fig. 3.5 Schematic Diagram Showing Scheme of Samples Prepared

As shown in the figure for each concentration of NaOH solution three mixes namely M1, M2 & M3 were prepared. For each of these mixes prepared three samples each for 7 days & 28 days were prepared for carrying out various tests. The size of the specimens prepared for these samples are as follows:-

- Cubical specimens of size 150mm x 150mm x 150mm were prepared for finding compressive strength of concrete.
- Cylindrical specimens of size 300mm height x 150mm dia. were prepared for finding split tensile strength of concrete.
- Beam specimens of size 150mm x 150mm x 700mm were prepared for finding flexural strength of concrete.

3.3.3 Mix Proportions Used in the Study

Design of geopolymer concrete mix in this study has been done on a trial and error basis. Since there are no IS codes available for the design of geopolymer concrete mix therefore all the mix proportions have been selected on the basis of past observations & literature available. The total aggregates (fine and coarse) have been taken as approximately 80% of entire concrete mix by mass. Fine aggregates have been taken as approximately 30% of the total aggregates. The ratio of fine aggregate to coarse aggregate (fA/CA) has been adopted as 0.479. The mass ratio for different batches of geopolymer concrete, (CA+fA)/FA, (CA+fA)/ (FA+GP), (CA+fA)/ (FA+GP+GGBS) has been kept as 3.94. The replacement of flyash with glass powder in the percentages of 5%, 10%, 15% & the replacement of flyash with GGBS in the percentages of 15%, 20% & 25% has been considered in this study.

As far as use of alkaline activator is concerned three different concentrations of NaOH solution i.e 4M, 8M, 12M have been used in the development of GPC. For each concentration of NaOH solution, three mixes (i.e. M1, M2, M3) were prepared. Water added in the samples prepared was as per requirement and had no role in the reaction mechanism of geopolymer concrete.

Table 3.10

Mix Proportion of Geopolymer Concrete Samples

	Ingredients						
	Flyash	GGBS	Glass	CA	CA	FA	NaOH
Units	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)
Designation							
Control	450	-	-	720	480	575	70.00
M1-4M	315	112.5	22.5	720	480	575	23.33
M2-4M	315	90	45	720	480	575	23.33
M3-4M	315	67.5	67.5	720	480	575	23.33
M1-8M	315	112.5	22.5	720	480	575	46.66
M2-8M	315	90	45	720	480	575	46.66
M3-8M	315	67.5	67.5	720	480	575	46.66
M1-12M	315	112.5	22.5	720	480	575	70.00
M2-12M	315	90	45	720	480	575	70.00
M3-12M	315	67.5	67.5	720	480	575	70.00

Apart from all these blended mixes a control mix containing only flyash as binder material & activated using 12M NaOH solution was prepared. These control mix specimens were subjected to elevated temperature curing for 48 hours @ 60°C respectively & subsequently subjected to ambient curing till the age of 28 days. The mix proportions of ingredients used for the development of GPC are shown in Table 3.10 for the three different concentrations of NaOH solution i.e 4M, 8M, 12M..

3.3.4 Casting Procedure followed in the Study

The casting procedure followed for preparation of geopolymer concrete samples of different molarity was entirely mechanized process. The salient features of the casting procedure followed are as follows:-

- To begin with all the materials to be used were taken out & cleaned of dirt & dust if any.
- After that all the materials were weighed according to the mix proportion selected .
- Then Flyash, GGBS and Glass powder were taken in a tray & mixed properly by hand mixing for 2-3 min to form a uniform coloured blend.
- To start the drum mixer the fine and coarse aggregates were added into the mixer and were mixed properly for 2 min followed by the incorporation of blended mixture into the mixer. To attain a uniform mix throughout the mixture the mixer was further rotated for 4-5 minutes.
- Subsequently NaOH solution of desired concentration was added into the mixer in stages & for each stage the mixer was rotated for 4-5 minutes so as to achieve a proper mix of desired geopolymer concrete.
- As per the workability requirements of the mixture water was added to the mix as and when required & the prepared mix was poured into moulds in three layers and vibrator layerwise.
- At last finishing of the moulds was done with the help of a trowel
- To prevent any undulation in the finished product during curing period they were placed safely on a levelled ground.

The photograph of the finished mould containing geopolymer concrete is shown below in Fig.3.6



Fig 3.6. Finished Mould Containing Geopolymer Concrete

3.4 TEST METHODS

The methods used for finding the properties of Flyash, GGBS, Glass Powder, coarse aggregates, fine aggregates and testing the strength of geopolymer concrete specimens are given below:

3.4.1 Specific Gravity

3.4.1.1 Definition & Purpose of Test

Specific gravity is ratio of weight of a given volume of the substance to the weight of an equal volume of some reference substance, or equivalently the ratio of masses of equal volume of two substances.

The purpose of carrying out this test is to know about physical characteristics of the different materials used. This specific gravity gives an idea of heaviness or lightness of the material. In case of aggregates it gives an idea of the quality and properties of the aggregate also. Specific gravity of all the pozzolanic components has been found out as per IS 2386 (Part - 3) 1963.

Specific gravity for fine aggregates in the lab was found out with the help of pycnometer of 500 ml capacity. For coarse aggregates it was found out with the help wire basket of size 200 mm dia x 200 mm height containing 4.75mm IS Sieve net. For supplementary cementitious materials such as Flyash, GGBS & Glass Powder it was found out with the help of specific gravity bottle.

3.4.1.2 Calculation

Specific gravity = $D/A - (B - C)$

Where

A = weight in g of saturated surface-dry sample,

B = weight in g of pycnometer or gas jar containing sample and filled with distilled water

C = weight in g of pycnometer or gas jar filled with distilled water only

D = weight in g of oven-dried sample

3.4.2 Sieve Analysis of Coarse and Fine Aggregates as per IS 2386 (Part - 1) 1963

Sieve analysis is used for determination of particle size distribution of fine and coarse aggregates by sieving or screening.

3.4.2.1 Definition & Purpose of Test

Sieve Analysis may be defined as a procedure of passing the aggregates or any other material through wire screens so as get an idea about composition of the mix.

The purpose of performing this test is to get a clear idea of the various sizes of particles present in the mix. The knowledge of the size distribution is very helpful in distinguishing various mixes into gap graded, uniform graded and well graded etc.

Sieve analysis for 20 mm & 10 mm coarse aggregates was performed in the lab with the sieves of sizes 80mm, 40mm, 20mm, 10mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 300µm, 150µm & Pan. For fine aggregates it was done with the help of sieves of sizes 4.75mm, 2.36mm, 1.18mm, 600µm, 300µm, 150µm & Pan respectively. The weight of the material obtained in each sieve was noted & the desired calculations were performed.

3.4.2.2 Calculation

% retained on a particular sieve = $(\text{weight of soil retained on that sieve} / \text{Total weight of soil taken}) \times 100$

Cumulative % retained = sum of % retained on all sieves of larger sizes and % retained on that particular sieve

Percentage finer than the sieve under reference = $100\% - \text{cumulative \% retained}$.

3.4.3 Compressive Strength

3.4.3.1 Definition & Purpose of Test

Compressive Strength may be defined as the capacity of a material or structure to withstand loads tending to reduce size. In other words it is just the opposite of tensile strength.

The main function of the concrete in structure is mainly to resist the compressive forces & since concrete being strong in compression and weak in tension it becomes imperative to know about its strong property so that other additions to it can be done accordingly. So this test basically aims to know about its load carrying capacity in compression.

The compressive strength of the cubical specimens of size 150mmx150mmx150mm was found out on Universal Testing machine of 1000 kN capacity as per the provisions of IS:516-1959. To carry out the compressive strength test the rate of loading adopted was 315 kN/min. The photograph of the testing setup is shown below in Fig. 3.7.



Fig. 3.7 Compressive Strength Test Setup

3.4.3.2 Calculation

The measured compressive strength of the specimen is calculated by dividing the maximum load applied to the specimen during the test by the cross-sectional area, calculated from the mean dimensions of the section and is expressed to the nearest kg per sq cm.

To take into account variation in different lots an average of three values is taken as the representative of the batch.

3.4.4 Flexural Strength

3.4.4.1 Definition & Purpose of Test

Flexural Strength also known as modulus of rupture or bend strength is a material property defined as the stress in a material just before it yields in a flexure test. The flexural strength represents the highest stress experienced within the material at its moment of failure.

The main purpose of performing this test is to have an assessment of the tensile strength of the material. For a homogeneous material flexural strength is the same as tensile strength but concrete being a heterogeneous material both are found out differently. Flexural strength is always measured in terms of stress.

The flexural strength of the beam specimens of size 150mmx150mmx700mm was found out on Universal Testing machine of 1000 kN capacity as per the provisions of IS:516-1959. The test on the beam specimen was performed using two point loading system & rate of loading adopted was 4kN/min. The photograph of the testing setup is shown below in Fig. 3.8.



Fig. 3.8 Flexural Strength Test Setup

3.4.4.2 Calculation

The flexural strength of the specimen shall be expressed as the modulus of rupture f_b , in which 'a' equals the distance between the line of fracture and the nearer support, measured in cm on the centre line of the tensile side of the specimen.

In our dissertation work all the beams failed according to criteria in which 'a' is greater than 20.0 cm for 15.0 cm specimen so the formula adopted for finding out the flexural strength is as follows:-

$$f_b = (p \times l) / (b \times d^2)$$

where

b = measured width in cm of the specimen.

d = measured depth in cm of the specimen at the point of failure.

l = length in cm of the span on which the specimen was supported.

p = maximum load in kg applied to the specimen.

3.4.5 Split Tensile Strength

3.4.5.1 Definition & Purpose of Test

Split tensile strength may be defined as a measure of the ability of material to resist a force that tends to pull it apart. It is expressed as the minimum tensile stress needed to split the material apart.

The main function of performing this test is to have an indirect assessment of the tensile strength of the material. The split tensile strength of the material is measured in terms of stress.

The split tensile strength of the cylinder specimens of size 150mm(dia)x300mm(height) was found out on Compression Testing machine of 5000 kN capacity as per the provisions of IS:5816-1999. According to IS:5816-1999 load was applied uniformly at the rate of 128 KN/min until failure of the cylinder occurred along the vertical diameter. In order to reduce the magnitude of the high compression stresses near the points of application of the load, narrow packing strips of plywood were placed between the specimen and loading platens of testing machine. The photograph of the testing setup is shown below in Fig. 3.9.

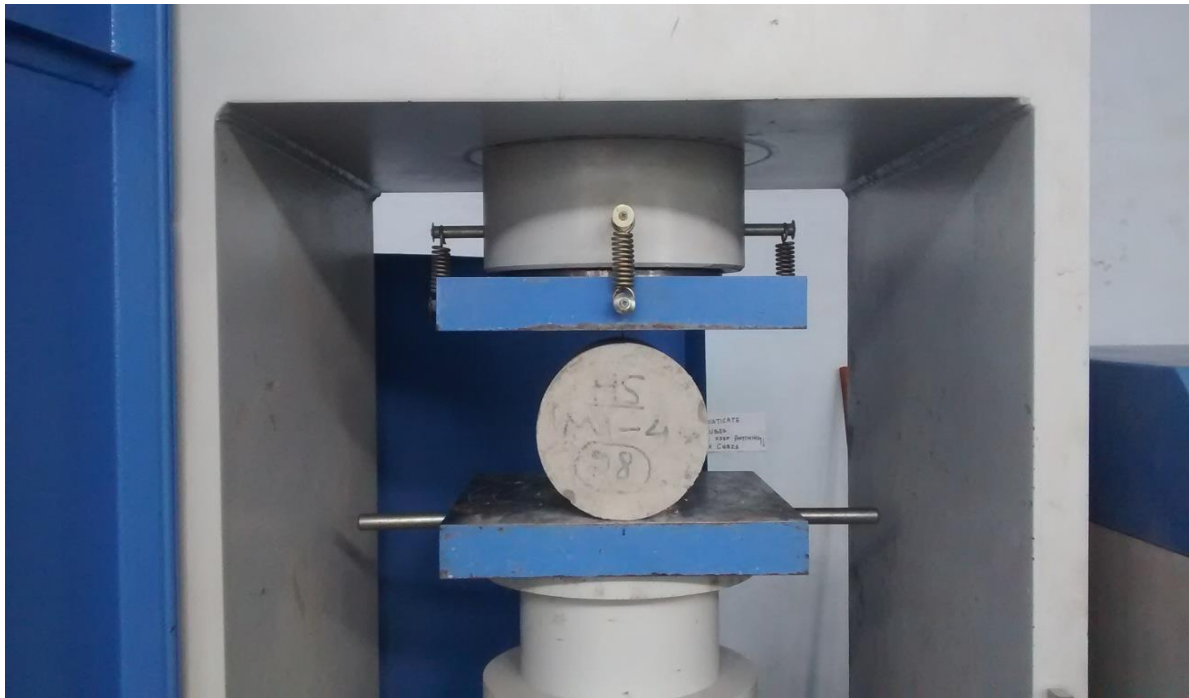


Fig. 3.9 Split Tensile Test Setup

3.4.5.2 Calculation

The magnitude of tensile stress (T) acting uniformly to the line of action of applied loading is given by formula:-

$$T = 0.637 P/DL$$

Where,

T= Split tensile strength (in MPa)

P = Applied load

D = Dia. of concrete cylinder sample (in mm)

L = length of concrete cylinder sample (in mm)

3.4.6 SEM & EDS TEST

3.4.6.1 Definition & Purpose of Test

EDS(Energy Dispersive X –ray Spectroscopy)

- Also known as energy dispersive X-ray analysis (EDXA) or energy dispersive X-ray microanalysis (EDXMA).
- It is an analytical technique used for the elemental analysis or chemical characterization of a sample. It relies on an interaction of some source of X-ray excitation and a sample.

- EDS makes use of the X-ray spectrum emitted by a solid sample when it is bombarded with a focused beam of electrons to obtain a localized chemical analysis.

SEM(Scanning Electron Microscope)

- It is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons.
- In this technique the electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography and composition.
- The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image.
- In this technique specimens can be observed in high vacuum, in low vacuum, in wet conditions (in environmental SEM), and at a wide range of cryogenic or elevated temperatures.
- SEM can achieve resolution better than 1 nanometer.
- The main purpose of carrying out these tests is to know the changes which are occurring in the microstructure of geopolymer concrete samples prepared. These tests can also be used to validate the experimental results obtained & its variations from the normal if any.

3.5 TEST CALCULATIONS

Compressive Strength

- Specimen Designation:- M1-4M
- Age of testing :- 28 Days
- Compressive strength=(Ultimate load/Area of cube) as per IS:516-1959

Where

Ultimate load :- 599.4 KN

Area of the cube:-150x150 mm²

Substituting the values we have:-

$$C.S=(599.4 \times 1000)/(150 \times 150)$$

$$C.S=26.64 \text{ N/mm}^2$$

Flexural Strength

- Specimen Designation:- M1-4M
- Age of testing :- 28 Days
- Flexural strength= $((pxl)/(bx d^2))$ as per IS:516-1959
- This formula has been considered in our case because the crack in the beam occurred in between two load points thereby making a greater than 20 cm.
- $f_b = ((pxl)/(bx d^2))$

Where

$$b = 15 \text{ cm}$$

$$d = 15 \text{ cm}$$

$$l = 60 \text{ cm.}$$

$$p = 1862 \text{ kg}$$

Substituting the values we have:-

$$f_b = ((1862 \times 60) / (15 \times 15^2))$$

$$f_b = 3.31 \text{ N/mm}^2$$

Split Tensile Strength

- Specimen Designation:- M1-4M
- Age of testing :- 28 Days
- $T = 0.637 P/DL$ as per IS:5816-1999

Where

T = Split tensile strength (in MPa)

P = Applied load

D = Dia. of concrete cylinder sample (in mm)

L = length of concrete cylinder sample (in mm)

Substituting the values we have:-

$$T = (0.637 \times 275 \times 1000) / (300 \times 150)$$

$$T = 3.89 \text{ N/mm}^2$$

4.1 GENERAL

In this chapter results obtained from various tests conducted on the geopolymer concrete specimens are presented and discussed to study the effect of addition of GGBS in percentages of 15%,20%,25% & Glass Powder in percentages of 5%,10%,15% on the compressive strength, flexural strength & split tensile strength of geopolymer concrete specimens. To make this study two dimensional molar concentration of NaOH i.e 4M, 8M & 12M as a variable has also been considered and its effect on compressive strength, flexural strength & split tensile strength has been studied. The compressive strength and flexural strength tests on the specimens have been performed after 7 and 28 days of curing whereas split tensile strength of the specimens has been checked for 28 days only. To get a better idea of the split tensile strength of geopolymer concrete specimens a comparison of the measured split tensile strength with the split tensile strength predicted as per various equations and codal provisions has been done.

To study the effect of these variables on the mechanical properties various graphs and bar charts showing the relative strength in different samples have been drawn. In addition to this to know about the effectiveness of ambient curing over oven curing a comparison of mechanical properties of blended mixes with the control mix has been done. A comparative study of various blended mixes with control mix has also been done with the help of SEM-EDS tests conducted on the specimens at the age of 28 days curing. For all the results obtained a discussion on the trend developed in the properties has been done & reasons for these trends have also been assigned on the basis of reaction mechanism & SEM-EDS test conducted on the specimens.

4.2 COMPRESSIVE STRENGTH

Compressive strength is the most common property used to describe a concrete. Since other properties of concrete often correlate well with the compressive strength, it is used as an indicator of the other mechanical properties. The results of the compressive strength tests of geopolymer concrete samples are given in Table 4.1 respectively. These are the mean values of the results obtained from three identical specimens.

Table 4.1
Compressive Strength Results of Geopolymer Concrete Samples

	Ingredients							Strength	
	Flyash	GGBS	Glass Powder	CA (20mm)	CA (10 mm)	FA	NaOH	7 days	28 days
Units	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(MPa)	(MPa)
Designation									
Control	450	-	-	720	480	575	70.00	7.37	15.11
M1-4M	315	112.5	22.5	720	480	575	23.33	20.44	26.64
M2-4M	315	90	45	720	480	575	23.33	17.28	23.91
M3-4M	315	67.5	67.5	720	480	575	23.33	15.33	21.95
M1-8M	315	112.5	22.5	720	480	575	46.66	14.93	23.33
M2-8M	315	90	45	720	480	575	46.66	12.05	20.35
M3-8M	315	67.5	67.5	720	480	575	46.66	11.11	18.13
M1-12M	315	112.5	22.5	720	480	575	70.00	12.53	20.66
M2-12M	315	90	45	720	480	575	70.00	15.64	23.06
M3-12M	315	67.5	67.5	720	480	575	70.00	10.40	17.42

For the control mix containing only flyash as binder & activated using 12M NaOH solution the compressive strength at 7 days has been found to be 7.37 MPa and at 28 days has been found to be 15.11 MPa respectively. The control mix studied over here has been subjected to 48 hours oven curing at 60°C & followed subsequently by ambient curing upto the age of testing.

In the 4M category, on replacement of flyash with 25% GGBS and 5 % Glass powder the mix M1-4M has been found to have compressive strength of 20.44 MPa after 7 days and 26.64 MPa after 28 days respectively. This implies a gain of strength of 177.34% at 7 days and gain of 76.30% at 28 days respectively. On subsequent replacement of flyash with 20% GGBS and 10 % Glass powder in mix M2-4M a gain of strength of 134.46% at 7 days and a gain of 58.24% at 28 days has been observed respectively. On further change in composition in M3-4M with 15% GGBS and 15% Glass powder as replacement of flyash a gain of strength of 108% at 7 days and a gain of 45.27% at 28 days has been observed respectively. This trend of compressive strength obtained clearly indicates the maximum gain of strength for highest percentage of flyash replaced with GGBS.

Moving on in the 8M category, the mix M1-8M (containing 70% Flyash, 25% GGBS and 5 % Glass powder) & activated using 8M NaOH solution has been found to have a compressive strength of 14.93 MPa after 7 days and 23.33 MPa after 28 days respectively. This implies a gain of strength of 102.6% at 7 days and gain of 54.40% at 28 days over control mix respectively In the mix M2-8M as the percentage of GGBS decreased by 5% & that of glass powder increased

by 5% in the mix composition of M1-8M the compressive strength showed a gain of strength of 63.50% at 7 days and 34.68% at 28 days over control mix respectively. In the mix M3-8M as the percentage of GGBS replacement further decreased by 5% & that of glass powder increased by 5% the compressive strength showed a gain of strength of 50.74% at 7 days and 19.99% at 28 days over control mix respectively. This trend clearly indicates the decrease in the percentage gain of compressive strength with increase in molar concentration of the activating solution.

On similar lines in the 12 M category the mix M1-12M having similar composition to M1-4M & M1-8M & activated using 12 M NaOH solution has been found to have compressive strength of 12.53 MPa after 7 days and 20.66 MPa after 28 days respectively. This implies a gain of strength of 70.01% at 7 days and gain of 36.73% at 28 days over control mix respectively. In the mix M2-12M as the percentage of flyash replacement with GGBS decreased by 5% & that of glass powder increased by 5% the compressive strength showed a gain of strength of 112.2% at 7 days and 52.61% at 28 days over control mix respectively. In the mix M3-12M as the percentage of GGBS further decreased by 5% & that of glass powder increased by 5% the compressive strength showed a gain of strength of 41.11% at 7 days and 15.29 % at 28 days over control mix respectively. This trend clearly indicates the sudden increase in the percentage gain of compressive strength in M2-12M mix thereby giving an indication of some other factor along with GGBS which is controlling this process of gain of strength.

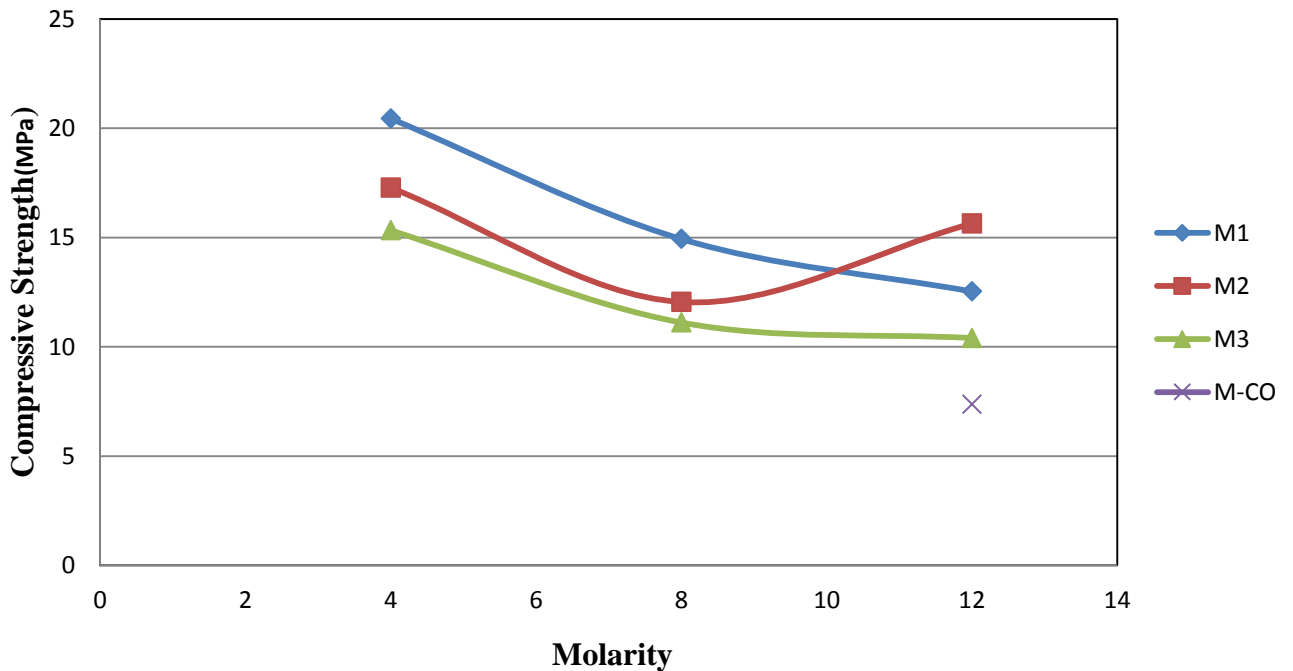


Fig 4.1 Effect of Concentration of NaOH on 7 day Compressive Strength

Fig.4.1 shows the effect of concentration of NaOH on the 7 day compressive strength of different mixes. It can be seen from Fig.4.1, that the control mix is having least compressive strength amongst all mixes considered as observed earlier also. The reason for this low strength development in the control mix is basically absence of calcium silicate hydrate gel contributed by GGBS & Glass powder to the mix This observation brings forth a point that a combination of GGBS & Glass powder have been able to successfully achieve our desired objective of adopting ambient curing for samples.

Furthermore, it can be seen that maximum compressive strength is achieved for 4M category samples as compared to 8M & 12 M category samples. It may also be noted that this pattern of compressive strength observed is not in conjunction with that of flyash based geopolymer concrete in which strength increases as concentration of NaOH solution increases. The reason for this variation is due to additional shrinkage occurring in geopolymer concrete samples prepared with high molar concentration solutions.

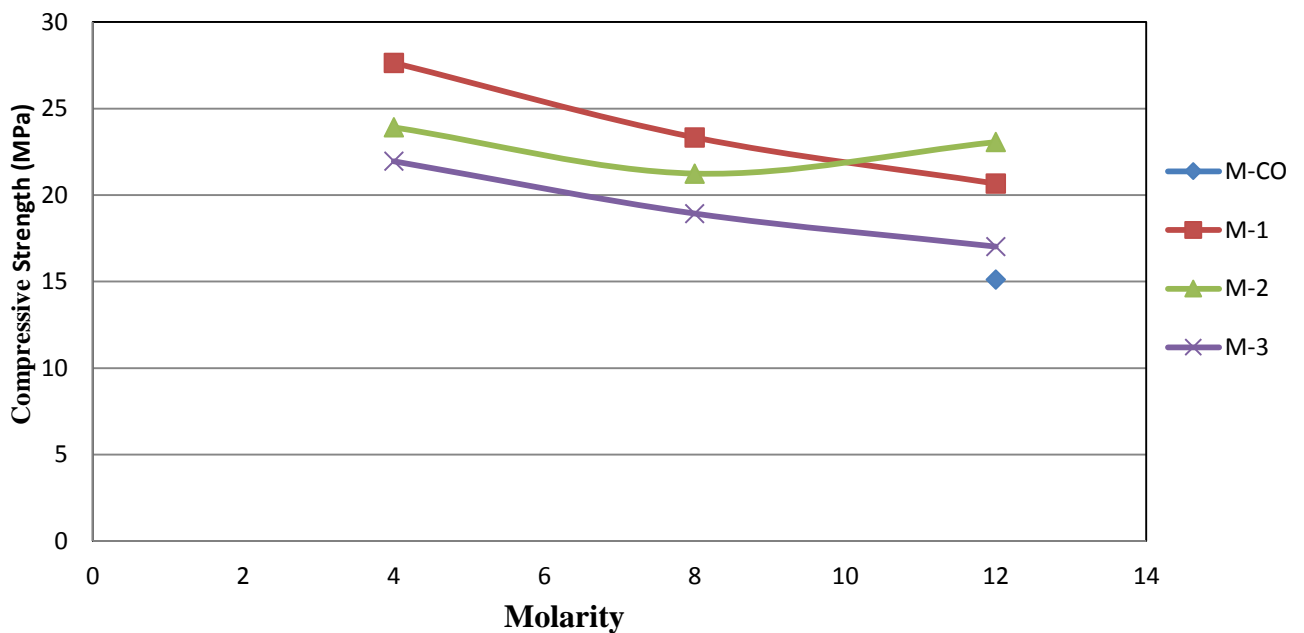


Fig 4.2 Effect of Concentration of NaOH on 28 day Compressive Strength

Fig 4.2 shows the effect of concentration of NaOH on the 28 day compressive strength of different mixes. It can be seen from Fig.4.2, that the control mix follows the same pattern as observed at 7 days & turns out to be the weakest specimen amongst all mixes. On the molarity

front also it can be seen that same pattern as observed at 7days is being followed with a variation in the percentage increase of compressive strength over control mix.

On seeing Fig.4.2, it may further noted that in the 12M category there is one abrupt variation that is the strength of M2-12M is highest in this molarity category & doesn't follow the general trend observed for the other molarity categories in this graph.

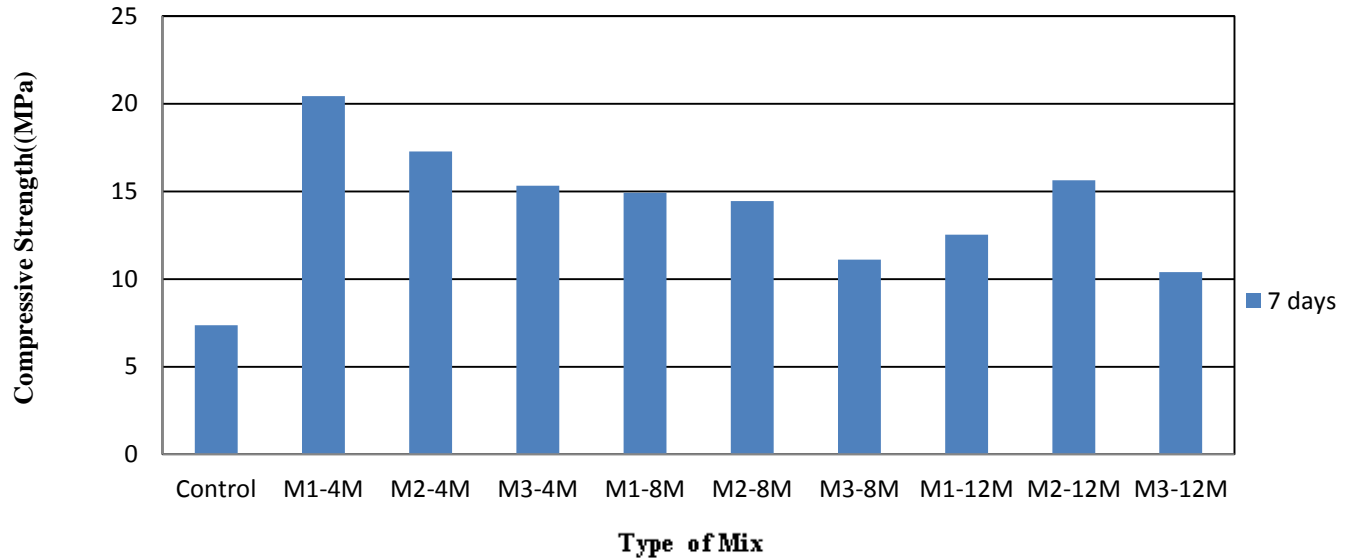


Fig 4.3 Compressive Strength Variation for Different Mixes of Geopolymer Concrete at 7 days

Fig. 4.3 shows the compressive strength of the geopolymer concrete mixes at 7 days. As shown in the figure, in the 4M category geopolymer concrete mix M1-4M achieves 33.33% higher 7-day compressive strength than M3-4M. For the 8M & 12M category the corresponding increase in 7-day compressive strength between M1 & M3 mixes is 34.38% & 20.48% respectively.

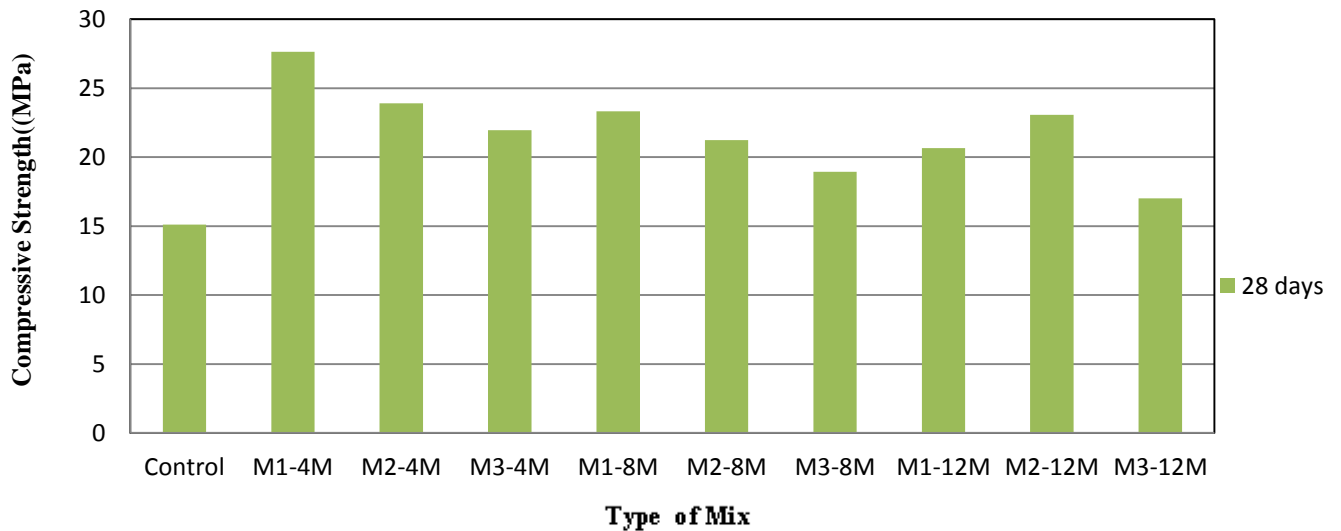
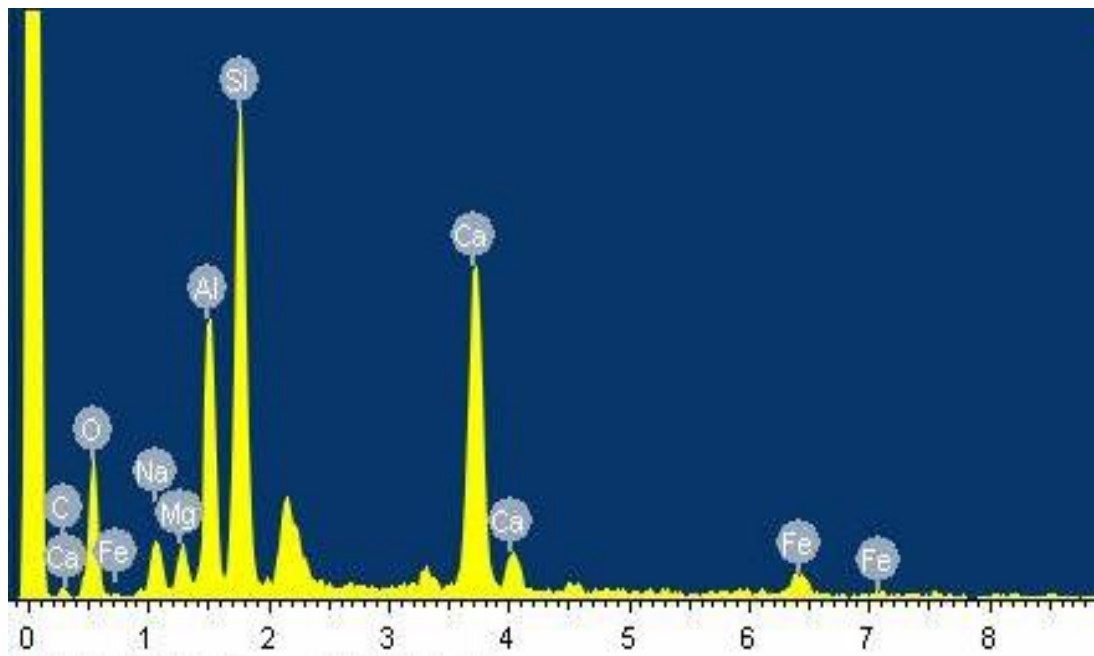
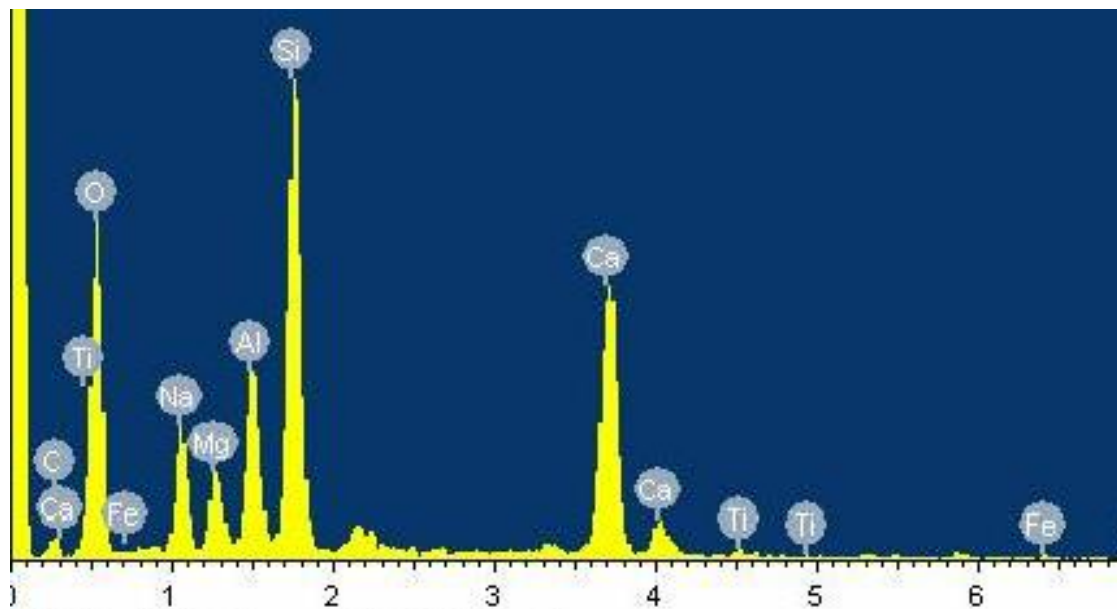


Fig 4.4 Compressive Strength Variation for Different Mixes of Geopolymer Concrete at 28 days

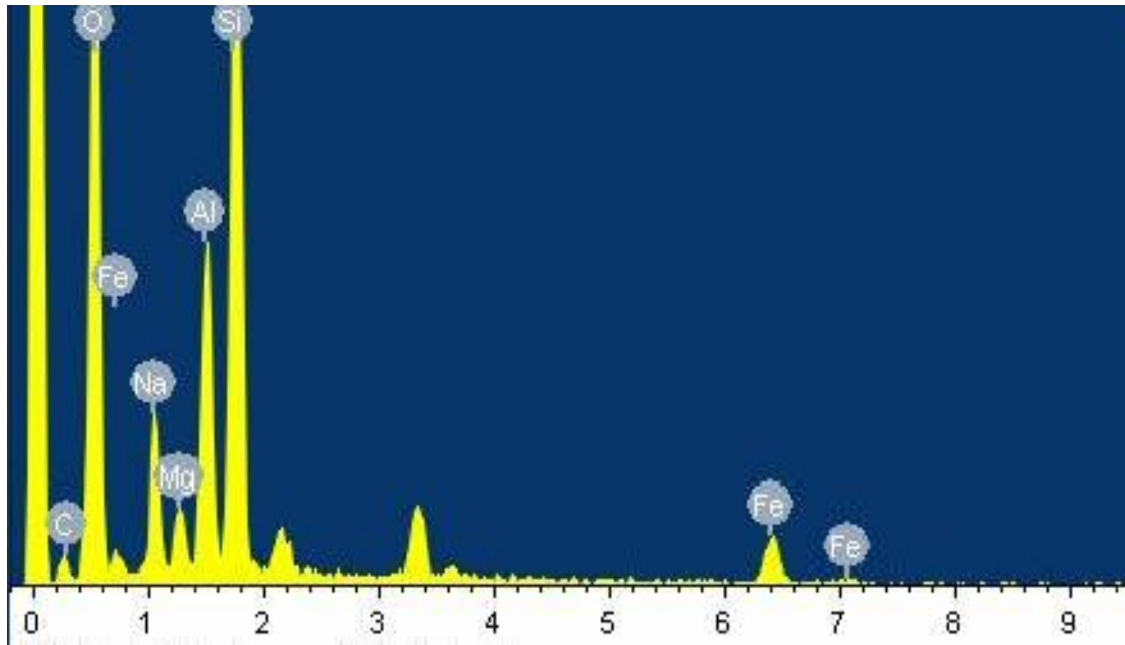
Fig. 4.4 shows the compressive strength of the geopolymer concrete mixes at 28 days. As shown in the figure, in the 4M category geopolymer concrete mix M1-4M achieves 21.36% higher 28-day compressive strength than M3-4M. For the 8M & 12M category the corresponding increase in 28-day compressive strength between M1 & M3 mixes is 28.68 % & 18.59% respectively.



M1-4M



M2-4M



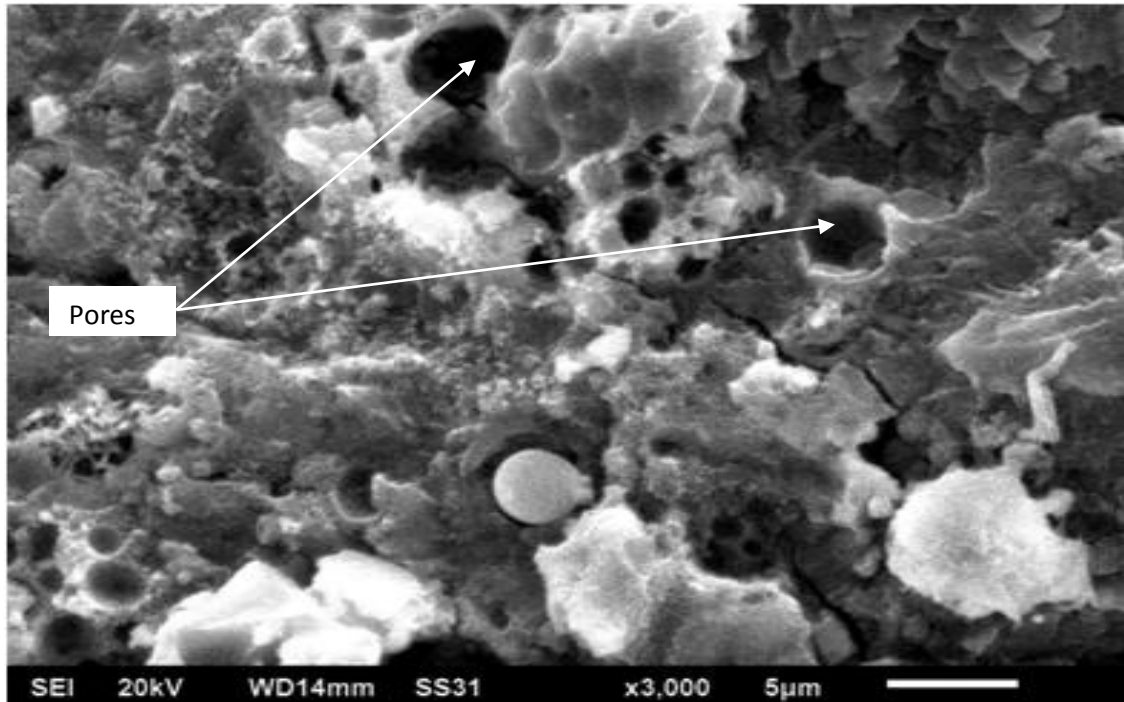
M3-4M

Fig 4.5 EDS results for M1-4M, M2-4M, M3-4M

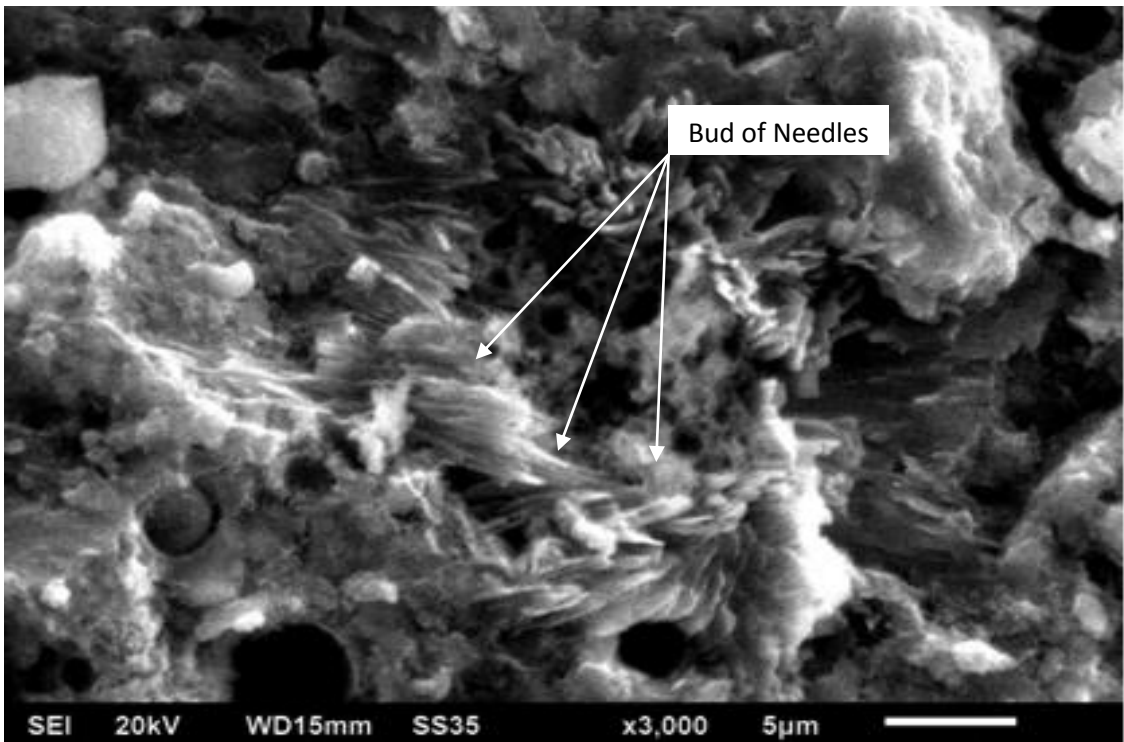
Fig 4.5 shows the EDS test results for M1-4M, M2-4M, M3-4M samples respectively. It can be seen from Fig 4.5 that the amount of alumina & calcium available in the mix is decreasing from M1-4M to M3-4M sample. This decrease in alumina & calcium is mainly on account of decrease in percentage of GGBS from mix M1-4M to M3-4M. The availability of the high amount of calcium and alumina in M1-4M mix leads to formation of additional calcium silicate hydrate gel with high amounts of tetra-coordinated Al in its structure as well as Na ions in the interlayer spaces.

Another important observation worth noting in Fig 4.5 is the increase in amount of silica from M1-4M to M3-4M which is mainly on account of increase in the percentage of Glass Powder from M1-4M to M3-4M. The availability of the high amount of silica in M3-4M mix leads to higher amount of gel formation and higher cross-linking of gel network thereby leading to higher compressive strength.

Since GGBS is mainly responsible for early age strength whereas glass powder is responsible for strength gain at later ages therefore it can be said that in the present study majority of the compressive strength achieved has been contributed by GGBS thereby leading to higher compressive strength for M1 mixes.



M1-12M



M2-12M

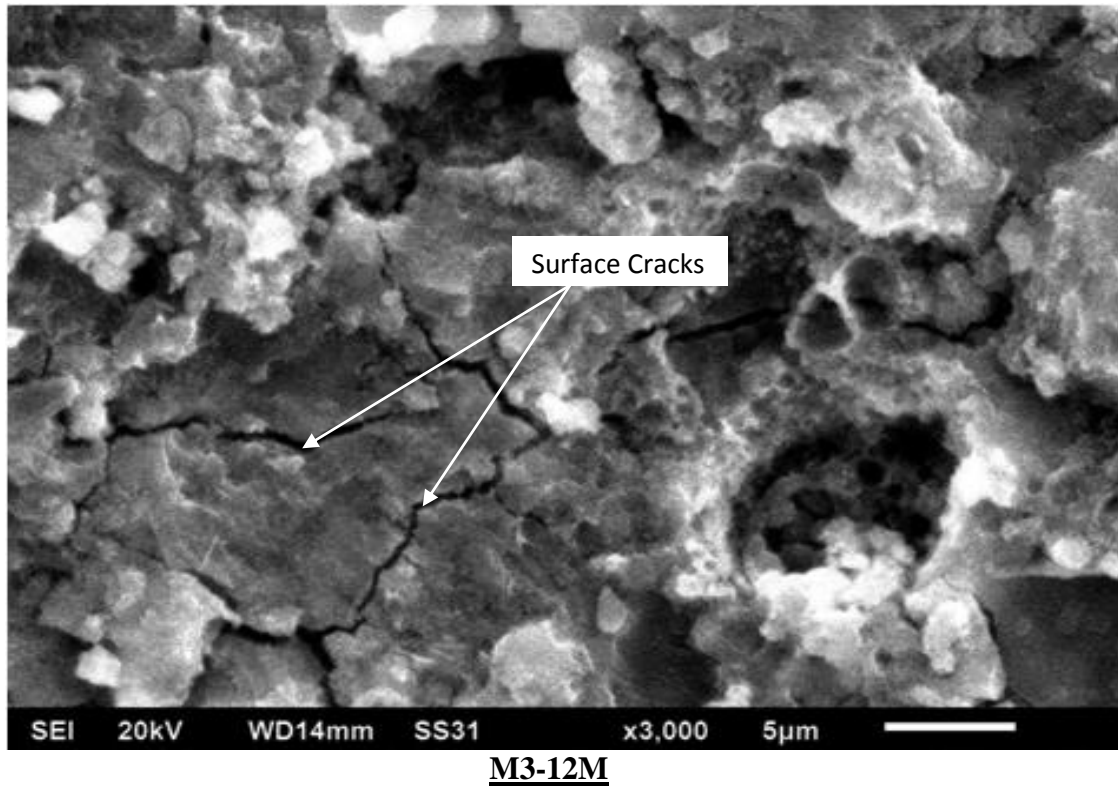
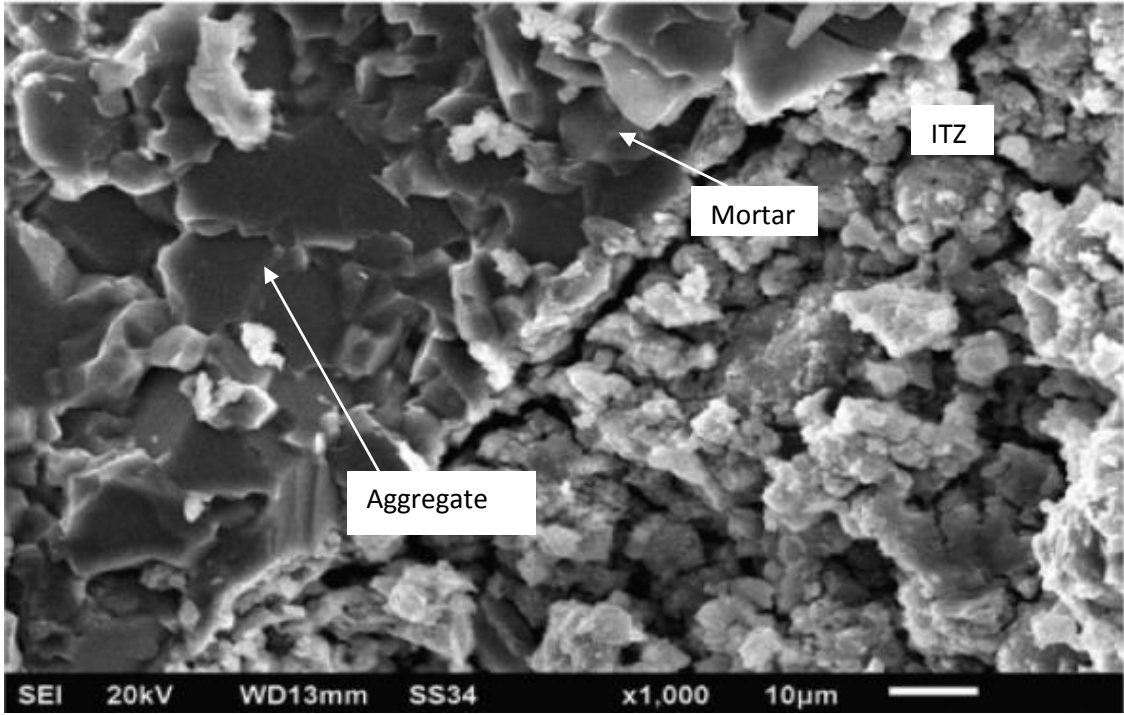


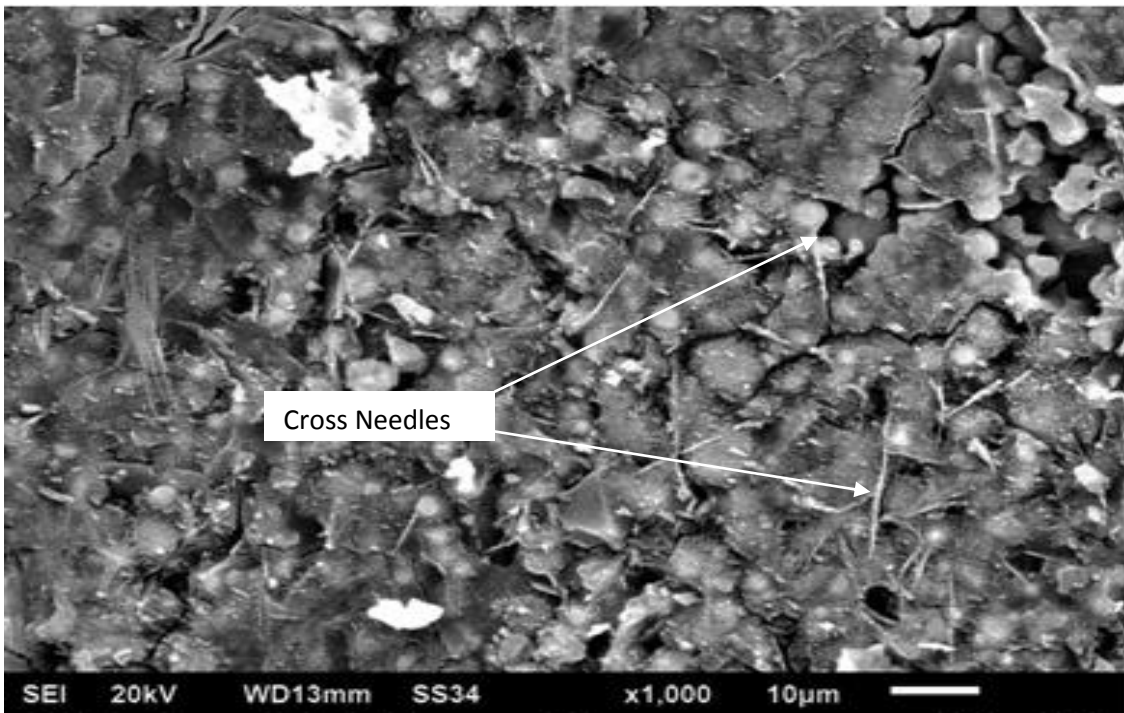
Fig 4.6 SEM Images of M1-12M, M2-12M & M3-12M

Fig 4.6 shows the SEM images of M1-12M, M2-12M, M3-12M respectively. It can be seen from Fig 4.6 that mix M2-12M (containing 70% Flyash, 20% GGBS and 10 % Glass powder) is having buds of needles present in its microstructure thereby leading to a stronger bond between particles as compared to M1-12M containing (70% Flyash, 25% GGBS and 5 % Glass powder) & M3-12M containing (70% Flyash, 15% GGBS and 15 % Glass powder) respectively. In addition to this it can be seen that in the 12M category all the samples are having large concentration of pores present in their microstructure but this weakness is somewhat compensated by formation of needles in M2-12M sample whereas other samples suffer on account of porosity in their microstructure.

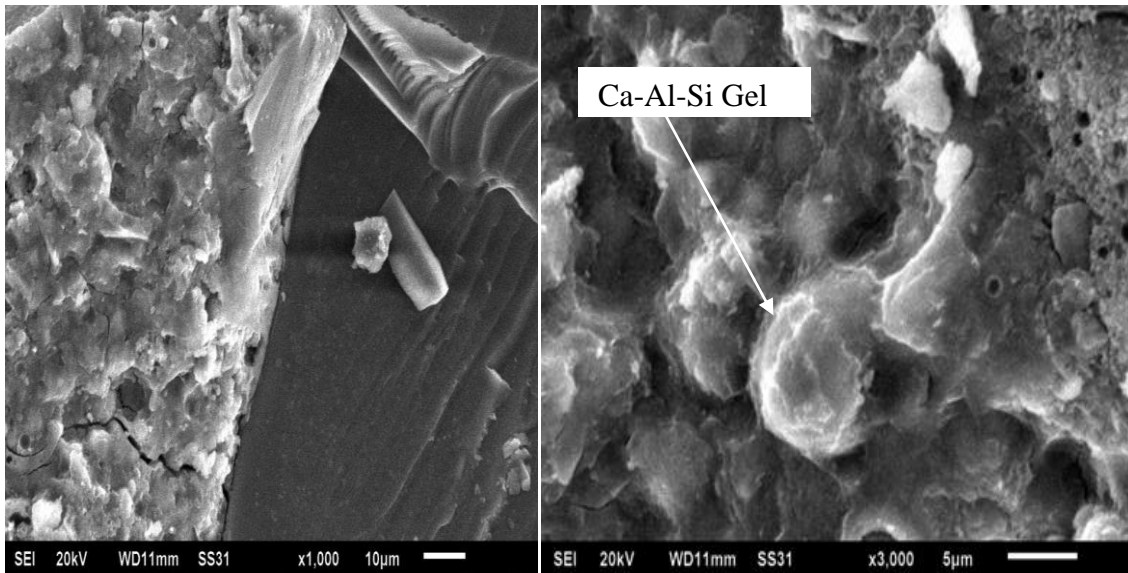
Another additional feature which can be observed in Fig 4.6 is the occurrence of cracks within the microstructure of geopolymer concrete samples. The formation of cracks primarily in M1-12M & M3-12M samples can be attributed as reason for lesser compressive strength as compared to M2-12M respectively. So looking at the results obtained & the pattern of SEM images it appears that M2-12M is the optimum mixture composition for this category.



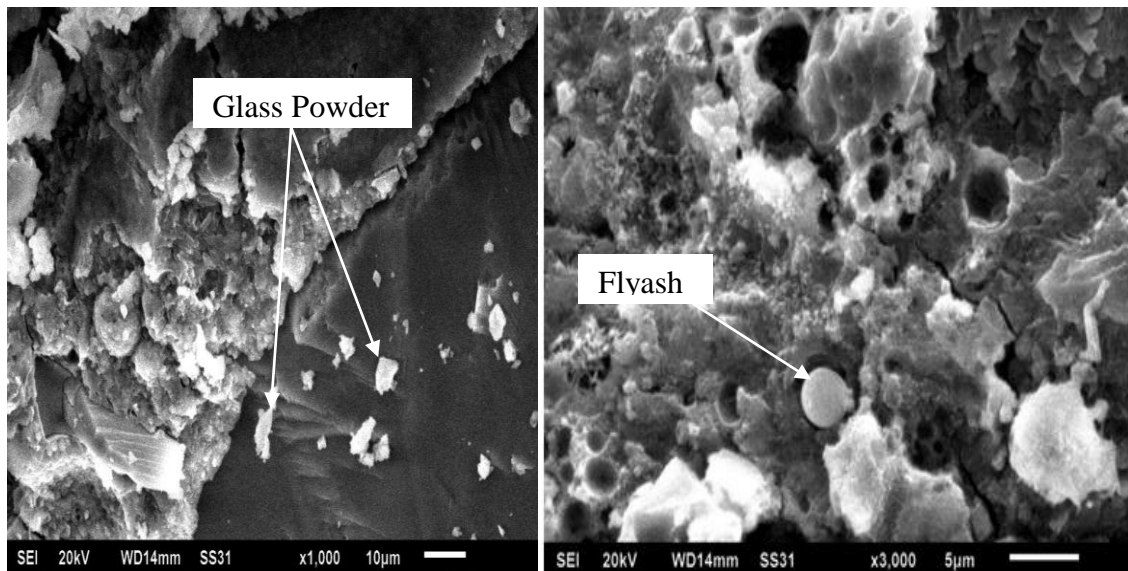
M-CO



M1-4M



M1-8M

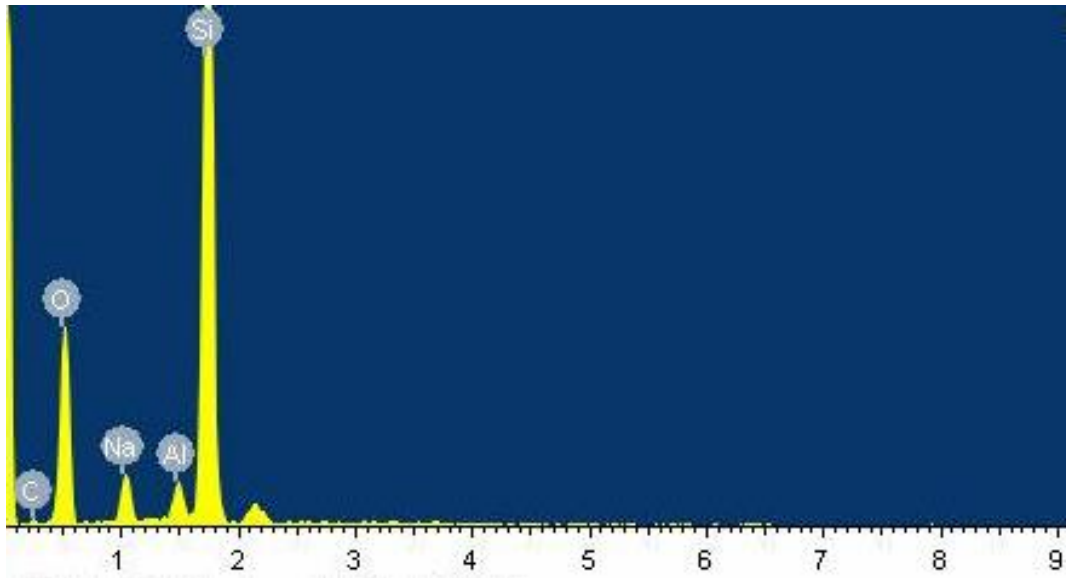


M1-12M

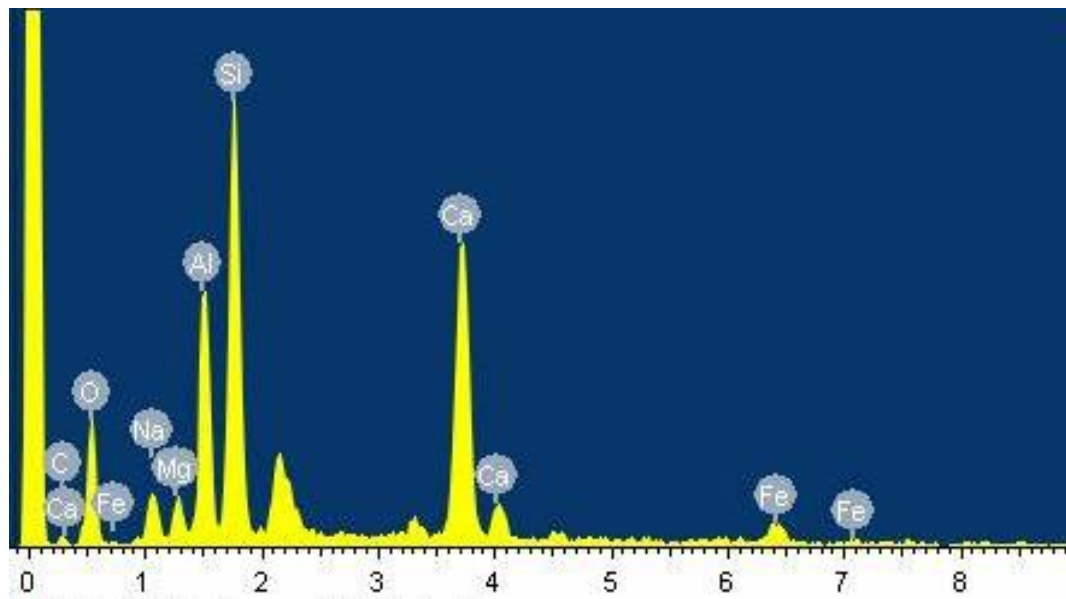
Fig 4.7 SEM Images of Control Sample, M1-4M, M1-8M, M1-12M

Fig 4.7 shows the SEM images of Control Sample, M1-4M, M1-8M, M1-12M respectively. On having a closer look at the figures it is found that 4M sample is having dense microstructure containing needles as compared to 8M & 12M samples & this possibly explains the occurrence of higher strength in 4M samples as compared to 8M & 12M samples. Another reason for this decrease in compressive strength with increase in concentration of activating solution is on

account of high shrinkage effects observed in high molarity solutions. On the basis of Fig 4.7 it can also be established that the 4M concentration works out to be optimum concentration. Furthermore, it can be seen from Fig 4.7 that control mix containing Flyash & activated using 12M NaOH solution is having a lot of dispersed cracks in its microstructure as compared to all the other samples & this provides the possible explanation for the lowest strength of control mix. The lowest strength attained for control sample can also be correlated to EDS results shown in Figure 4.8.



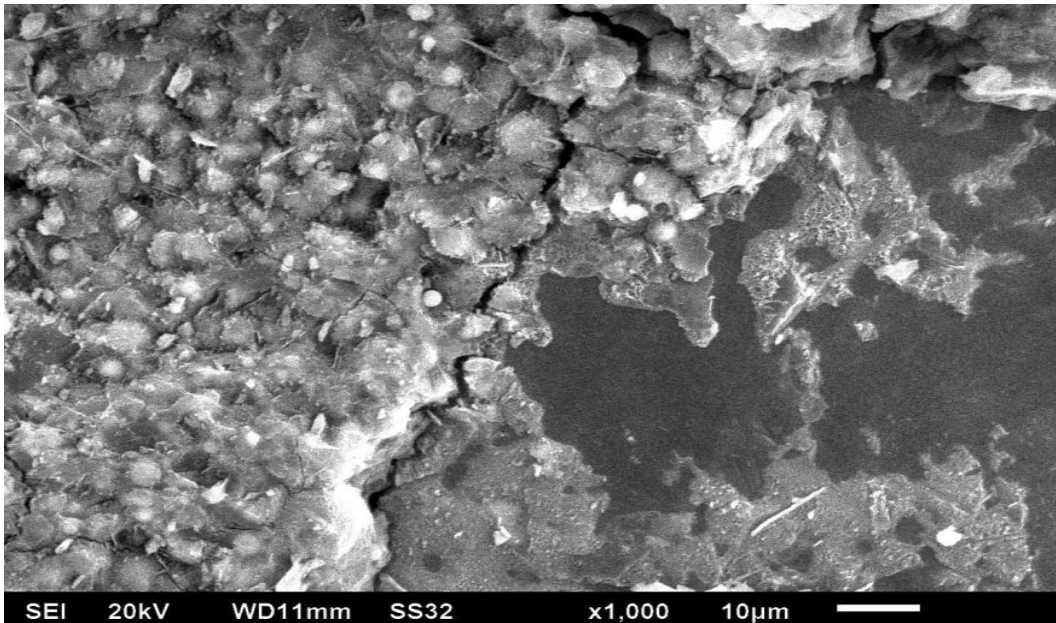
M-CO



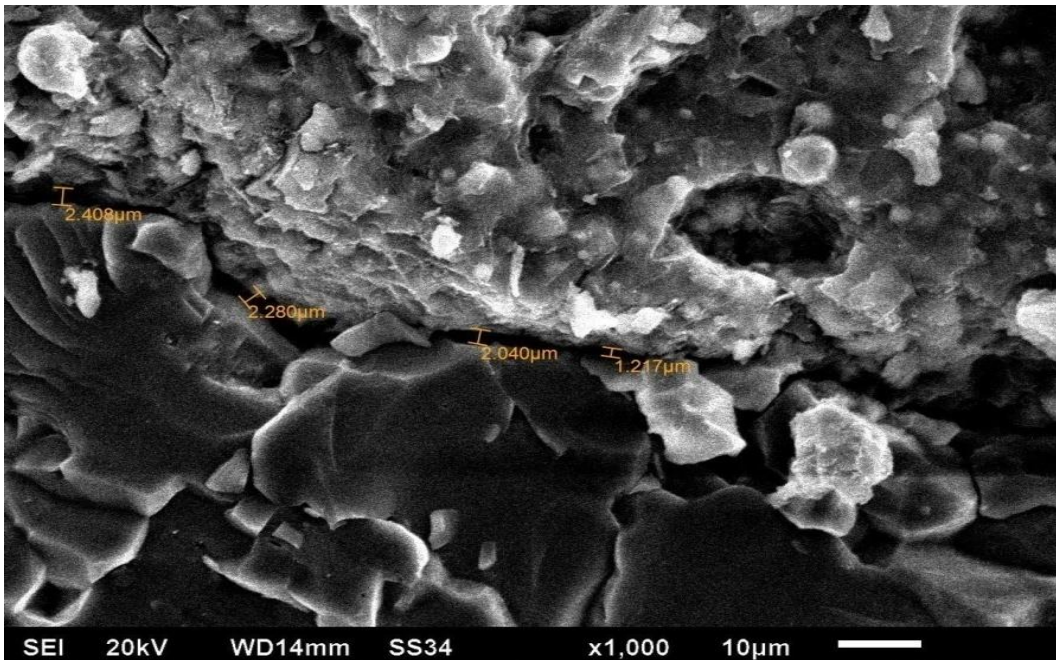
M1-4M

Fig 4.8. EDS Images of M-CO & M1-4M

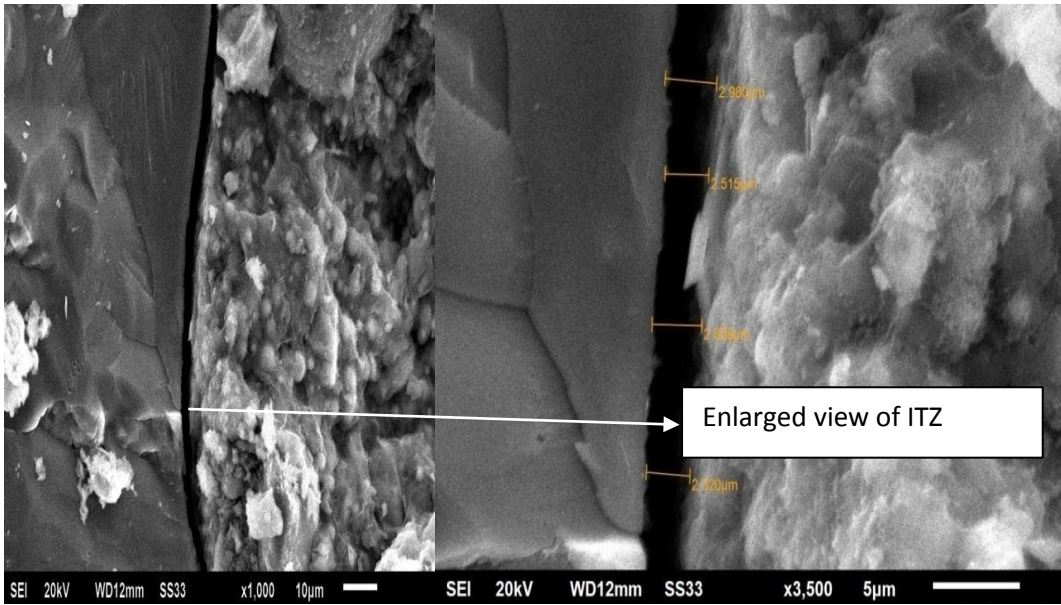
As shown in the figure 4.8 control sample is having only silica & alumina as binder whereas blended mix is having silica, alumina & calcium respectively. So it can be concluded that blended mix is having additional binder material to be activated by sodium hydroxide solution thereby leading to enhanced strength for blended mix.



M1-4M



M2-4M



M3-4M

Fig 4.9 SEM Images of M1-4M,M2-4M & M3-4M

On observing all the mix compositions considered in Fig 4.9 it can be seen that M1-4M has the highest compressive strength at 28 days respectively. The reason for this is formation of whole lot of interlinking cross needles shown in Fig 4.9.

Furthermore it can also be seen in Fig 4.9 that the width of interfacial transition zone is increasing from M1-4M to M3-4M thereby indicating a weak bond between mortar paste & aggregate. Thus it explains the reason for decrease in strength of the samples from M1-4M to M3-4M.

So it can be concluded that both mix composition & alkaline activator concentration have significant influence on compressive strength. Further, it can be said that by using varying combinations of the binder ingredients, it is possible to produce a mix with 28 days compressive strength of upto 25 MPa when subjected to ambient curing.

4.3 FLEXURAL STRENGTH

Flexural Strength also known as modulus of rupture or bend strength is a property defined as the stress in a material just before it yields in a flexure test. The flexural strength represents the highest stress experienced within the material at its moment of failure. The results of the flexural strength of the geopolymer concrete samples are shown in the Table 4.2

Table 4.2 Flexural Strength Results of Geopolymer Concrete Samples.

	Ingredients							Strength	
	Flyash	GGBS	Glass Powder	CA (20mm)	CA (10 mm)	FA	NaOH	7 days	28 days
Units	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(MPa)	(MPa)
Designation									
Control	450	-	-	720	480	575	70.00	Broke	Broke
M1-4M	315	112.5	22.5	720	480	575	23.33	2.72	3.31
M2-4M	315	90	45	720	480	575	23.33	2.41	2.95
M3-4M	315	67.5	67.5	720	480	575	23.33	2.26	2.82
M1-8M	315	112.5	22.5	720	480	575	46.66	2.18	2.42
M2-8M	315	90	45	720	480	575	46.66	1.97	2.13
M3-8M	315	67.5	67.5	720	480	575	46.66	1.79	1.91
M1-12M	315	112.5	22.5	720	480	575	70.00	1.87	1.83
M2-12M	315	90	45	720	480	575	70.00	2.16	2.34
M3-12M	315	67.5	67.5	720	480	575	70.00	1.98	1.89

For the control mix containing only flyash as binder & activated using 12M NaOH solution the flexural strength at 7 & 28 days could not be found as the specimen broke at the time of demoulding. The reason for breaking of the specimen is mainly on account of low reactivity of flyash at ambient temperature & hence lesser gain of strength upto the age of demoulding.

In the 4M category, the mix M1-4M (containing 70% Flyash, 25% GGBS and 5 % Glass powder) & activated using 4M NaOH solution was found to have flexural strength of 2.72 MPa after 7 days and 3.31 MPa after 28 days respectively. In the mix M2-4M as the percentage of GGBS decreased by 5% & that of glass powder increased by 5% the flexural strength decreased by 11.40% at 7 days and 10.88% at 28 days respectively. In the mix M3-4M as the percentage of GGBS further decreased by 5% & that of glass powder increased by 5% the flexural strength decreased by 6.22% at 7 days and 4.41% at 28 days respectively.

In the 8M category, the mix M1-8M (containing 70% Flyash, 25% GGBS and 5 % Glass powder) & activated using 8M NaOH solution was found to have flexural strength of 2.18 MPa after 7 days and 2.42 MPa after 28 days respectively. In the mix M2-8M as the percentage of GGBS decreased by 5% & that of glass powder increased by 5% the flexural strength decreased by 9.63% at 7 days and 11.98% at 28 days respectively. In the mix M3-8M as the percentage of GGBS further decreased by 5% & that of glass powder increased by 5% the flexural strength decreased by 9.14% at 7 days and 10.33% at 28 days respectively.

In the 12 M category the mix M1-12M (containing 70% Flyash, 25% GGBS and 5 % Glass powder) & activated using 12 M NaOH solution was found to have flexural strength of 1.87 MPa after 7 days and 1.83 MPa after 28 days respectively. In the mix M2-12M as the percentage of GGBS decreased by 5% & that of glass powder increased by 5% the flexural strength increased by 15.51% at 7 days and 27.87% at 28 days respectively. In the mix M3-12M as the percentage of GGBS further decreased by 5% & that of glass powder increased by 5% the flexural strength decreased by 8.33% at 7 days and 19.23% at 28 days respectively.

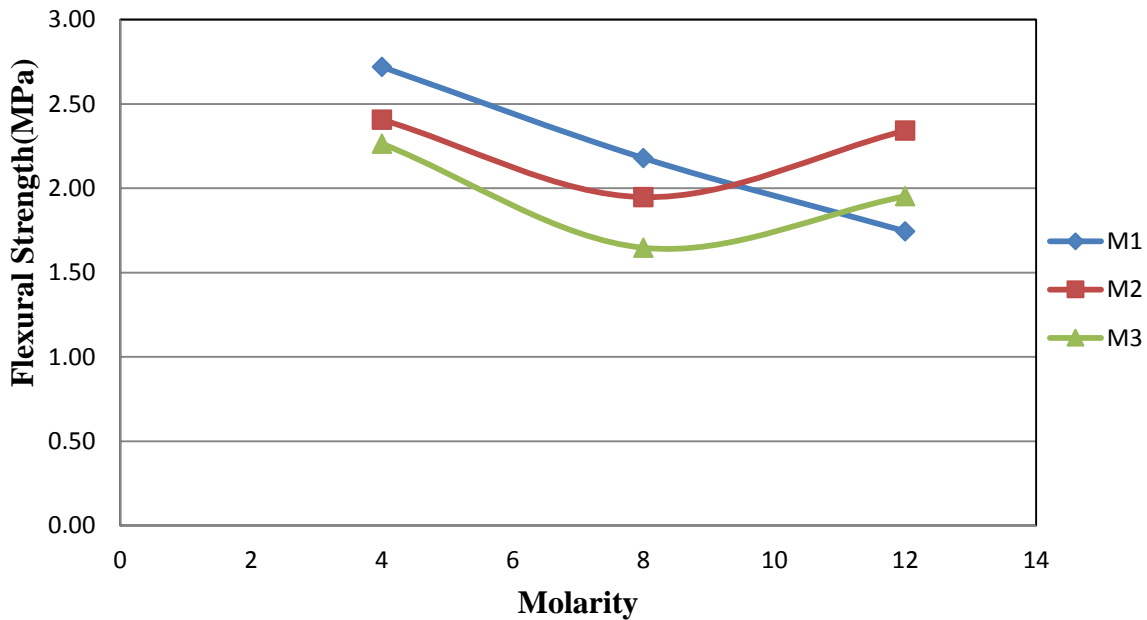


Fig 4.10 Effect of Concentration of NaOH on 7 day Flexural Strength

Fig.4.10 shows the effect of concentration of NaOH on the 7 day flexural strength of different mixes. It can be seen from Fig.4.10, that the maximum flexural strength is achieved for 4M category samples as compared to 8M & 12 M category samples. It may be noted that this pattern of flexural strength observed is similar to the pattern observed in compressive strength & the reason for it has already been discussed in the compressive strength section.

Furthermore, it is to be observed from this figure that no control mix result has been shown on this figure on account of breaking of control mix specimen while demoulding. The reason for breaking of this specimen at the time of demoulding is due to inadequate gain of strength upto the age of demoulding on account of low reactivity of flyash at ambient conditions. Another factor that aided this breaking of the sample was the higher self weight of the sample used for checking flexural strength as compared to cubes used for checking compressive strength.

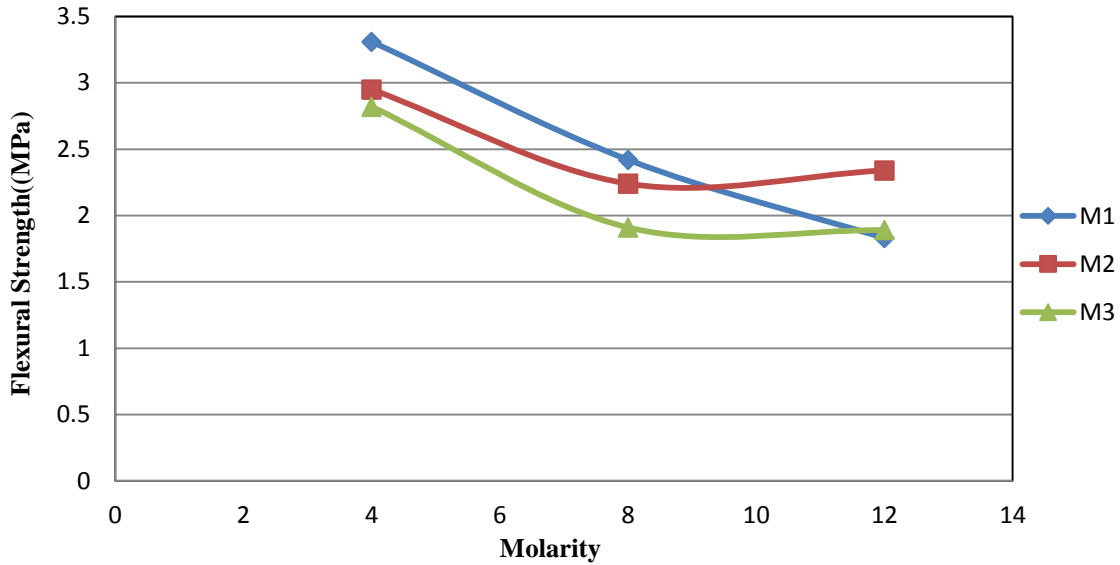


Fig 4.11 Effect of Concentration of NaOH on 28 day Flexural Strength

Fig 4.11 shows the effect of concentration of NaOH on the 28 day flexural strength of different mixes. On seeing Fig.4.11, it may be noted that in the 12M category there is one abrupt variation that is the strength of M2-12M is highest in this category & doesn't follow the general trend observed for the other categories in this graph. The reason for this variation has already been discussed in the compressive strength section.

Furthermore, it can be seen from the fig 4.11 that as the percentage of GGBS decreases from M1 to M3 so is the decrease in flexural strength except 12M category. The possible reason for this is the same as observed for compressive strength.

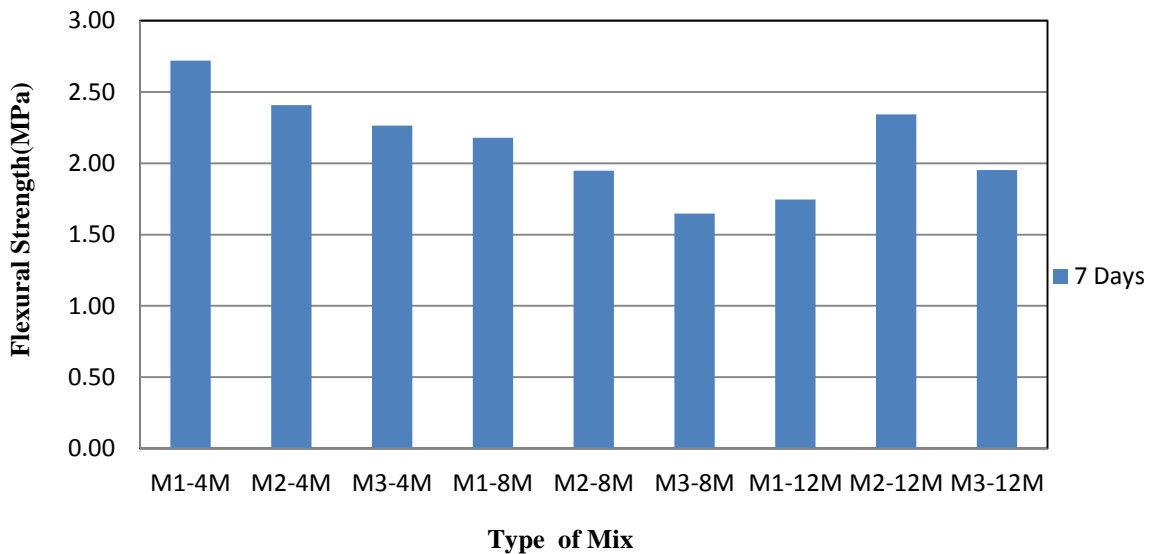


Fig 4.12 Flexural Strength variation for Different Mixes of Geopolymer Concrete at 7 days

Fig. 4.12 shows that the strength of the geopolymer concrete mixes for 7 days. As shown in the figure, in the 4M category geopolymer concrete mix M1-4M achieves 20.35% higher 7-day flexural strength than M3-4M. For the 8M the corresponding increase in 7-day flexural strength between M1 & M3 mixes is 21.78% & for 12M category the corresponding decrease in 7-day flexural strength between M1 & M3 mixes is 5.44% respectively.

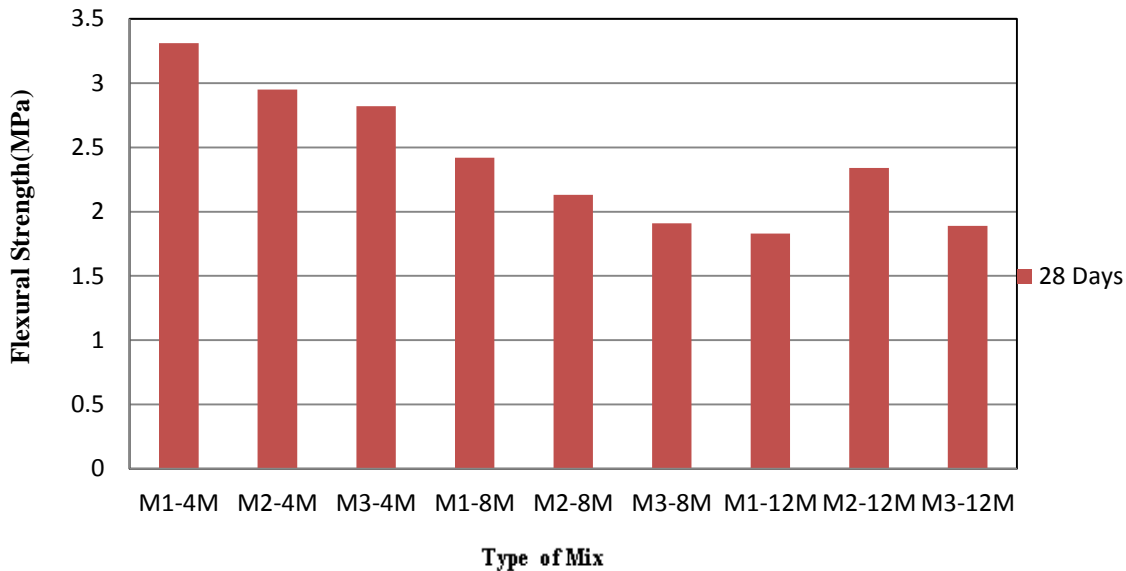
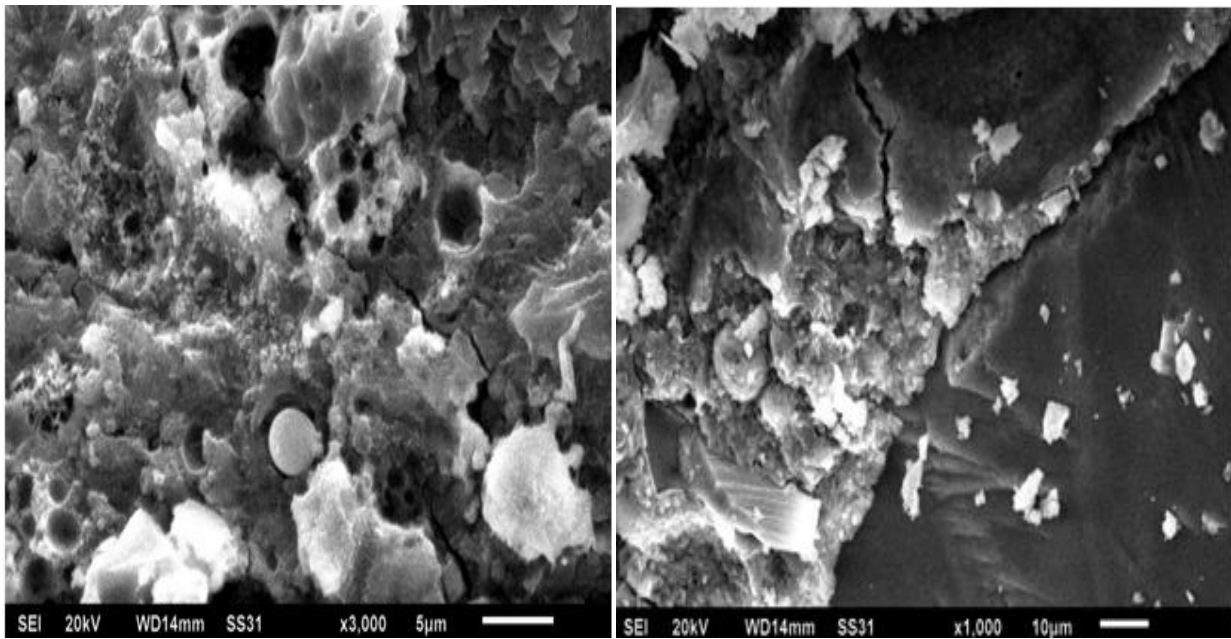


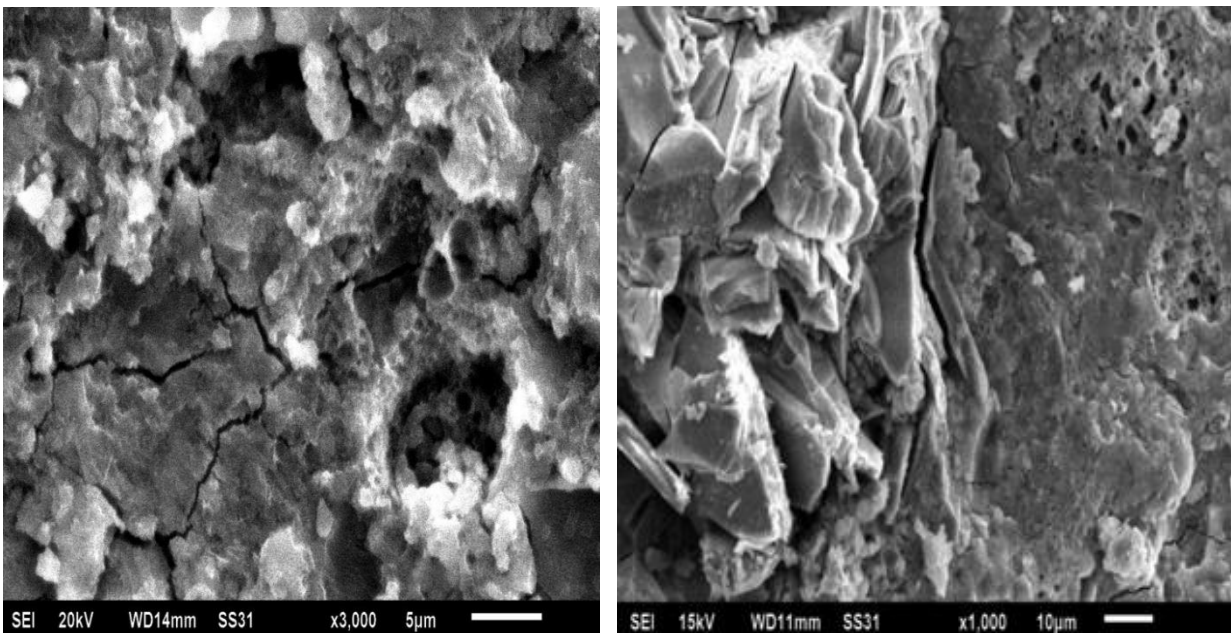
Fig 4.13 Flexural Strength Variation for Different Mixes of Geopolymer Concrete at 28 days

Fig. 4.13 shows that the strength of the geopolymer concrete mixes for 28 days. As shown in the figure, in the 4M category geopolymer concrete mix M1-4M achieves 17.37% higher 28-day flexural strength than M3-4M. For the 8M category the corresponding increase in 28-day flexural strength between M1 & M3 mixes is 26.70% & for 12M category the corresponding decrease in 28-day flexural strength between M1 & M3 mixes is 3.18% respectively.

On a comparative analysis of Fig 4.12 & Fig 4.13 it can be seen that in the 12M category M1-12M & M3-12M samples have 28 day flexural strength lesser than 7 day flexural strength. The reason for this exception is due to high shrinkage in mixes containing higher amount of alkaline solids. Another contributing factor to this exception is formation of micro cracks within the body of specimen. These micro cracks have been found to have more influence on flexural strength as compared to compressive strength thereby reducing the flexural strength of the specimen with age.



M1-12M



M3-12M

Fig 4.14 SEM Images of M1-12M & M3-12M

Fig 4.14 shows the SEM images of M1-12M, M3-12M respectively. On having a closer look at the figures it is found that these samples develop a lot of cracks within the microstructure of the

sample & this possibly explains the reason for decrease in flexural strength with age. Another reason for this decrease in flexural strength can be seen attributed to the flaky & porous structure of these samples. On account of high percentage of pores & flakiness shrinkage takes place in these specimens with time thereby leading to decrease in flexural strength.

So on summarizing the discussion on flexural strength results it can be said that an inconsistent trend in the flexural strength values obtained at 7 & 28 days has been observed. Further, it can be said that comparative study of gain of strength w.r.t to control mix has not been possible due to non availability of the control mix results.

4.4 SPLIT TENSILE STRENGTH

Split tensile strength of the geopolymer concrete specimen can be considered to be an indirect assessment of the tensile strength of the material. It is expressed as the minimum tensile stress needed to split the material apart and is measured in terms of stress. The results for the split tensile strength of geopolymer concrete samples are shown in the Table 4.3.

Table 4.3 Split Tensile Strength Results of Geopolymer Concrete Samples

	Ingredients							28 days
	Flyash	GGBS	Glass	CA	CA	FA	NaOH	
Units	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(MPa)
Designation								
Control	450	-	-	720	480	575	70.00	1.70
M1-4M	315	112.5	22.5	720	480	575	23.33	3.89
M2-4M	315	90	45	720	480	575	23.33	3.34
M3-4M	315	67.5	67.5	720	480	575	23.33	2.98
M1-8M	315	112.5	22.5	720	480	575	46.66	3.06
M2-8M	315	90	45	720	480	575	46.66	2.60
M3-8M	315	67.5	67.5	720	480	575	46.66	2.34
M1-12M	315	112.5	22.5	720	480	575	70.00	2.43
M2-12M	315	90	45	720	480	575	70.00	3.03
M3-12M	315	67.5	67.5	720	480	575	70.00	2.14

For the control mix containing only flyash as binder & activated using 12M NaOH solution the split tensile strength at 28 days has been found to be 1.70 MPa respectively. The control mix described over here has been subjected to 48 hours oven curing at 60°C & followed subsequently by ambient curing upto the age of testing.

In the 4M category, on replacement of flyash with 25% GGBS and 5 % Glass powder the mix M1-4M has been found to have split tensile strength of 3.89 MPa after 28 days which implies a gain of strength of 128.82% over control mix respectively. On subsequent replacement of flyash with 20% GGBS and 10 % Glass powder in mix M2-4M a gain of strength of 96.47% at 28 days has been observed respectively. On further change in composition in M3-4M with 15% GGBS and 15% Glass powder as replacement of flyash a gain of strength of 75.29% at 28 days has been observed respectively. This trend of compressive strength obtained clearly indicates the maximum gain of strength for highest percentage of flyash replaced with GGBS.

Moving on in the 8M category, the mix M1-8M (containing 70% Flyash, 25% GGBS and 5 % Glass powder) & activated using 8M NaOH solution has been found to have a split tensile strength of 3.06 MPa after 28 days respectively. This implies a gain of strength of 80% at 28 days over control mix respectively. In the mix M2-8M as the percentage of GGBS decreased by 5% & that of glass powder increased by 5% in the mix composition of M1-8M the split tensile strength showed a gain of strength of 52.94% at 28 days over control mix respectively. In the mix M3-8M as the percentage of GGBS replacement further decreased by 5% & that of glass powder increased by 5% the split tensile strength showed a gain of strength of 37.64% at 28 days over control mix respectively. This trend clearly indicates the decrease in the percentage gain of compressive strength with increase in molar concentration of the activating solution.

On similar lines in the 12 M category the mix M1-12M having similar composition to M1-4M & M1-8M & activated using 12 M NaOH solution has been found to have split tensile strength of 2.43 MPa after 28 days respectively. This implies a gain of strength of 42.94% at 28 days over control mix respectively. In the mix M2-12M as the percentage of flyash replacement with GGBS decreased by 5% & that of glass powder increased by 5% the split tensile strength showed a gain of strength of 78.23% at 28 days over control mix respectively. In the mix M3-12M as the percentage of GGBS further decreased by 5% & that of glass powder increased by 5% the split tensile strength showed a gain of strength of 25.88 % at 28 days over control mix respectively. This trend clearly indicates the sudden increase in the percentage gain of compressive strength in M2-12M mix thereby giving an indication of some other factor along with GGBS which is controlling this phenomenon of gain of strength.

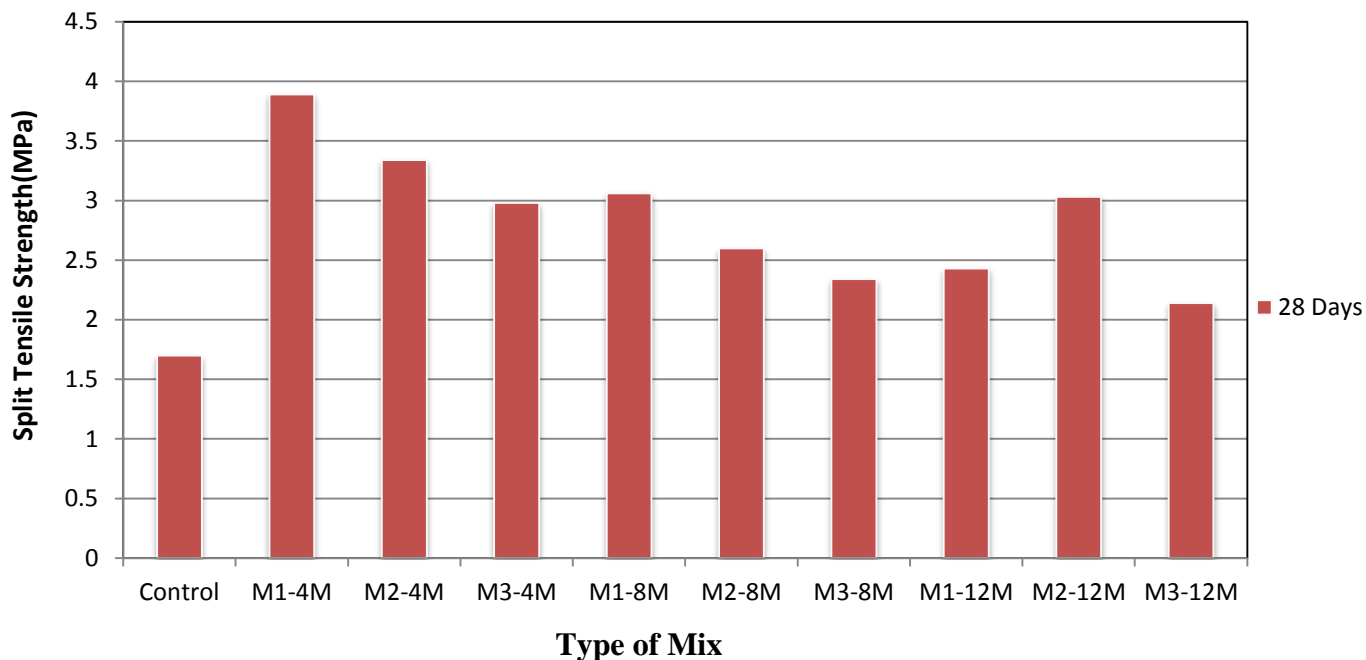


Fig 4.15 Split Tensile Strength Variation for Different Mixes at 28 days

Fig 4.15 shows the variation of split tensile strength at 28 days for different mixes. On seeing Fig.4.15, it may be noted that in the 12M category there is one abrupt variation that is the strength of M2-12M is highest in this category & doesn't follow the general trend observed for the other categories in this graph. The reason for this is formation of bunch of needles in the microstructure of M2-12M.

On examination, it can be seen from the Fig.4.15 that as the percentage of GGBS decreases from M1 to M3 so is the decrease in split tensile strength except 12M category. The reason for this pattern is availability of extra amount of calcium & alumina contributed by the GGBS in the mix thereby leading to enhanced gel formation.

From Fig.4.15 it can be further observed that the maximum split tensile strength is achieved for 4M category samples as compared to 8M & 12 M category samples. The reason for this is additional shrinkage effects in the higher molarity samples which lead to formation of cracks & pores and thereby lesser strength.

Furthermore, it is to be observed from this figure that control mix follows the same pattern as observed for compressive & flexural strength & turns out to be the weakest specimen amongst all mixes. The reason for this is inadequate binder material present in the form of flyash.

Table 4.4
Comparison of Measured Split Tensile Strength with Predicted Strength by Different Researchers

Mix	Measured Strength (MPa)	As per Lee & Lee (2013) (MPa)	As per Sofi et al. (2007) (MPa)	Measured/ Lee & Lee (2013)	Measured/ Sofi et al., (2007)
Control	1.70	1.75	1.87	0.97	0.91
M1-4M	3.89	2.32	2.48	1.68	1.57
M2-4M	3.34	2.20	2.35	1.52	1.42
M3-4M	2.98	2.11	2.25	1.41	1.32
M1-8M	3.06	2.17	2.32	1.41	1.32
M2-8M	2.60	2.03	2.17	1.28	1.20
M3-8M	2.34	1.92	2.04	1.22	1.15
M1-12M	2.43	2.05	2.18	1.19	1.11
M2-12M	3.03	2.16	2.30	1.40	1.32
M3-12M	2.14	1.86	1.98	1.15	1.08

Table 4.4 shows the comparison of measured split tensile strength with the split tensile strength of alkali activated concrete as per the equations proposed by Lee & Lee(2013) and Sofi et al.(2007).It can be seen from the table 4.4 that the measured split tensile strength for alkali-activated concrete exceeds the predicted split tensile strength for geopolymer concrete.

In addition to this it can be seen that the measured values are greater than the predicted values obtained from Lee & Lee(2013) by approx 33% & Sofi et al.(2007) by approx 25% respectively. Furthermore it can be observed from table 4.4 that the variance of heat cured control mix values from the predicted values is lesser as compared to values obtained for ambient cured samples.

Going through the research papers it was found that Lee and Lee(2013) and Sofi et al.,(2007) used high solution-to-binder ratios for making geopolymer concrete. In his work Lee & Lee(2013) used $s/b = 0.56$ whereas Sofi et al.,(2007) didn't specify the value of this ratio. The comparatively low solution to binder ratio i.e ($s/b=0.15$) used in our dissertation work could be one of the reasons for enhanced measured split tensile strength.

Table 4.5

Comparison of Measured Split Tensile Strength with Predicted Strength by OPC Concrete Codal Provisions

Mix	Measured Strength (MPa)	As per AS 3600 (MPa)	As per ACI 318 (MPa)	Measured/ AS 3600	Measured/ ACI 318
Control	1.70	1.40	2.18	1.21	0.78
M1-4M	3.89	1.86	2.89	2.09	1.35
M2-4M	3.34	1.76	2.74	1.90	1.22
M3-4M	2.98	1.69	2.62	1.76	1.14
M1-8M	3.06	1.74	2.70	1.76	1.13
M2-8M	2.60	1.62	2.53	1.60	1.03
M3-8M	2.34	1.53	2.38	1.53	0.98
M1-12M	2.43	1.64	2.55	1.48	0.95
M2-12M	3.03	1.73	2.69	1.75	1.13
M3-12M	2.14	1.49	2.31	1.44	0.93

Table 4.5 presents the comparison of measured split tensile strength with the split tensile strength of alkali activated concrete as per AS 3600 & ACI-318. The equations given by AS 3600 & ACI-318 are basically for use with OPC Concrete but in this case it has been used to predict split tensile strength for alkali activated concrete.

It can be seen from the table 4.5 that the measured split tensile strength exceeds the predictions for split tensile strength as per AS 3600 & ACI 318. In addition to this it can be seen that the measured values are comparatively closer to ACI 318 values as compared to AS 3600 values. Furthermore it can be seen from table 4.5 that the variance of control mix values from the predicted values is lesser as compared to variance in case of ambient cured samples.

On compilation of the results obtained for split tensile strength as per various proposed models it can be said that more no. of specimens have to be tested so as to develop a relationship for predicting split tensile strength in cognizance with the testing conditions maintained. In general terms the pattern of split tensile strength development is similar to the compressive strength development in geopolymer concrete samples.

5.1 GENERAL

The present chapter deals with the conclusions drawn from the results obtained after testing the geopolymer concrete specimens for compressive, flexural & split tensile strength respectively. The conclusions presented in this chapter have been given property wise & have been finalized on the basis of experimental results along with SEM & EDS tests. To explore further on the dissertation work undertaken some gaps have been identified and they have been included under the heading scope for further work. Based upon the results discussed in the previous chapter, following are the major conclusions for the properties studied.

5.2 COMPRESSIVE STRENGTH

- From the view point of strength M-1 mix containing 70% Flyash, 25% GGBS & 5% GP works out to be the optimum mix for preparation of geopolymer concrete samples.
- The observance of abrupt variation regarding increase of strength in M2-12M mix indicates that only addition of GGBS is not the sole criteria for increase of strength.
- The optimum molarity of NaOH solution for achieving the highest strength of GPC mixes at 7 as well as 28 days curing works out to be 4M as per the molar concentrations considered.
- An average increase of about 30% in the compressive strength has been observed for a period of 7 to 28 days thereby indicating gain of strength similar to OPC Concrete.

5.3 FLEXURAL STRENGTH

- The breaking of control mix specimen activated using 12 M solution suggests that 12M is probably not the desired concentration for activation of flyash based geopolymer concrete. As the alkaline activation solution has been weakened due to absence of sodium silicate so may be a lower concentration of NaOH solution can be used for activation purpose.
- The results of the flexural strength obtained indicate an inconsistent trend thereby indicating the need for further investigation into the reason for such inconsistent trends.
- The failure of all the beam specimens indicated a brittle mode of failure thereby generating the need for incorporation of some form of fibres or reinforcement to bring about a change in this failure mode.
- To reduce the self weight of beam specimen may be specimens of 100x100x500mm can be used and its behavior regarding change of flexural strength from 7 to 28 days can be studied.

5.4 SPLIT TENSILE STRENGTH

- Tensile strength of ambient cured geopolymer concrete increased with the increase of compressive strength. The effect of the mixture variables on the development of tensile strength was similar to that on the development of compressive strength.
- The values of split tensile strength for alkali-activated concrete are found to be in variance with the values obtained from proposed equations of Lee & Lee(2013) & Sofi et al.(2007) thereby indicating the need for carrying out further tests so as to derive an equation for the set of conditions considered.
- An average increase of about 70% in the split tensile strength is observed for all the blended mixes as compared to control mix thereby indicating formation of Ca-Si-Al gel in blended mixes.
- The values of split tensile strength for alkali-activated concrete have been found to be greater than the calculated values as per ACI 318 & AS 3600 thereby indicating the limitation of these codal equations in correctly predicting the split tensile strength values of alkali activated concrete.

5.5 SCOPE FOR FURTHER WORK

By using various combinations of supplementary cementitious materials for preparation of GPC a compressive strength of upto 25MPa has been achieved for curing at room temperature. Now the further extension of this scope of work can be as follows:-

- The work can be extended to see if there is any significant difference in the strength of samples kept covered & uncovered during the process of curing.
- The work can be extended to find out the optimum molarity for the combination of supplementary cementitious materials used in this study.
- The work can be extended to find substitutes of alkaline activator used in this study which will not only make it economical but also ready to use without skilled supervision
- The work can be extended to study the rate of gain of strength in samples cast with activator solution for the same mix proportion.

REFERENCES

- 1.) Aleem, M.I. Abdul., Arumairaj, P.D., 2012. Optimum mix for the geopolymer concrete. *Indian Journal of Science and Technology* 5(3), 2299-2301.
- 2.) Deb, Partha Sarathi., Nath, Pradip., Sarker, Prabir Kumar., 2014. The effects of ground granulated blast-furnace slag blending with flyash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials and Design* 62, 32-39.
- 3.) Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., van Deventer, J.S.J., 2007. Geopolymer technology: The current state of the art. *J Mater Sci* 42(9), 2917–2933.
- 4.) Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. *Int J LCA* 12(5), 282–288.
- 5.) Gao, X., Yu, Q.L., Brouwers, H.J.H., 2015. Reaction Kinetics, gel character and strength of ambient temperature cured alkali activated slag-flyash blends. *Construction and Building Materials* 80, 105-115.
- 6.) IS:383-1970: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, Bureau of Indian Standard, New Delhi - 1970.
- 7.) IS:516-1959: (Reaffirmed 2004): Methods of Test for Strength of Concrete, Bureau of Indian Standard, New Delhi – 2004
- 8.) IS:1999-1959: (Reaffirmed 1999): Methods of Sampling and Analysis of Concrete, Bureau of Indian Standard, New Delhi - 1999.
- 9.) IS:2386(Part I, III), 1963: Methods of Test for Aggregates for Concrete, Bureau of Indian Standard, New Delhi - 1963.
- 10.) IS:3812-1981: Specification for flyash for use as pozzolana and admixture, Bureau of Indian Standard, New Delhi - 1981.
- 11.) IS:5816 –1999: Methods of Test for Splitting Tensile Strength of Concrete, Bureau of Indian Standard, New Delhi – 1999.
- 12.) IS:12089-1987: Specification for granulated slag for manufacture of portland slag cement, Bureau of Indian Standard, New Delhi - 1987.

- 13.) Kamali, Mahsa., Ghahremaninezhad, Ali.,2015 . Effect of glass powders on the mechanical and durability properties of cementitious materials. *Construction and Building Materials* 98, 407-416.
- 14.)Lee, N.K., Lee, H.K., 2013. Setting and mechanical properties of alkali-activated flyash/slag concrete manufactured at room temperature. *Construction and Building Materials* 47, 1201-1209.
- 15.)Mithanthaya , I.R. ., Rao, N.Bhavanishankar., 2015. Effect of Glass Powder and GGBS on Strength of Flyash Based Geopolymer Concrete. *International Journal of Engineering Trends and Technology* 19(2), 66-71.
- 16.)Naidu, Ganapati., Prasad, A.S.S.N., Adishesu, S., Satayanarayana, P.V.V.,2012. A Study on Strength Properties of Geopolymer concrete with addition of G.G.B.S. *International Journal of Engineering Research and Development* 2(4), 19-28.
- 17.)Nazari, Ali., Maghsoudpour, Ali., Sanjayan, Jay G. .,2015.Flexural strength of plain and fibre-reinforced boroaluminosilicate geopolymer. *Construction and Building Materials* 76, 207-213.
- 18.)Shayan, Ahmad., Xu, Aimin., 2004. Value-added utilisation of waste glass in concrete. *Cement and Concrete Research* 34, 81-89.
- 19.)Thomas, Robert J., Peethamparan, Sulapha., 2015.Alkali-activated concrete: Engineering properties and stress-strain behaviour. *Construction and Building Materials* 93, 49-56.
- 20.)Turner, Louise K., Collins, Frank G., 2013. Carbon dioxide equivalent (CO₂-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials* 43, 125-130.
- 21.)Wongpa, J., Kiattikomol, K., Jaturapitakkul, C., Chindaprasirt,P., 2010. Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete. *Materials and Design* 31, 4748-4754.