A STUDY ON STRENGTH OF STEEL SLAG INCOPORATED LOWCALCIUM FLYASH BASED GEOPOLYMER CONCRETE”

Nandi Reddy Madhuri Reddy[1],Smt. G. Bhagyamma[2]

[1]M.Tech., Scholar, Dept. of Civil Engineering, AnnamAcharya Institute Of Technology And Sciences Kadapa,
[1]Professor, Dept. of Civil Engineering , AnnamAcharya Institute Of Technology And Sciences Kadapa.

Abstract: For the construction of any structure, Concrete is the mostly used material. Concrete usage around the world is second after water(V. M. Malhotra, 2000). The main ingredientto produce concrete is Portland cement. On the other side global warming and environmentalpollution are the biggest menace to the human race on this planet today. The pr oduction of cement means the production of pollution because of the emission of CO2 during its production (D.M. J. Sumajouw, 2007). There are two different sources of CO2 emission during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source and other one isthe chemical process of calcining limestone into lime in the cement kiln also produces CO2. Indiawhich is the second largest cement manufacturer world wise reports almost 150 MT of CO2emissions in 2015(R. M. Andrew, 2017). The cement industry contributes about 5% of totalglobal carbon dioxide emissions. And also, the cement is manufactured by using the raw materials such as lime stone, clay and other minerals. Quarrying of these raw materials also causes environmental degradation. To produce 1 ton of cement, about 1.6 tons of raw materials are re-quired and the time taken to form lime stone is much longer than the rate at which humans use it.But the demand of concrete is increasing day by day for its ease of preparing and fabricating inall sorts of convenient shapes. So to overcome this problem, the concrete to be used should beenvironmental friendly.

KEY WORDS: Geopolymer Concrete, Fly Ash, Ground Granulated Blast Furnace Slag(GGBS), Sodium Hydroxide, Sodium Silicate Solution , Compressive Strength, Tensile Strength ,Water Permeability.

I. INTRODUCTION

For the construction of any structure, Concrete is the mostly used material. Concrete usage around the world is second after water(V. M. Malhotra, 2000). The main ingredient to produce concrete is Portland cement. On the other side global warming and environmental pollution are the biggest menace to the human race on this planet today. The production of cement means the production of pollution because of the emission of CO2 during its production(D. M. J. Sumajouw, 2007). There are two different sources of CO2 emission during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source and other one is the chemical process of calcining limestone into lime in the cement kiln also produces CO2.India which is the second largest cement manufacturer world wise reports almost 150 MT of CO2 emissions in 2015(R. M. Andrew, 2017). The cement industry contributes about 5% of total global carbon dioxide emissions. And also, the cement is manufactured by using the raw materi-als such as lime stone, clay and other minerals. Quarrying of these raw materials also causes en-vironmental degradation. To produce 1 ton of cement, about 1.6 tons of raw materials are re-quired and the time taken to form lime stone is much longer than the rate at which humans use it. But the demand of concrete is increasing day by day for its ease of preparing and fabricating in all sorts of convenient shapes. So to overcome this problem, the concrete to be used should be environmental friendly.

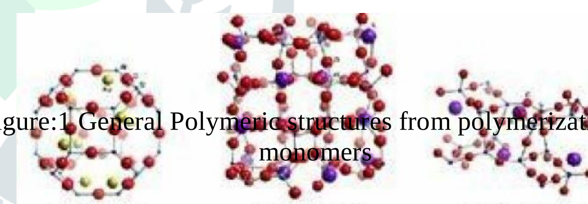


Figure:1 General Polymeric structures from polymerization of monomers

To produce environmental friendly concrete, we have to replace the cement with some other binderswhich should not create any bad effect on environment. The use of industrial by products as binders canreduce the problem. In this respect, the new technology geo-polymer concrete is a promising technique. Interms of reducing the global warming, the geo-polymer technology could reduce the CO2 emission to theatmosphere caused by cement and aggregates industries by about 80%(J. Davidovits, 1994c). And also theproper usage of industrial wastes can reduce the problem of disposing the waste products into theatmosphere.

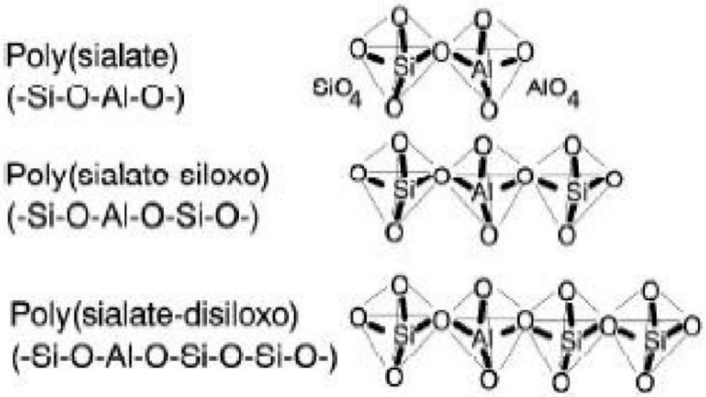


Fig no:2 Chemical Structures of Polysialates

The term geo-polymer was first coined by Davidovits in 1978 to represent a broad range of mate-rialscharacterized by chains or networks of inorganic molecules. Geo-polymers are chains or networks of mineralmolecules linked with co-valent bonds. Geopolymer is produced by a poly-meric reaction of alkaline liquidwith source material of geological origin or by product material such as fly ash, rice husk ash, GGBS etc.Because the chemical reaction that takes place in this case is a polymerization process, Davidovitscoined theterm 'Geopolymer' to represent these binders.Geo-polymers have the chemical composition similar toZeolites but they can be formed an amorphous structure. He also suggested the use of the term 'poly(sialate)' for the chemical designation of Geopolymers based on silico-aluminate.Sialate is an abbreviation for siliconoxo-aluminate.Poly(sialates) are chain and ring polymers with Si4+ and AL3+ in IV-fold coordination with oxygen and range from amorphous to semi-crystalline with the empirical formula: Mn (-(SiO2) z–AlO2)n. wH2O.Where "z" is 1, 2 or 3 or higher up to 32; Mis a monovalent ion such as potassium or sodium, and "n" is a degree of polycondensation (Davidovits, Palomo & van Jaarsveld, 1988, 1988b.). (Davidovits, Palomo & van Jaarsveld, 1994b, 1999)has also distinguished 3 types of polysialates, namely the Poly(sialate) type (-Si-O-Al-O), the Poly (sialate-siloxo) type (-Si-O-Al-O-Si-O) and the Poly(sialate-disiloxo) type (-Si-O-Al-O-SiO). The structures of these polysialates can be schematized as in Figure 2.

II. MATERIALS

GROUUND GRANULATED BLAST FURNACE SLAG (GGBFS):

Ground granulated blast furnace slag known as GGBS or GGBFS or Slag is a by-product from the blast furnaces used to make iron and steel. These are operated at a temperature of about 1,500^{0}C and are fed with a carefully controlled mixture of iron-ore, coke and limestone. The iron is reduced to iron and the remaining materials form a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and it is used for manufacture of GGBFS by rapidly quenched in large volumes of water. The quenching optimizes the cementitious properties and produce granules similar to that of coarse aggregate. This granulated slag is then dried and grounded to a fine powder.

It significantly reduces the embodied $CO_2$of the structure. It can replace the cement from 30% to 50%. Concrete made with GGBFS sets more quickly than concrete made with ordinary Portland cement depending on the amount of GGBFS used in the mix and gains strength over a long period. The physical properties of slag are given below in table

Properties	Results
Colour	Near white
Specific gravity	3.2

FLY ASH

Fly ash is an industrial coal by-product manufactured by burning coal in electrostatic precipitator. It has been widely used in cement manufacture over 100 years as it has cementitious properties which were discovered in early 19th century. It can be used as replacement of cement form 20 to 80 percentages and is supplied as separate component.

The physical properties of fly ash are given in below table

Properties	Results
Colour	Dark Grey
Specific gravity	1.6

COARSE AGGREGATE

Coarse aggregate of size 10mm and 20mm were bought from a local vendor which were used in this study. The properties of coarse aggregate were given in table

Property	**Result**	**IS STANDARDS**
Specific gravity	2.65	IS:2386-Part3,1963
Crushing value	8.7	IS:2386-Part4,1963
Impact value	15.04	IS:2386-Part4,1963
Water absorption	0.43%	IS 2386- Part 3, 1963

FINE AGGREGATE

Fine aggregate used in study According to standards IS 383:1917 it was sieved. The properties of fine aggregate used were given in

Property	**Result**	**IS STANDARDS**
Specific gravity	2.67	IS:2386-Part3,1963
Water absorption	0.98%	IS 2386- Part 3, 1963
Sieve analysis	Zone-II	IS:383-1917

SODIUM HYDROXIDE

Generally Sodium hydroxide is available in market in various forms as flakes, pellets and in powder forms.The sodium hydroxide solution used in this study was prepared by adding required amount of water tosodium hydroxide pellets of laboratory grade 97% pure bought from Loba Chemie.

SODIUM SILICATE SOLUTION

Sodium silicate solution used in this study is bought from local vendor. We used direct sodium silicate solution having density 1.6 and we diluted that solution with density 1.3 by adding appropriate water to the solution. The chemical properties of the solution used in this study were discussed below table

Na_2O/SiO_2	63.5% to 67.5%
Water	2.3 to 2.5
Na_2O	7.5% to 8.5%
SiO_2	17.25% to 21.25%

WATER

Water used in this study was portable water which is free from alkaline salts and organic matter.

OBJECTIVE AND SCOPE OF STUDY

General steel slag and fly ash as complete replacement of cement entails economical, technical and energy saving benefits. To ascertain its technical feasibility to incorporate in concrete production, a study on its strength is needed.

Objective

The objective of the present study is

- To study the usage of steel slag and fly ash as replacement of cement
- To study the boarder usage of alkaline liquid as replacement of water.
- To study the possibility of usage of sodium silicate solution and sodium hydroxide as alkaline liquid.
- To investigate the strength and durability of Geopolymer concrete by conducting Compressive, flexural strength tests and water penetration test.

Scope of the study

This project aims mainly to study the strength properties and durability of steel slag incorporated fly ash based Geopolymer concrete by conducting compressive strength test, flexural strength test and water permeability test for M40 grade by following conventional concrete mix design methods with proper modifications.

III.EXPERIMENTAL STUDY

MIX DESIGN

The mix design in case of geo-polymer concrete is based on conventional method of conventional cement concrete with proper modifications. In case of conventional concrete the material proportion can be found out for the required strength by using (IS:10262:2009 BIS, 2009) and(IS:456:2000 BIS, 2005). But for geo-polymer concrete there is no design method or codal provisions. Hence by trial and error mixes were prepared. The mix design given in the code (IS:10262:2009 BIS, 2009)for conventional M40grade cement concrete was taken as design method for geopolymer concrete with modifications given byLloyd & Rangan, 2010was taken as reference for same grade of Geopolymer concrete by changing the percentage levels of GGBFS. The geopolymer concrete is wet-mixed for four minutes and cured under ambient temperature. In this manner without changing the quantities mentioned above and by taking the ratio of Na2SiO3 to NaOH as 1:2 and alkaline liquid to cementitious material ratio as 0.8 and by changing the mo-larity of NaOH solution from 8M to 16M final mixes were prepared. All the quantities mentioned above are determined for 1m3 concrete. Quantities required for specific specimen size are calculated and used for casting the respective specimens.Mix design is done for M40grade geo-polymer concrete using code IS 10262:2009 and code IS 456with proper modifications

1) Target Mean Strength of geopolymer concrete:

From IS: 10262-2009, the target mean strength for the specified characteristic cube

Strength is

Fck= fck + 1.65 X S

ThenFck = 40+ (5 * 1.65) = 48.25 N/mm2

('s' is standard deviation N/mm2 s =5, from table 1 IS 10262:2009)

2) Selection of Water-Cement Ratio

The free Water Cement ratio required for the target mean strength of 48.25 N/mm2 is

W/C =0.40.

3) Selection of water content

For 20mm aggregate maximum water content =186 L (25mm to 50mm slump)

Designing for 100mm slump

So for every 25mm increase in slump 3% in water should be increased

Water content = 200kg/m3 = alkaline liquid content

4) Determination of cementitious material content

Water/cementitious = 0.4

Cementitious content =500 kg/m3

Fly ash: slag = 70:30

Volume of fly ash = 350 kg/m3

Volume of slag (GGBS) = 150 kg/m3

5) Determination of proportion of coarse aggregate and fine aggregate content

In table 3 from IS 10262:2009 for 20mm coarse aggregate and zone-II fine aggregate,

Coarse aggregate = 0.64% and fine aggregate = 0.36%, of the total aggregate volume respectively

6) Mix calculations

Volume of concrete = 1m3

Volume of material = (volume of material/specific gravity) x 1/1000

Volume of fly ash = (350/1.6) x 1/1000 = 0.219 m3

Volume of slag = (150/3.2) x 1/1000 = 0.046 m3

Volume of water = (200/1) x 1/1000 = 0.2 m3

Remaining volume of the mix = (a-(c+d)-e) = 0.535 m3

Volume of coarse aggregate = 0.64 x 0.535 x 2.65 x 1000 = 907.36 kg/m3

Volume of fine aggregate = 0.36 x 0.535 x 2.67x 1000 = 514.24 kg/m3

Na2SiO3: NaOH = 2:1

Volume of Na2SiO3 = 133.33 kg/m3

Volume of NaOH = 66.67 kg/m3

Quantity of geo polymer concrete for 1m3

Coarse aggregate = 907.36 kg/m3

Fine aggregate = 514.24 kg/m3

Fly ash = 350 kg/m3

Slag = 150 kg/m3

Na2SiO3 solution = 266.66 kg/m3

NaOH solution = 133.34 kg/m3

The final mix proportions are shown in the tables 3.1 and 3.2 below

Name of the mix	Coarse aggregate (kg/m^3)	Fine ag-gregates (kg/m^3)	Fly ash (kg/m^3)	Slag(GGBS) (kg/m^3)	Sodium silicate solution (kg/m^3)	Sodium hydroxide solution (kg/m^3)	Alkaline solution to (Fly ash + GGBS) ratio
GP 1	907.36	514.24	350	150	266.66	133.34 (16M)	0.8
GP 2	907.36	514.24	350	150	266.66	133.34 (14M)	0.8
GP 3	907.36	514.24	350	150	266.66	133.34 (12M)	0.8
GP 4	907.36	514.24	350	150	266.66	133.34 (10M)	0.8
GP 5	907.36	514.24	350	150	266.66	133.34 (8M)	0.8

Table 3.1 Mixing proportions of the Geo-polymer concrete (GP) with 30% Slag addition

Table 3.2 Mixing proportions of Geopolymer concrete (GP) with 20% Slag addition

Name of the mix	Coarse aggregate (kg/m^3)	Fine ag-gregates (kg/m^3)	Fly ash (kg/m^3)	Slag(GGBS) (kg/m^3)	Sodium silicate solution (kg/m^3)	Sodium hydroxide solution (kg/m^3)	Alkaline solution to (Fly ash + GGBS) ratio
GP 6	907.36	514.24	400	100	266.66	133.34 (16M)	0.8
GP 7	907.36	514.24	400	100	266.66	133.34 (14M)	0.8
GP 8	907.36	514.24	400	100	266.66	133.34 (12M)	0.8
GP 9	907.36	514.24	400	100	266.66	133.34 (10M)	0.8
GP 10	907.36	514.24	400	100	266.66	133.34 (8M)	0.8

PREPARATION OF ALKALINE LIQUIDS

Note: Molarity = moles of solute / litre of solution

In this project the compressive strength and flexural strength of geo polymer concrete was examined for the mixes of varying molarities 8M, 10M, 12M, 14M and 16M. The molecular weight of sodium hydroxide solution is 40. So 1M solution contains 40 grams of NaOH. To prepare 16M sodium hydroxide solution 640 grams of sodium hydroxide pellets were weighed and were dissolved in distilled water to form 1 litre of solution. So weights to be added to get required molarity for 1 litre of solution are given in below table

Required molarity	Weight of sodium hydroxide pellets (grams)
16M	640
14M	560
12M	480
10M	400
8M	320
6M	240
4M	160

MANUFACTURING& CASTING OF GEOPOLYMER CONCRETE

The conventional method used in making conventional cement concrete was adopted to prepare geo-polymer concrete. Firstly, coarse aggregate, fine aggregate, fly ash and slag are mixed in in the pan mixture for 3 to 4 minutes in dry condition. Later alkaline liquid which is a combination of sodium hydroxide and sodium silicate solutions is added to the dry mix. The mixing is done for about 5 to 8 minutes for proper bonding of all material. All the mixes from GP1 to GP 10 were casted by giving proper compaction. The compaction was done by adding concrete into moulds in three layers by giving 25 blows with tampering rod for each layer and at the end moulds are placed on vibrator for 15 seconds. After preparation of mix moulding, demoulding and curing are done to the specimens to acquire good strength.

Fig no: 3 Geopolymer concrete mixes

PREPARATION OF CUBES AND BEAMS

Concrete mix of M40 is prepared by adding different proportions of fly ash and slag, coarse ag-gregate, fine aggregate and alkaline solution. Moulds of size 150 x 150 x 150, 500 x 100 x 100 were taken and greased. Now the Geopolymer concrete mix was placed in moulds in 3 layers and to each layer 25 blows were tempered by using tampering rod and allowed to dry for 24 hours. Then these cubes are demoulded and kept aside for 30 minutes and were placed in curing for 3, 7 and 28 days.

Fig no: 4Geopolymer concrete cubes with different molarity of NaOH solution

CURING PROCESS

All the concrete specimens were cured in atmospheric temperature condition where the specimens are left at the atmospheric condition after demoulding which was done after 24 hours of casting and left for the entire period till testing. During this process the cubes were exposed to a huge temperature variation of almost 16^0 to 18^0 centigrade for every single day during the test conduction.

TESTS OF SPECIMENS

The following tests were conducted to determine the strength of Geopolymer concrete.

COMPRESSIVE STRENGTH TEST

For each proportion nine cubes were casted and the surfaces of the cubes are allowed to dry for 24 hours in saturated condition. Curing of the cubes was done for 3, 7, and 28 days. A gradual load is applied on the surface of the cube to obtain maximum compressive load.Compressive strength is defined as the maximum compressive stress that under a gradually applied load, a given solid material can sustain without fracture.

$F_{ck} = P / A$

Where,

P = Applied load in N

A= Area in mm^2

FLEXURAL STRENGTH TEST

For each mix proportion nine beams were casted and curing was done. Samples were allowed to dry at ambient temperature. Testing of samples at different stages means for 3, 7 and 28 days were done and readings were noted.Flexural strength is a measure of the tensile strength of concrete beams or slabs. It identifies the amount of stress and force of an

S.NO	Name of the mix	Compressive strength of specimens (N/mm^2)		
		3 days	7 days	28 days
1	GP 6	12.88	31.11	38
2	GP 7	11	28.44	33
3	GP 8	10	17.77	23.33
4	GP 9	7.77	13.33	18
5	GP 10	5.33	8	12.33

unreinforced concrete slab, beam or the structure can withstand, such that it resists any bending failures.

$R = PL / bd^2$

Where

R = Modulus of rupture

P = Applied load(N)

L = Length (mm)

B = Breadth (mm)

D = Diameter (mm)

WATER PERMEABILITY TEST

The equipment used in this investigation meets the requirements of IS 3085:1965 which is used for determination of permeability of ordinary concrete. The standard test pressure of 3.5 kg/cm^2 is applied till the flow reaches the steady state and test is further continued three days

The permeability was defined by Darcy's Law as follows:

$K = QL/AH$

Where

K = Permeability coefficients (m/s)

Q = Flow rate (m^3/s)

L = Depth of specimen (m)

H = Head of water

A = Area of the cube

IV.RESULTS&DISCUSSIONS

Based on experimental investigation, the results of cube are mentioned below.

COMPRESSIVE STRENGTH TEST

Compressive strength of specimens cured by 3, 7 and 28 days with 30% GGBFS addition

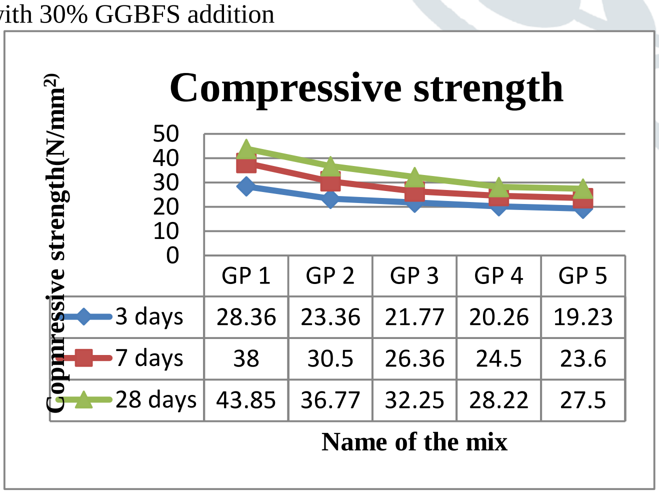


Fig no: 1 Compressive strength graph of geopolymer concrete with 30% slag addition.

The above graph shows 3, 7 and 28 days compressive strengths of Geopolymer concrete mixes with 30% slag and 70% fly ash. From the above graph we clearly observed that the strength of Geopolymer mix increases with increase in molarity of sodium hydroxide solution. Maximum strength was obtained at early age due to polymerization of alkaline liquids. More than 50% of total strength is achieved during 3 days of curing; this is due to higher amount of GGBS(Saha & Rajasekaran, 2017).

Compressive strength of specimens cured by 3, 7 and 28 days with 20% GGBFS addition.

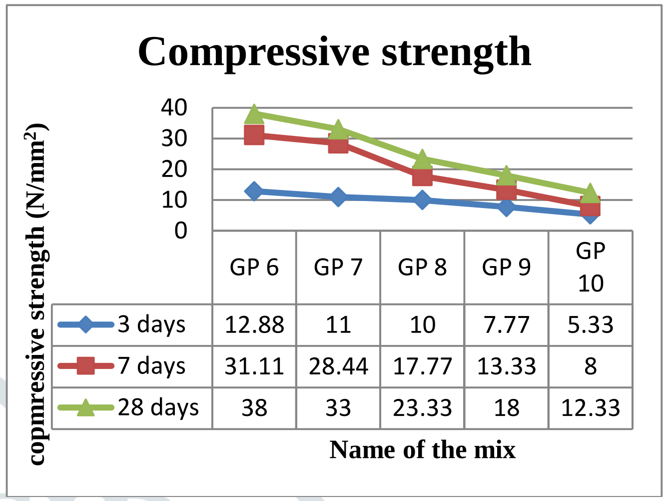


Fig no: 2 Compressive strength graph of geopolymer concrete with 20% slag addition

The above graph shows 3, 7 and 28 days compressive strength of Geopolymer concrete mixes with 20% slag and 80% fly ash. We observed that the compressive strength increases with increase in molarity of sodium hydroxide solution. We can see that the early age strength is not significant due to increase in initial setting time because of lower amount of slag percentage(Saha & Rajasekaran, 2017).

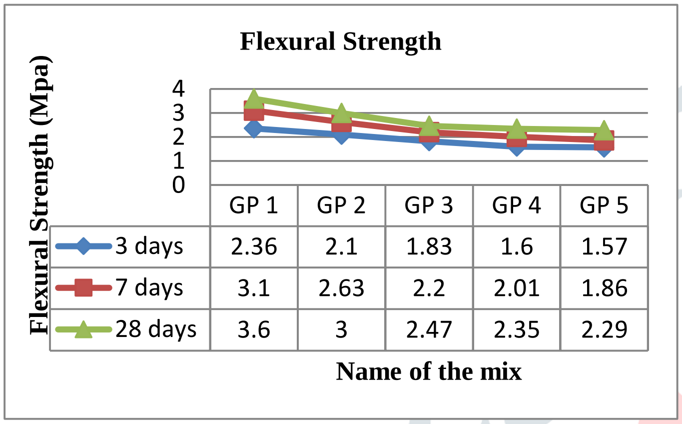
S.NO	Name of the mix	Compressive strength of specimens (N/mm^2)		
		3 Days	7 Days	28 Days
1	GP 1	28.36	38	43.85
2	GP 2	23.36	30.5	36.77
3	GP 3	21.77	26.36	32.55
4	GP 4	20.26	24.5	28.2
5	GP 5	19.23	23.6	27.5

FLEXURAL STRENGTH TEST

Flexural strength of specimens cured by 3, 7 and 28 days with 30% GGBFS addition.

S.NO	Name of the mix	Flexural strength of specimens cured by (N/mm^2)		
		3 Days	7 Days	28 Days
1	GP 1	2.36	3.1	3.6
2	GP 2	2.1	2.63	3
3	GP 3	1.83	2.2	2.47
4	GP 4	1.6	2.01	2.35
5	GP 5	1.57	1.86	2.29

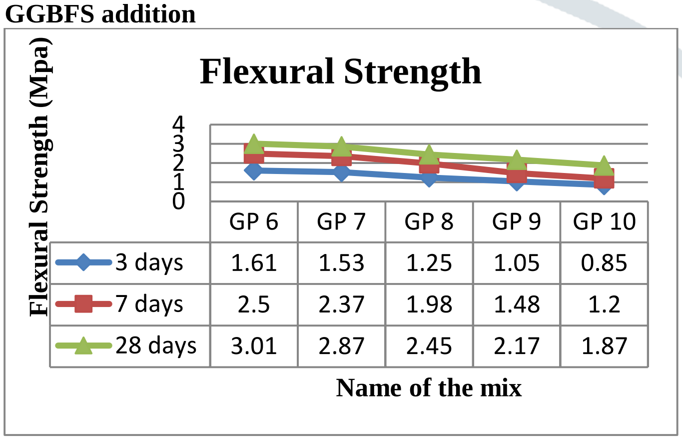
Flexural strength graph of geopolymer concrete with 30% GGBFS addition



Flexural strength of specimens cured by 3, 7 and 28 days with 20% slag addition

S.NO	Name of the mix	Flexural strength of specimens cured by (N/mm^2)		
		3 Days	7 Days	28 Days
1	GP 6	1.61	2.5	3.01
2	GP 7	1.53	2.37	2.87
3	GP 8	1.25	1.98	2.45
4	GP 9	1.05	1.48	2.17
5	GP 10	0.85	1.2	1.87

Flexural strength graph of geopolymer concrete with 30% GGBFS addition



Test results of water permeability of geopolymer concrete with 30% slag addition

Name of the mix	Length of water penetrated (mm)	Pressure applied (kg/cm^2)	Head of water (mm)	Time (hrs)	Coefficient of permeability (K), (m/s)
GP 1	110	3.5	460	72	2.06×10^{-9}
GP2	114	3.5	460	72	2.13×10^{-9}
GP 3	120	3.5	460	72	2.24×10^{-9}
GP 4	125.5	3.5	460	72	2.35×10^{-9}
GP 5	129	3.5	460	72	2.41×10^{-9}

GP5 mix up to3.75 cm GP4 mix up to 2.8 cm

GP3 mix up to 2.35cm GP2 mix up to 2.3 cm

GP5 mix up to 2.1 cm

Vertical penetrations of water

V.CONCLUSION

Based on the experimental work reported in this study, following conclusions were drawn.

- Higher concentration in terms of molarity of sodium hydroxide solution results in the higher compressive strength of fly ash and GGBFS based geopolymer concrete.
- The fresh flyash-based geo-polymer concrete is easily handled up to 60 minutes without any sign of setting and without any degradation in the compressive strength.
- The mixes GP1 and GP6 gives higher compressive strength as it has high molarity of so-dium hydroxide solution with 30% and 20% slag addition respectively.
- The mixes GP1 and GP6 gives higher Flexural strengths as it as high molarity of sodium hydroxide solution with 30% and 20% slag addition respectively
- We observe that both compressive strength and flexural strength are increased with the increase in the molarity of the sodium hydroxide.
- By increasing the amount of GGBS the initial and final setting time of geopolymer con-crete decreases which

results in attaining high early strength.

- With the incorporation of steel slag, fly ash based Geopolymer concrete can be cured in the atmospheric temperature and be able to get good compressive and flexural strength.
- When a comparison was done in strength between the different replacements of slag for the same molarity, the variation observed was only marginal. But when same slag re-placements of different molarities were considered, the increase in strength was high.
- Depth of penetration of water is inversely proportional to the Molarity of NaOH solution due to with increase in molarity of NaOH solution there is excellent bonding between geopolymer binders and aggregates.As geo-polymer concrete technology is a new one, there is lot of scope to work in this topic. In the present study we used fly ash and GGBFS as a binder instead of cement and alkaline liquids to bind the materials. We recommend extending this topic by using by-products like rice husk ash, pulverized fuel ash etc. And also, investigation of Long term properties like durability, creep, drying shrinkage may also give the suitability of geo-polymer concrete in the field.By im-plementing such methods the durability can be increased and strength of the material can also be increased.

To provide Economical Concrete:

- It should be easily adopted in field.
- It should reduce the cost of construction.
- It should promote low cost housing for the people.
- It should make the maximum usage of locally available materials.
- It should be environmental friendly.

REFERENCES

1. Aliabdo, A. A., Abd Elmoaty, A. E. M., & Salem, H. A. (2016). Effect of cement addition, solution resting time and curing characteristics on fly ash based geopolymer concrete per-formance. Construction and Building Materials, 123, 581–593.
2. Aliabdo, A. A., Elmoaty, A., Elmoaty, M. A., & Salem, H. A. (2016). Effect of water addi-tion, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete per-formance. Construction and Building Materials, 121, 694–703.
3. Arioz, E., Arioz, O., & Kockar, O. M. (2012). An experimental study on the mechanical and microstructural properties of geopolymers, 42(August), 100–105.
4. Assi, L. N., Deaver, E., Elbatanouny, M. K., & Ziehl, P. (2016). Investigation of early com-pressive strength of fly ash-based geopolymer concrete. Construction and Building Materials, 112, 807–815.
5. Cho, Y., Yoo, S., Jung, S., Lee, K., & Kwon, S. (2017). Effect of Na 2 O content , SiO 2 / Na 2 O molar ratio , and curing conditions on the compressive strength of FA-based geopolymer, 145, 253–260.
6. D. M. J. Sumajouw, D. Hardjito, S. E. Wallah, and B. V. Rangan, “Fly ash-based geopolymer concrete: Study of slender reinforced columns,” J. Mater. Sci., vol. 42, no. 9, pp. 3124–3130, 2007.
7. Ferdous, M. W., Kayali, O., & Khennane, A. (2013). A detailed procedure of mix design for fly ash based geopolymer concrete, (December), 11–13.
8. Gunasekara, C., Law, D. W., & Setunge, S. (2016). Long term permeation properties of dif-ferent fly ash geopolymer concretes. Construction and Building Materials, 124, 352–362.
9. Guo, X., Shi, H., & Dick, W. A. (2010). Compressive strength and microstructural character-istics of class C fly ash geopolymer. Cement and Concrete Composites, 32(2),
10. Hadi, M. N. S., Farhan, N. A., & Sheikh, M. N. (2017). Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method. Construction and Building Ma-terials, 140, 424–431.
11. J. Davidovits, “Properties of Geopolymer Cements,” First Int. Conf. Alkaline Cem. Concr., pp. 131–149, 1988, 1994.
12. Joseph, B., & Mathew, G. (2012). Influence of aggregate content on the behaviour of fly ash based geopolymer concrete. Scientia Iranica, 19(5), 1188–1194.
13. Ken, P. W., Ramli, M., & Ban, C. C. (2015). An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products, 77, 370–395.
14. LI, Z., & LI, S. (2018). Carbonation resistance of fly ash and blast furnace slag based geo-polymer concrete. Construction and Building Materials, 163, 668–680. Chindaprasirt, P. (2007). Workability and strength of coarse high calcium fly ash geopolymer, 29, 224–229.
15. Lyu, S., Hsiao, Y., Wang, T., Cheng, T., & Ueng, T. (2013). Cement and Concrete Research Microstructure of geopolymer accounting for associated mechanical characteristics under various stress states, 54, 199–207.
16. Malkawi, A. B., Fadhil, M., Fauzi, A., &

Almattarneh, H. (2016). Effects of Alkaline Solu-tion on Properties of the HCFA Geopolymer Mortars. Procedia Engineering, 148, 710–717.
17. N, A., Lloyd and B, V., Rangan. (2010). “Geopolymer Concrete with Fly Ash”.
18. Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials, 66, 163–171.
19. Nath, P., & Sarker, P. K. (2017). Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. Construction and Building Materials, 130, 22–31.
20. R. M. Andrew, “Global CO 2 emissions from cement production,” no. August, pp. 1–52, 2017.
21. Ryu, G. S., Lee, Y. B., Koh, K. T., & Chung, Y. S. (2013). The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Construction and Building Materials, 47(2013), 409–418.