ASSESSING THE WORKABILITY AND MECHANICAL PROPERTIES OF HIGH AND LOW CALCIUM FLYASH BASED GEO POLYMER CONCRETES DEVELOPED WITH ALTERNATIVE CONCRETING INGREDIENTS

1. S. Jagadeesan, PhD Scholar, Department of Civil & Structural Engineering, Annamalai University, Annamalainagar-608002, Tamilnadu, India.

Correspondence : jagadeesanaee1@gmail.com

2. M. Purushothaman, Associate Professor, Department of Civil & Structural Engineering, Annamalai University, Annamalainagar-608002, Tamilnadu, India.

Email Id: emp4624@gmail.com

ABSTRACT

A replacement for all the ingredients of the concrete making materials determines the future of construction industry to sustain in the market by establishing concrete as a very eco-friendly material. Once concrete becomes a green material it helps in the reduction of global heating and emission of mendacious amounts of CO_2 into the atmosphere caused by the cement and concrete manufacturing industries. Such an important paradigm shift that has occurred in the alternative materials technology and research led to the advent of new concrete called Geo Polymer Concrete (GPC). In order to examine the stimulus of the alternative materials in the mechanical characteristics of concrete, a concrete design mix proportion designed to achieve a compressive strength of concrete not less than 30MPa was considered in this study. The standard materials used in the production of Portland Cement Concrete (PCC) was totally replaced by equivalent alternative materials in GPC. Here, cement was replaced by flyash, river sand by manufactured sand, crushed stone aggregates by steel slag aggregates, water by alkaline activator solution. The age of concrete was tested for 7 and 28 days curing period. PCC was cured with water as usual whereas for GPC, ambient curing (30^oC) for class-C high calcium flyash concrete and heat curing at elevated temperatures (60^{o}C-80^{o}C for 24 hrs) for class-F low calcium flyash concrete was carried out. A comparative analysis was made between PCC and GPC to study the Strengths and stiffnesses such as modulus of rupture and tensile strength. stiffnesses such as modulus of rupture and tensile strength.compressive, indirect tensile strength, rupture modulus, good adhesion and elasticity modulus are mechanical qualities. The test results reported that the GPC established a better performance in comparison with PCC and hence the role of GPC will be significant in the future for the construction industry as well as to the environment.

Keywords: geopolymer, polymerization, alkaline reaction, molarity, binder material, curing temperatures, calcium based, oxides, ions, hydrates, gel formation, activator based, alternative materials.

1. INTRODUCTION

In today's industrial revolution 4.0, the challenges ahead for the civil engineering fraternity is to develop a performance based construction material that shall be both eco-friendly as well as cost effective to march towards a sustainable development. In terms of cement production and consumption, India has overtaken the United States as the world's second largest country.In terms of cement production and consumption, India has overtaken the United States as the world's second largest country. In terms of cement production and consumption, India has overtaken the United States as the world's second largest country. To make OPC, huge amounts of raw materials must be extracted from the earth's natural resources, which is a process that consumes a great deal of energy. Every tonne of Portland cement produced releases an equivalent amount of CO2 into the atmosphere, because the modern cement manufacturing process uses all the available technology to make OPC. The years 2014–2024 are being hailed as the "decade of sustainability" on the international stage. **[1]**, a holistic approach of utilizing the industrial wastes and by-products such as fly ash, slag and pozzolana composites in civil engineering applications has become inevitable.

2. LITERATURE REVIEW

Geopolymer is a unique material that replaces cement by 100% with many suitable cementitious materials. OPC binders may be replaced by geopolymer binders because of their reported early strength and long-term durability [2]. Rather than calcium-silicate hydrate bonds, the geopolymer product's strength is derived from alumina-silicate combination. Davidovits invented Geopolymer in 1979 as a three-dimensional alumina silicate, and it can be made from a variety of additional cementing materials, such as coal and lignite fly ash, rice husk ash, palm oil fuel ash, GGBFS, silica fume, limestone, metakaolin, and natural Pozzolona **[3].**

River sand being the major component next to the binder material in the concrete mix is most commonly used as a filler material and utilization of it has resulted in multifold demand due to enormous day-to-day construction requirements. Nevertheless, the depletion of river sand has resulted in scarcity. The natural sand available from the riverside consists of organic and inorganic matters and the organic matter existing in the sand creates voids and cracks after the process of hardening of concrete, which in turn affects the strength and permeability properties of the concrete. The mounting issues on extraction of natural sand from riverbeds led to several devastating effects on the environment such as decline of underground water table influencing agricultural process, life of the aquatic species, erosion of river embankments, water retaining capacities and loss of recharge bore wells. A justification for this undue extraction of sand from natural resources like rivers shall be overcome by the practice of synthetic sand called manufacture sand (M.sand) in the place of fine aggregates **[4].** Abundant alternatives for river sand such as M-sand, fly ash, limestone, copper slag, sawdust were explored **[5-6]**. Among all the mentioned alternatives in the literature, M-sand was quite enduring to prove its efficacy as a better alternative in the place of river sand as fine aggregate in the standard concrete **[7].**

Steel slag is one of the industrial by-product obtained in the process of conversion of iron to steel and as a result of this process, a large percentage of the waste is still being disposed in empty/unused lands causing man made pollution dumpsites. The yearly production of steel in today's scenario is consummated around 90-135 million metric tons which amounts to a large disposal of steel slag in the production process. This steel slag is pertinent material, which could be ideally used in situations warranting reuse and recycle rather than disposing them as a waste material **[8].** The steel slag produced from electric arc furnace in the steel manufacturing unit is an industrial by-product obtained during the time of melting of steel scrap from the impurities and fluxing agents and that can be used as a replacement material for coarse aggregates **[9].** India imports large amount of steel scrap and ranks third among the global competitors and when processed in the furnace produces large amount of steel slag that could benefit the concrete industry as a suitable replacement material for natural gravel coarse aggregate **[10].**

In this study, a complete replacement for conventional concrete materials forming geopolymer concrete by alternative materials obtained from the industrial by-products is taken into consideration. The performance of geopolymer concrete on its mechanical characteristics is analyzed in comparison with the control concrete. The parameters for the study include cube compressive strength, indirect tensile strength, modulus of rupture, bond strength and elasticity modulus.

3. MATERIALS

3.1 Binder Materials

OPC of 43 grade conforming to IS 8112-2013 was used as the binder material for Portland Cement Concrete (PCC) with a particle size of 10 microns. OPC was completely replaced by flyash conforming to IS 3812 (Part 1)-2003 in this study. A geopolymer concrete binder was made by using flyash from Tuticorin and Mettur Thermal Power Stations, Tamilnadu and Neyveli Lignite Corporation (NLC), Tamilnadu, as well as flyash from Neyveli Lignite Corporation. The particle size distribution tests on fly ash found that nearly eighty percent of the flyash was less than fifty microns [11], a fine-grained, spherical material. Table 1a and 1b show the results of the tests on the binder materials.OPC of 43 grade conforming to IS 8112-2013 was used as the binder material for Portland Cement Concrete (PCC) with a particle size of 10 microns. OPC was completely replaced by flyash conforming to IS 3812 (Part 1)-2003 in this study. A geopolymer concrete binder was made by using flyash from Tuticorin and Mettur Thermal Power Stations, Tamilnadu and Neyveli Lignite Corporation, Tamilnadu, as well as flyash from Neyveli Lignite Corporation. The particle size distribution tests on fly ash found that nearly eighty percent of the flyash was less than fifty microns [11], a fine-grained, spherical material. Table 1a and 1b show the results of the tests on the binder materials.

The physical properties of binder materials are given in Table 1a.

Table 1a. Physical Properties of Binder Materials

Property	Cement	Flyash	
	OPC 43 Grade	Class C – High Calcium	Class F – Low Calcium
Specific Gravity	3.15	1.92	2.12
Fineness (m2/kg)	225	372	376
Initial Setting Time (min.)	30	35	37
Final Setting Time (min.)	600	548	554

The chemical properties of binder materials are given in Table 1b.

Table 1b. Chemical Composition of Binder Materials

Cement - - OPC 43Grade		Flyash-Class C		Flyash-Class F	
Elements	% Mass of Elements	Elements	% Mass of Elements	Elements	% Mass of Elements
SiO2	22.65	SiO2	35.7	SiO2	38.6
Al2O3	04.32	Al2O3	15.8	Al2O3	16.5
Fe2O3	02.33	Fe2O3	16.1	Fe2O3	17.1
CaO	64.32	CaO	34.85	CaO	15.6
Na2O	00.06	TiO2	0.46	TiO2	1.35
K2O	00.05	K2O	1.85	K2O	2.18
TiO2	-	MnO	0.16	MnO	0.15
MgO	02.23	Na2O	0.19	SO3	3.05
SO3	02.12	P2O5	0.04	NiO	0.05
LOI	02.12	LOI	1.11	CuO	0.08

3.2 Fine Aggregate

Fine aggregates used in this study was in accordance with IS 383-1970. The fine aggregate used in PCC was obtained from a locally available natural river sand and its size ranged from 75 μm to 5 mm and whereas for GPC, M.sand obtained from the stone quarries was used. The requisite properties of fine aggregate materials obtained from tests are demonstrated in Table 2.

Table 2. Properties of Fine Aggregate Materials

Properties	**River Sand**	**M. Sand**
Specific gravity	2.67	2.66
Fineness modulus	3.15	4.28
Bulk density (kg/m3)	1667	1751
Water absorption (%)	1.0	0.92
Grading Zone	Zone – II	Zone – II
Size	Passing through 4.75 mm sieve	Passing through 4.75 mm sieve

3.3 Coarse Aggregate

According to IS 383-1970, coarse aggregates were used in this study. The coarse aggregate in PCC was crushed granite stone with a particle size range of 7 mm to 20 mm.. Steel slag used in GPC was collected from a hot-rolling steel mill, Madagadipet, Pondicherry, India. The large sized slag in the form of boulders was air-dried, crushed according to utility size and sieved with IS 4.75mm sieve as required for laboratory tests. IS 456-2000 states that in situations where slag aggregates are used, it is important to corroborate that it should not contain more than 0.5% of sulphates in the form of SO_3 and 10% of water absorption. The properties of coarse aggregate materials obtained from laboratory tests are given in Table 3.

Table 3. Properties of Coarse Aggregate Materials

Properties	**Crushed Stone / Gravel**	**Steel Slag**
Specific gravity	2.63	3.2
Fineness modulus	6.32	2.86
Bulk density (kg/m3)	1336	1040
Water absorption (%)	0.50	2.86
Moisture content (%)	0	0.25
Maximum size (mm)	20	20 below
Crushing value (%)	25	12.4
Abrasion value (%)	34	14.5
Impact value (%)	32	15.0
SO3 (%)	-	0.145

3.4 Mixing Agents

In accordance with IS 456-2000, the water used for mixing and curing should be free from hazardous contents of oils, acids, alkali salts and sugars as well as any other substances that may be detrimental to concrete or steel. Hence, potable water is generally preferable for mixing concrete.

During the preparation of PCC, potable drinking water with pH value of 6.5 was used as the mixing agent. In the case of producing GPC, Alkaline Activator Solution (AAS) was used for mixing the binder and aggregate materials instead of water. Sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) solutions were used to make this AAS. In order to dissolve the NaOH pellets, the sodium hydroxide was watered down by one litre of distilled water. This was followed by a 24-hour rest period for the NaOH stock in a volumetric flask to ensure that all reactions had been completed. 37.6 percent solids (28.7 percent silicate and 8.9 percent sodium) and 62.4 percent water were found in the sodium silicate solution. Calculating the molar mass of NaOH, which contains 22.99 g/mol of Na, 16.00 g/mol of O, and 1.008 g/mol of H, yielded a sodium hydroxide preparation about one litre of distilled water. For this reason, one mole of NaOH is equivalent to 40 grammes of granulated NaOH. To reduce water content and to achieve desired workability with expected slump values ranging beyond 100mm, superplasticizer-CONPLAST 430 was used as percentage weight of binder material flyash.

4. METHODS

4.1 Design Mix Proportions and Quantities

The effect of mechanical properties of GPC was investigated with varying parameters like class of flyash (Class C and Class F), varying NaOH molar concentration (8M and 14M) and constant parameters like the alkaline activator solution to binder ratio is 0.35. In terms of total mass, 70% of the aggregates were coarse, and only 30% were fine.

The aggregates and the fly ash were dry mixed in a mechanical mixer for 3 minutes. After that, alkaline activator solution was added to the dry mix followed by thorough mixing for 5-6 minutes inorder to obtain a perfect consistent mix. The fresh geopolymer concrete were poured into standard moulds of cubes, cylinders and prisms for carrying out the respective strength tests. Slump test for the fresh concrete was performed for the stipulated mixes to determine the workability of both PCC and GPC. The mix proportions and quantities for conventional PCC and GPC are shown in Tables 4a and 4b respectively. The mix proportions and quantities of PCC are given in Table 4a.

Table 4a. Mix Proportions and Quantities of PCC

Material	**Binder: Cement**	**FA: R. Sand**	**CA: Gravel Stone**	**Water**	**Superplasticizer**
Quantity (kg/m3)	426	598	1266	192	Nil
Proportion	1	1.40	2.97	-	-
Note: W/c ratio = 0.45					

The mix proportions and quantities of GPC are given in Table 4b.

Table 4b. Mix Proportions and Quantities of GPC

Material	**Binder: Flyash**	**FA: M. Sand**	**CA: Steel Slag**	**Sodium Silicate Solution (Na2SiO3)**	**Sodium Hydroxide Solution (NaOH)**	**Extra Water**	**Super plasticizer**
Quantity (kg/m3)	408	554	1294	103	41	14.5	10.2
Proportion	1	1.36	3.17	0.25	0.10	-	-
Note: 1. Molarity or Molar concentration of NaOH = 8M and 14M 2. Alkali Activator Solution (AAS) ratio = Na2SiO3 / NaOH = 2.0 3. Liquid / Binder ratio = AAS / Flyash = 0.35 4. Extra water added to the mix for moisture requirement = 3.5% Wt. of Binder 5. Superplasticizer added to the mix on workability criteria = 2.5% Wt. of Binder							

The specimens planned for casting was subjected to appropriate curing conditions for 7 and 28 days strength. PCC specimens was subjected to water curing. GPC specimens with class-C flyash was subjected to ambient curing (30^{o}C or room temperature) whereas with class-F flyash was subjected to heat curing (in oven at 65^{o}C for 24 hrs.) immediately after demoulding. The quantities of specimens required to assess the mechanical properties of PCC and GPC were formulated based on the variations in parameters of design mix proportions and strength tests performed. Accordingly, the number of cube, cylinder and prism specimens required for testing were arrived and tabulated in Tables 5a and 5b respectively.

The details of the PCC specimens for casting, curing and testing are given in Table 5a.

Table 5a. Test Matrix of PCC Specimens

S. No.	Name of the Test	Shape & Size of the Specimen	No. of Samples for Curing & Testing		Test Reference
			7 days	28 days	
1	Compression Test	Cube – 150x150x150mm	03	03	IS:516-1959
2	Split Tension Test	Cylinder – 150 mm dia. x 300mm ht.	03	03	IS:5816-1999
3	Flexure Test	Prism - 100x100x500mm	03	03	IS:516-1959
4	Pullout Test	Cube – 150x150x150mm embedded with a 20mm dia. rod of 600mm length	03	03	IS: 2270 Part I-1967
5	Elasticity Test	Cylinder – 150 mm dia. x 300mm ht.	03	03	IS:516-1959

The details of the GPC specimens for casting, curing and testing are given in Table 5b.

Table 5b. Test Matrix of GPC Specimens

S. No.	Name of the Test	Shape & Size of the Specimen	Class of Flyash	Na2SiO3/ NaOH ratio	AAS/ Flyash ratio	NaOH Molarity (M)	No. of Samples for Curing & Testing	
							7 days	28 days
1	Compression Test	Cube – 150x150x150mm	C	2.0	0.35	8	03	03
						14	03	03
			F	2.0	0.35	8	03	03
						14	03	03
2	Split Tension Test	Cylinder – 150 φ x 300mm	C	2.0	0.35	8	03	03
						14	03	03
			F	2.0	0.35	8	03	03
						14	03	03
3	Flexure Test	Prism - 100x100x500mm	C	2.0	0.35	8	03	03
						14	03	03

			F	2.0	0.35	8	03	03
						14	03	03
4	Pullout Test	Cube – 150x150x150mm embedded with a 20mm dia. rod of 600mm length	C	2.0	0.35	8	03	03
						14	03	03
			F	2.0	0.35	8	03	03
						14	03	03
5	Elasticity Test	Cylinder – 150 φ x 300mm	C	2.0	0.35	8	03	03
						14	03	03
			F	2.0	0.35	8	03	03
						14	03	03

4.2 Slump Cone Test

The workability of concrete as per IS 456-2000 always depends on the concrete mix proportions such that it satisfies the conditions of compaction and placing of concrete. The workability of concrete is carried out in accordance with IS 1199-1959. In the mix design of PCC and GPC, the degree of workability considered for structural members as per IS 456-2000 suggestion pertains to “Medium” category such that the slump value ranges between 75-100 mm as shown in Figure 1.

a. Concreting the Slump Cone **b. Measuring of Slump Value**

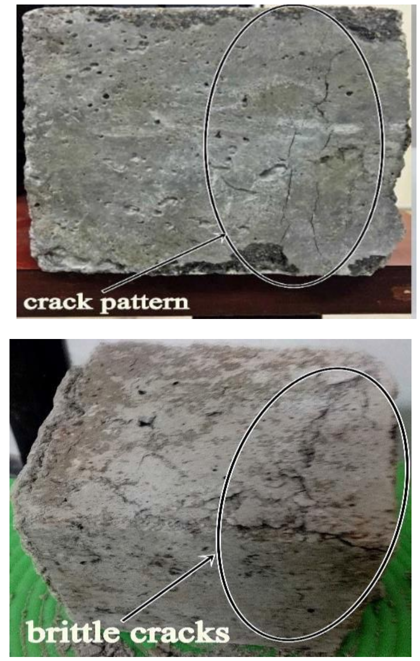
Figure 1. Slump Cone Test

4.3 Compression Test

The test method to determine the compressive strength of hardened concrete with reference to apparatus, age at test, number of specimens, procedure, calculation and report was performed in accordance with IS 516-1959. The test set-up with cube specimen under loading and failure of specimens at peak loads are shown in Figure 2.

PCC

GPC



a. Cube under Loading **b. Cube after Testing**

Figure 2. Compression Test

4.4 Split Tension Test

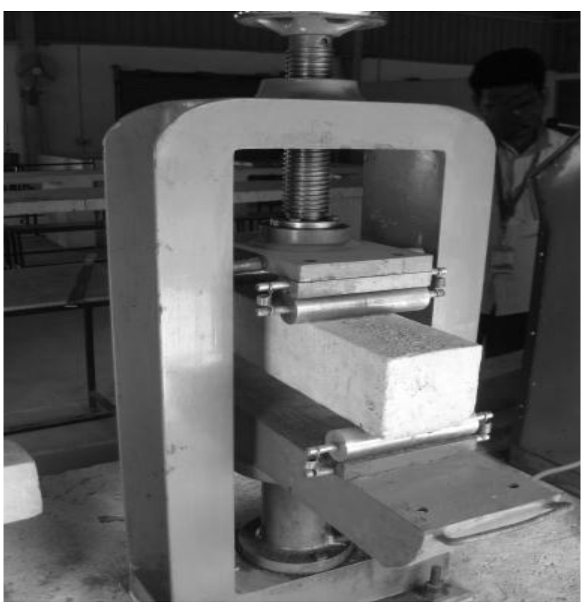
The test method to determine the indirect tensile strength of hardened concrete with reference to apparatus, age at test, number of specimens, procedure, calculation and report was performed in accordance with IS 5816-1999. The test set-up with cylinder specimen under loading and failure of specimen at peak loads are shown in Figure 3.

a. Cylinder under Loading **b. Cylinder after Testing**

Figure 3. Split Tension Test

4.5 Flexure Test

The test method to determine the modulus of rupture of toughened concrete with reference to apparatus, age at test, number of specimens, procedure, calculation and report was performed in accordance with IS 516-1959. The test set-up with prism specimen under loading and failure of specimen at peak loads are shown in Figure 4.



a. Prism under Loading **b. Prism after Testing**

Figure 4. Flexure Test

4.6 Pullout Test

The test method to determine the bond strength of toughened concrete with reference to scope, apparatus, test specimens, test procedure, calculation of bond stress and record of results was performed in accordance with IS 2270 (Part I)-1967. The test set-up consisting of cube specimen embedded with a reinforcement rod under loading and failure of specimen at peak loads are shown in Figure 5.

a. Cube embedded with steel rod under Loading

b. Cube embedded with steel rod after Testing

Figure 5. Pullout Test

4.7 Elasticity Test

The test method to determine the elasticity modulus of hardened concrete with extensometer attachment with reference to size of specimens, preparation of test specimens, age at test, apparatus, procedure, calculation and report was performed in accordance with IS 516-1959. The test set-up consisting of a cylinder specimen encased in an extensometer under loading and failure of specimen at peak loads are shown in Figure 6.

a. Cylinder under Loading **b. Cylinder after Testing**

Figure 6. Elasticity Test

5. RESULTS

The specifications of concrete used in this study is demonstrated in Table 6.

Table 6. Specifications of Concrete

PCC-M30	Plain Cement Concrete of M30 grade
GPC-C8M	Geo Polymer Concrete with class-C flyash and 8 Molar concentration of NaOH
GPC-C14M	Geo Polymer Concrete with class-C flyash and 14 Molar concentration of NaOH
GPC-F8M	Geo Polymer Concrete with class-F flyash and 8 Molar concentration of NaOH
GPC-F14M	Geo Polymer Concrete with class-F flyash and 14 Molar concentration of NaOH

The workability of fresh concrete obtained through slump measurements is presented in Table 7.

Table 7. Slump Test Results

Concrete ID	**Slump Value (mm)**
PCC-M30	92
GPC-C8M	89
GPC-C14M	78
GPC-F8M	85
GPC-F14M	80

The test results on mechanical properties of hardened concrete is presented in Table 8.

Table 8. Mechanical Properties Test Results

Concrete ID	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)		Bond Strength (MPa)		Modulus of Elasticity (MPa)
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	28 days
PCC-M30	23.50	36.84	0.78	3.10	0.93	3.72	3.98	15.90	2.67x10^5
GPC-C8M	24.20	37.35	2.50	3.57	2.97	4.24	4.72	9.75	3.56x10^5
GPC-C14M	26.96	38.52	2.99	4.28	3.46	4.94	5.91	10.62	3.99x10^5
GPC-F8M	38.15	45.11	3.20	4.81	2.25	3.42	2.32	7.65	4.25x10^5
GPC-F14M	54.32	61.28	3.96	5.17	3.12	4.58	3.49	8.33	4.68x10^5

6. DISCUSSION

6.1 Workability

Figure 7 shows the workability of PCC and GPC concrete obtained through slump tests performed as per the guidelines mentioned in IS 1199-1959. In general, the workability of flyash based GPC would be lower than the PCC because of the adhesive feature of the silicate present in the flyash binder. However, GPC can go well with compaction on a vibrating table even for lower slump. Workability of flyash/alkali based concretes can be classified based upon the condition of compaction and slump values attained [12]. For slump value exceeding 90mm then it can be regarded as a highly workable concrete, slump value ranging between 50-90mm shall be regarded as medium workable concrete and if the slump value falls below 50mm then the concrete is considered to be a low workable concrete. In this study, the slump of PCC 92mm was found to be higher when compared to GPC ranging between 78 to 89mm. Hence, the PCC concrete was found to be highly workable whereas the GPC was found to be listed in the category of medium workable concrete.

In addition, the three major factors that contributed to GPC's decline: (i). Sodium silicate to sodium hydroxide ratio and alkaline activator solution to binder ratio are both affected by the molarity of the sodium hydroxide concentration, while GPC's workability decreased as the molar concentration of sodium hydroxide increased from 8M to 14M, according to the test results. The slump reduced from 89mm (8M) to 78mm (14M) in class-C flyash GPC and from 85mm (8M) to

80mm (14M) in class-F flyash GPC with a reduction in percentage of 14.10% and 6.25% respectively. The sodium hydroxide solution's viscosity increased from 8M to 14M, which may be the cause. Both Na2SiO3 to NaOH and AAS to binder ratios remained constant, so the effect on slump values was insignificant.

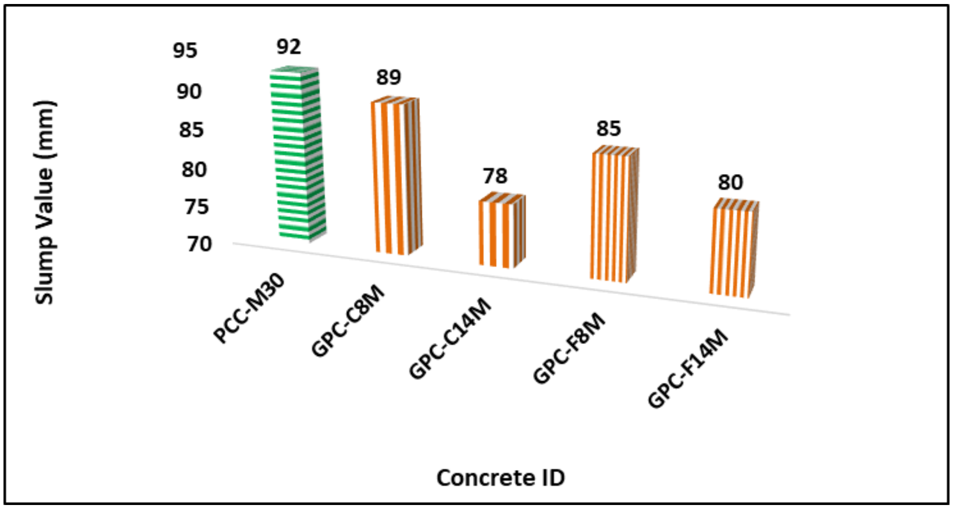


Figure 7. Workability of PCC and GPC

6.2 Compressive Strength

Figure 8 depicts the results of compressive strength tests performed in accordance with IS 516-1959 on PCC and GPC specimens. In comparison to PCC, GPC specimens have a greater compressive strength at 7 and 28 days based on the flyash class, aggregate to binder ratio, NaOH concentration, and the ratio of Na_2SiO_3 to NaOH.

GPC-C14compressive M's strength was found to be 17.74 percent and 13.30 percent higher than GPC-C8for M's 7-day and 28-day strength, respectively. GPC-F147- M's and 28-day compressive strengths were 42.39 percent and 35.85 percent higher, respectively, than GPC-F8 M's. Compressive strength for 7 days increased by 2.98 %, 14.72 %, 62.34 % and 131.15 % when compared to PCC-M30 for the four GPC-C8M/C14M/F8M grades. It was found that the compressive strength of GPC-C8M, GPC-C14M, GPC-F8M, as well as GPC-F14M, all increased when compared to PCC-M30 in terms of 28-day compressive strength. Overall, GPC had a higher compressive strength than PCC.

The reason for GPC attaining higher compressive strengths was due to the increase in molar concentrations of NaOH. The large amount of Na ions present in NaOH higher the swift rate of dissolution of flyash resulting in the formation of aluminosilicate gel that acted as a bonding agent between binder and aggregate to keep it intact. This greater bond action was the reason to produce higher compressive strengths. The aggregate to binder ratio is another primary reason for the interlocking shear between the aggregate and binder paste that decides the compressive strength. Hence, the optimal proportioning of aggregate to binder ratio of 65% to 35% resulted in higher compressive strength without any shrinkage, internal micro cracks and porosity **[13]**. From the results, it was identified that class-F flyash GPC gained higher compressive strengths compared to class-C flyash GPC. The obtained results were indicative of the reason that the mode of heat curing in class-F flyash GPC significantly increased the compressive strength compared to ambient curing of class-C flyash GPC. In addition, this increase in compressive strength was more noticeable in 7 and 28 days curing period. Increasing the curing temperature in heat curing mode of GPC greatly hastens the formation of the geopolymer gel, increase the dissolving rate of Silica and Alumina present in flyash and provides the requisite energy to overcome the barriers to delaying geopolymerization mechanism of high molar NaOH concentrations **[14].**

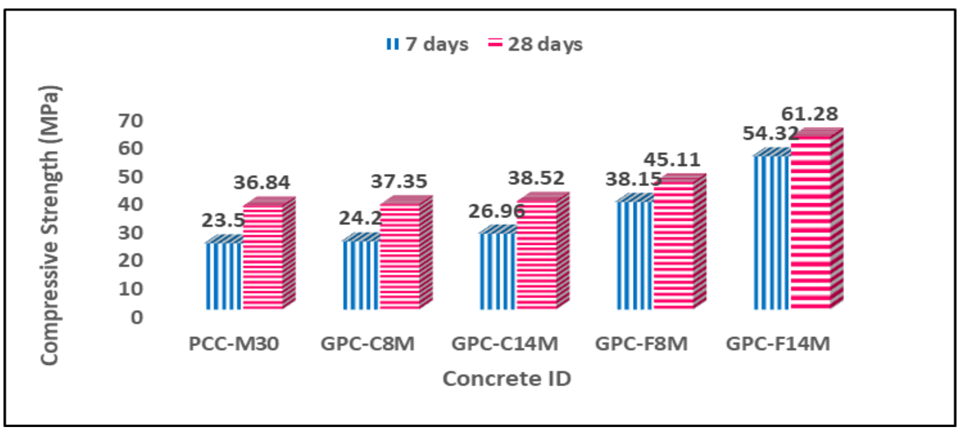


Figure 8. Compressive Strength of PCC and GPC

6.3 Split Tensile Strength

In accordance with IS 5816-1999, PCC and GPC specimens were tested for splitting tensile strength, as shown in Figure 9. IS 456-2000's compressive strength is expressed as fcr = 0.7 fck, which is the equivalent for tensile strength (MPa). According to the findings, GPC had a higher splitting tensile strength than PCC.Within the GPC mixes, 14M-NaOH concentration mix showed higher results than 8M-NaOH concentrations at 7 and 28 days curing. The increase in molar concentration of sodium (Na) ion contributed to this increase in splitting tensile strength **[15-16].** Comparing the class of flyash GPC mix, class-F flyash GPC mix showed higher spitting tensile strengths than class-C flyash GPC mix. The heat curing of class-F flyash GPC mix contributed to the increase in splitting tensile strength **[15-16].**

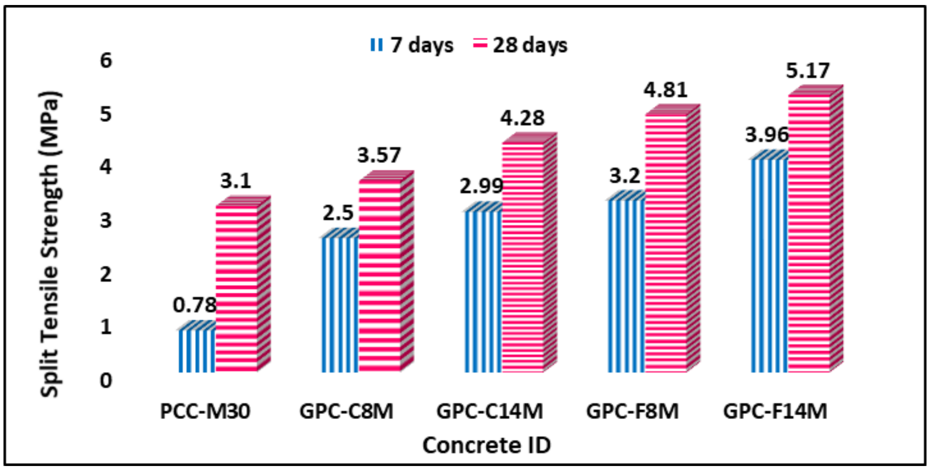


Figure 9. Split Tensile Strength of PCC and GPC

6.4 Flexural Strength

Figure 10 shows the test results of modulus of rupture of PCC and GPC specimens obtained in accordance with IS 516-1959. From the results, it was observed that the modulus of rupture of GPC excels PCC. Within the GPC mixes, 14M-NaOH concentration mix showed higher results than 8M-NaOH concentrations at 7 and 28 days curing. The increase in molar concentration of sodium (Na) ion contributed to this increase in flexural strength **[15-16].** Comparing the class of flyash GPC mix, class-C flyash GPC mix showed increased flexural tensile strengths than class-F flyash GPC mix. The heat curing of class-F flyash GPC mix resulted in the brittle failure of the prism specimen due to lack of bending action. This brittle failure of the specimen may be attributed to the quick evapouration of alkali activator liquid component leading to extreme dryness even before the hydration of binder matrix in the concrete. **[15-16].**

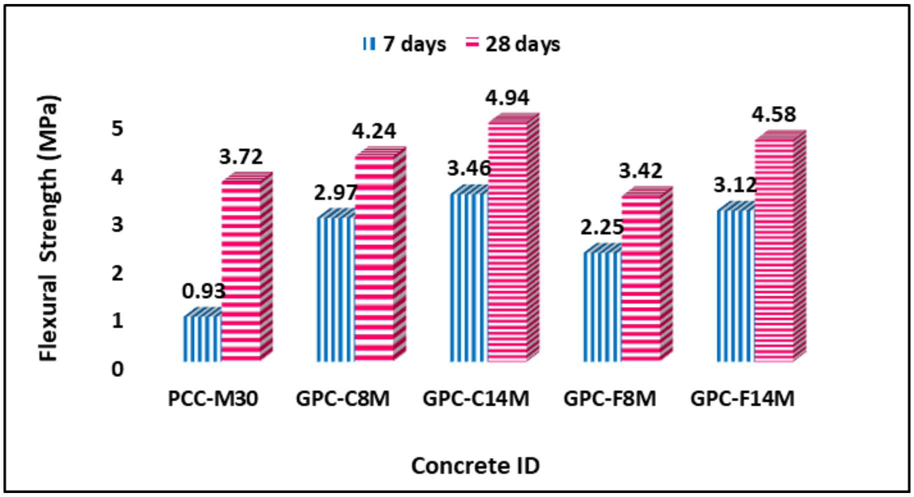


Figure 10. Flexural Strength Behaviour of PCC and GPC

6.5 Bond Strength

PCC and GPC specimens were tested for bond strength in accordance with IS 2270 (Part I)-1967, as shown in Figure 11. A reinforcing rod's shear stress/shear force interaction with the surrounding concrete in reinforced concrete results in the bond strength.. Bond slip of reinforcement takes place when adequate bond force is not prevailing over the surrounding concrete surface thus resulting in the failure of composite adhesion. The mechanism of initiating the bond force happens by three factors i. chemical adhesion ii. friction iii. mechanical interaction between steel and concrete **[17].** The test results showed that the ultimate bond strength of the embedded deformed rods in class-C flyash GPC was little higher than class-F flyash GPC and in overall the 28 days bond strength of PCC mix was higher than the GPC mix. It was noticed from the mode of failure of the specimens (Figure 5b) that all the specimens failed in pull out mode and no specimen failed due to yielding of the reinforcement rods. The GPC specimens exhibited splitting failure of the cubes at top, middle and bottom levels. The 7 days curing specimen had a splitting failure at middle level whereas it was at bottom for the 28 days curing specimens **[17].**

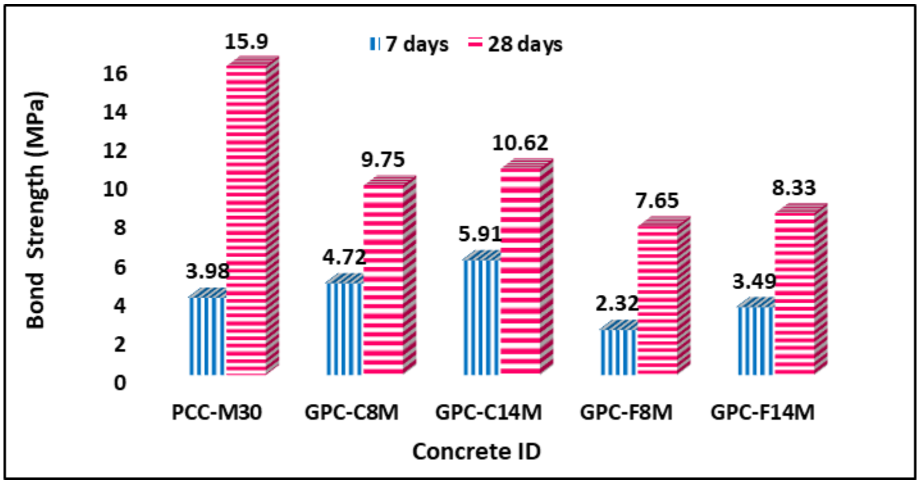


Figure 11. Bond Strength Behaviour of PCC and GPC

6.6 Modulus of Elasticity

According to IS 516-1959, the elasticity modulus of PCC and GPC specimens was measured as shown in Figure 12. Concrete's compressive strength is inversely proportional to its elasticity. The elastic properties of the aggregates, curing conditions, and the age of the concrete to a lesser extent, mix proportions, and the type of binder material all influence the modulus of concrete. According to IS 456-2000, the short-term static modulus of elasticity (Ec = 5000 fck) obtained theoretically may differ by as much as 20% from actual values measured in tests (MPa). The elasticity modulus of the GPC mix was found to be higher than that of the PCC mix in the tests. The importance of NaOH molar concentration [17] and flyash class was given to the significant elasticity modulus performance. Flexibility increased from PCC-M30 to GPC-F14M over time. The increase in compressive strength of PCC-M30 to GPC-F14M may be a factor.

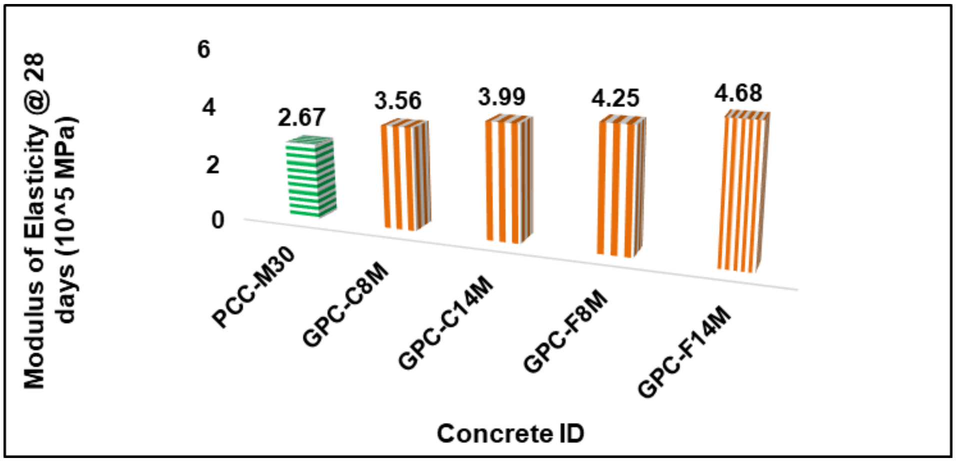


Figure 12. Elasticity Behaviour of PCC and GPC

7. CONCLUSION AND FUTURE WORK

From the comprehensive experimental investigation and test results, the effect of class of flyash, molar concentration of NaOH and age of curing period on the mechanical features of the geopolymer concrete in its fresh and toughened state was investigated and the ensuing conclusions are derived from its inferences:

- The workability of PCC mix was higher when compared to GPC mix as indicated by the slump values.
- The compressive strength of GPC mixes at 7 and 28 days was higher than PCC mix.
- The split tensile had a gradual increase in its strength from concrete mix series PCC-M30 to GPC-F14M.
- The flexure strength of GPC mix were higher than PCC mix and within the GPC mixes, class-C flyash mix had a slight edge over class-F flyash mix.
- The ultimate bond strength of PCC mix surpassed almost all the GPC mixes of 28 days strength in particular.
- The modulus of elasticity gradually increased from concrete mix series PCC-M30 to GPC-F14M.
- In overall, GPC incorporating industrial waste by-products possessed excellent mechanical properties to be used as an alternative concrete making material in the place

of conventional concrete materials that depletes the natural resources affecting the environment.

- For future work, NDT shall be carried out to validate the mechanical properties test results obtained through destructive tests. In addition, the NaOH molar concentration for 8M, 10M, 12M, 14M shall be carried out individually for the two classes of flyash to study its performance. The ratio of Na2SiO3 to NaoH and Alkali Activator Solution to Binder ratio shall be appropriately changed and tested for its performance.

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