

Geopolymer Concrete Optimization Investigating the Influence of Pozzolanic Minerals and Slag Binder Combination on Workability and Mechanical Strength Characteristics at Ambient Temperature

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ABSTRACT

Due to its environmental benefits and promise as a long-term alternative to standard concrete construction, geopolymer concrete (GPC), also known as earth friendly concrete, has been the subject of continuous study. Detailed studies focusing on the influence of all design mix elements on the fresh and strong properties of GPC, on the other hand, are still absent. In terms of field use, GPC is still a relatively new material that has yet to attract general acceptance as a building material. As a result, in order to push this relatively new material technology to field and site applications, extensive research must be done to acquire more reliable information. The goal of this research is to provide a comprehensive assessment of the parameters influencing the fresh and hardened properties of ambient cured fly ash and slag-based geopolymer concrete (FS-GPC). To manufacture ambient cured FS-GPC, manufacturing by-products such as fly ash from thermal power plants and ground granulated blast furnace slag from steel firms were employed. A series of research were conducted to investigate the effect of various the variables on the fresh and mechanical properties of FS-GPC, such as slag content (10, 20, 30, and 50%), the volume of Alkaline Activator Solution (AAS) (35 and 40%), Sodium Silicate (SS) to Sodium Hydroxide (SH) ratio (SS/SH = 2.0, 2.5, and 3.0), the concentration of sodium hydroxide (10 M, 12 M, and 14 M), and incorporating extra water. The slump cone experiment was used to evaluate the workability of the new FS-GPC mixtures. The mechanical characteristics of the mixes were evaluated using compressive strength, split tensile strength, flexure strength, and static modulus tests. The results demonstrated that increasing the slag concentration, NaOH solution molarity, and SS/SH ratio considerably affects the workability of FS-GPC. By raising the molarity of the NaOH solution and slag concentration while decreasing the AAS content from 40% to 35%, compressive strength was enhanced. The effect of the SS/SH ratio on the mechanical properties of FS-GPC, on the other hand, varies. The incorporation of more water in order to enhance the workability of the GPC matrix reduced compressive strength. Prior study equations for predicting tensile and flexural strength and elastic modulus of FS-GPC blends were also validated. Empirical calculations for estimating the splitting tensile strength, flexural strength, and elastic modulus of ambient cured FS-GPC are proposed according to the results of this study's experiments. Acceptable FS-GPC blends in terms of workability and mechanical qualities have been suggested as well for use in field applications.

Keywords: Ambient curing, Alkali Activator Solution, Class-C High calcium flyash, Geopolymer, Ground Granulated Blast-Furnace Slag, Mechanical properties, Workability, Blending, Binder material.

1. INTRODUCTION

Due to growing infrastructure demand, the building industry has surged significantly during the last two decades. Cement is without a doubt the most widely used material in every aspect of construction. Over two billion metric tons of cement are produced worldwide each year, in accordance with estimates [1]. Cement manufacture has a significant environmental impact due to Greenhouse Gas (GHG) emissions. As a result, the cement manufacturing industries are responsible for huge amounts of CO₂ emissions into the atmosphere due to energy consumption, i.e., fuel and raw material conversion. According to one study, producing one ton of cement requires 1.6 tons of raw materials, resulting in the release of one ton of CO₂ into the atmosphere [2]. Only the cement industry contributes 7-8% of total greenhouse gas emissions. As a result, serious environmental issues about the production of Ordinary Portland cement

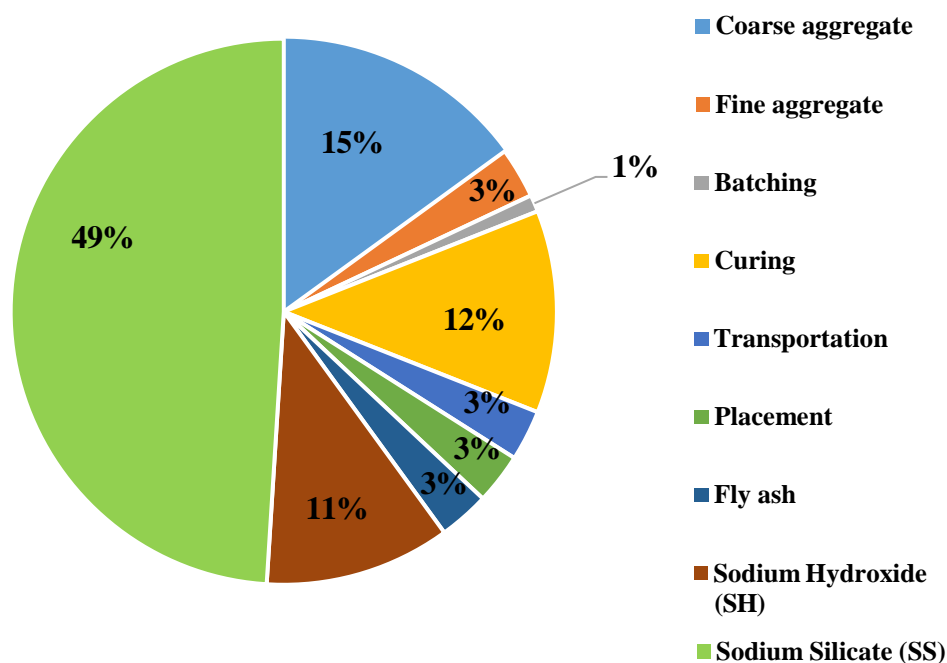
(OPC) have lately been highlighted. As a result, scientists are striving to replace standard OPC with ecologically harmless compounds that have similar properties to OPC. Apart from the emission of greenhouse gases, there has been a significant growth in the production of industrial by-products and waste materials such as Fly Ash (FA), molten slag, silica powders, lime stone dust, and ceramic wastes [3,4]. Fly ash, for instance, is a fine powder formed as an outcome of pulverized coal combustion in power plants [5].

However, since fly ash is not used in all developing countries, the end result is frequently an unusable material that is deposited into landfill sites. The average overall utilization rate of fly ash, which is mostly utilized in building materials, in China, for example, is 70% [4]. There are various concerns with fly ash, including the requirement for a large quantity of land for disposal. In a similar manner slag is a by-product of the steel and iron companies that is produced during the iron and steel burning process, and it accounts for around fifteen percent of crude steel manufacture. Nevertheless, the bulk of emerging nations do not use steel slag entirely. In accordance with World Iron and Steel Association data, China's crude steel output in 2019 was 996 million tons, meaning that steel slag emissions could have reached 100 million tons, despite China's complete utilization rate of steel slag being only about 25% [6]. For environmentalists and academics, the disposal or control of these contaminants, as well as the establishment of substitutes to standard OPC, has become a challenging endeavour [2]. The traditional strategy is to develop superior and more viable technologies that can employ these products to make binding substances like OPC. This will help to resolve the issues associated with the management of these products, preserving earth's resources while mitigating the consequences of global warming. Geopolymer Concrete (GPC) is one way for completely eliminating the need of cement while simultaneously encouraging the efficient use of these resources [7-9]. There is no doubt about the positive environmental impact of using geopolymer concrete over ordinary concrete because it reduces the release of greenhouse gases during cement manufacturing [10,11]. However, the environmental benefits and outcomes of GPC Life Cycle Assessment (LCA) vary depending on a range of factors and vary by location. Numerous studies have concluded that geopolymer concrete has environmental advantages [7,8,12]. Meshram and Kumar (2021) carried out a comparative LCA of GPC and OPC manufacturing in the Indian context. The usage of GPC reduces the consumption of energy, carbon dioxide emissions, and total budget due to the efficient utilization of by-products/waste materials, making it a material that is beneficial to the environment [7,13,17,18]. These emissions, nevertheless, vary based on location and mix, and are influenced by a variety of factors such as location, curing, transit distance from the raw materials, and activator solution manufacturing. Figure 1 [8] illustrates the contribution to CO₂ emissions as a percentage of the total of each ingredient/activity for GPC and OPC/conventional concrete, from raw material procurement to curing of 1 m³ of concrete.

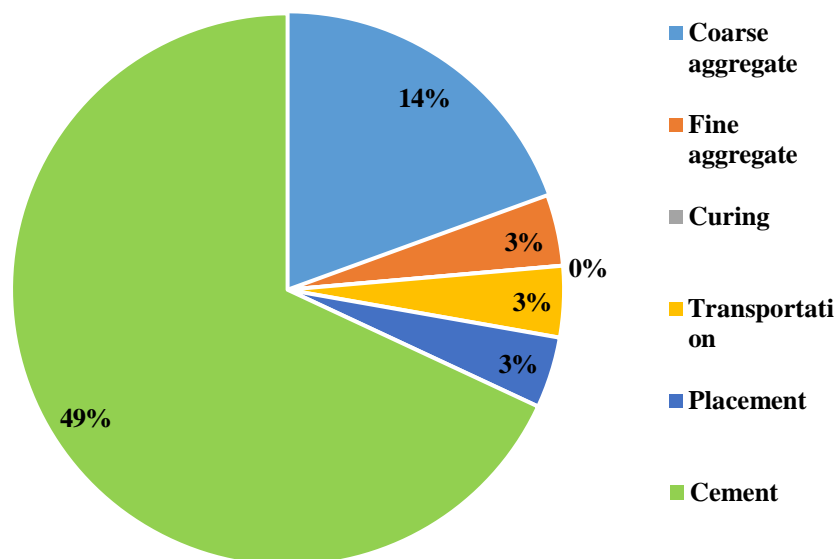
This is a typical CO₂ emission scenario for a specific mix design and location. The estimations reported here were based on the processes associated with the production of 1 m³ of Grade 40 concrete (i.e., compressive strength of 40 MPa) in Australia's Melbourne Metropolitan region, which included materials that were readily accessible, manufacturing, and building techniques. The OPC is by far the most significant source to emissions, accounting for 76.4% of the carbon dioxide (CO₂) released in average concrete. The geopolymer binding agents (Fly Ash + Sodium Silicate (SS) + the sodium hydroxide (SH)) accounts for 63% of total emissions in the GPC. By weight, the geopolymer binder releases 201 kg of CO₂, which is 25% less than the OPC binder (269 kg of CO₂ emissions) in traditional concrete. The alkali activators required for GPC synthesis need a significant amount of energy. Total CO₂ emissions from sourcing to curing of OPC/conventional concrete and GPC are estimated to be 354 kg and 320 kg, respectively [8]. The elevated temperature (40-80 C) curing of the GPC for at least 6 h to achieve strength similar to the OPC concrete generates a significant variance in pollutants during both concrete curing processes. CO₂ emissions during curing operations, on the other hand, can be reduced to less than 1 kilogram by improving ambient conditions during curing in the GPC structure. When ambient curing conditions are included, the overall carbon dioxide emissions for the GPC construction would be 281 kg, which is 21% less than the CO₂ emissions of traditional concrete (per cubic meter) in this specific example. When heat curing has been carried out at temperatures ranging from 60 to 100 degrees Celsius, GPC is found to have superior strength and durability than OPC concrete [19,20]. Thermal curing of GPC at severe temperatures, as demonstrated by Wallah and Rangan (2006), results in greater compressive strength than ambient curing [21]. Heat curing of GPC may be possible for precast concrete piece manufacture. Such curing Under certain circumstances, however, may make in situ application of

GPC challenging. Ingredients with a high calcium concentration, which include slag, can be used to improve the reactivity of FA, allowing GPC application for in situ building. When slag is added to FA-based GPC, it produces geopolymeric gel as well as Calcium Silicate Hydrate (C-S-H). These hydrates help to establish GPC at a comfortable temperature and improve its mechanical properties [22]. Several studies on GPC have been undertaken, with FA and SG serving as source materials [19-23]. Okoye et al. (2015) concluded that increased temperature drying is the best choice for developing a stronger GPC by experimenting with various dosages of silica fume in combination with fly ash and metakaolin [23]. Lee et al. [24] created and examined the physical/mechanical characteristics of marble-based geopolymer concrete. Geopolymer concrete constructed from marble was determined to be a viable material for use in applications related to engineering. Hadi et al. (2019) researched into the impacts of several parameters on the compressive strength, setting time, and workability of geopolymer pastes [25]. The best mix design of geopolymer paste was identified to contain SG content of 40% and AAs content of 50% based on compressive strength, setting time, and workability test findings. The study's key limitation is that it concentrated on geopolymer cement pastes to discover the best composition.

Furthermore, different amounts of alkaline stimulating solution were not taken into account. The outcome of slag concentration on the properties of ambient cured FS-GPC paste blends may be influenced by the molarity of the NaOH solution. Aliabdo et al. (2019) [26] studied the effect of many variables on the mechanical characteristics of alkali activated blast furnace slag concrete. The primary limitation of this investigation is that the specimens were cured using heat. The results of this study may differ from those of ambient cured samples. Furthermore, because only slag was used as a source material in this investigation, these findings are not applicable to the alkali activated fly ash and slag combined geopolymer concrete. Bellum et al. (2019) studied the mechanical properties of fly ash and slag-based alkali-activated geopolymer concrete [27]. GPC mixtures containing 30% fly ash and 70% slag perform better at 14 M of NaOH after being cured in an oven for 24 hours at 70 degrees Celsius. Nevertheless, should be noted that the ambient curing conditions were not considered while estimating the proper slag amount and NaOH molarity. Additionally, the optimal combinations should have an alkaline activating solution content and an alkaline solution SS/SH ratio. To augment the present understanding base, detailed study such as the current one is necessary, with a focus on assessing the effect of every pertinent variable on the fresh and mechanical properties of GPC.



(a) Geopolymer Concrete (GPC)



(b) Conventional Concrete (OPC)

Figure 1. The individual contribution of ingredients and activities to CO₂ Emissions: A comparative study for one cubic meter of Geopolymer Concrete (GPC) and Ordinary Portland Cement (OPC) concrete production

The two widely accepted requirements for producing OPC mixtures for concrete are workability and compressive strength. GPC's mix fraction, on the other hand, is not as similar to OPC's. The mix design technique is more sophisticated due to the fact that are more components that contribute to the production of GPC. The ratio of cement, coarse and fine aggregates, the water-cement ratio, cement fineness, aggregate gradations, and other factors all contribute to the strength of OPC concrete. The amount of strength of a GPC mix will usually be dependent on various components and their ratios, such as the type of source components used, such as FA, SG, and alkaline activators, activating solution content, curing methods, mixing procedure, alkaline solution focused attention, and so on; therefore, designing it against an established objective strength is difficult. In the context of field use, GPC is still a relatively fresh substance that has yet to garner general acceptance as a building material. As a result, it is necessary to undertake thorough research that consider all of the critical properties for the purpose to gather a great amount of knowledge about the material and extend this relatively novel materials technology to field and site applications.

The goal of this research is to provide a comprehensive assessment of the key factors impacting the workability and mechanical properties of fly ash and slag-based geopolymer concrete (FS-GPC). Mechanical properties investigated in the current research included compressive strength, tensile strength, flexural strength, and modulus of elasticity. This study utilized into consideration the effect of ground granulated blast furnace slag (SG) content (10, 20, 30, and 50%), amount of alkaline activator solution (35 and 40%), sodium silicate to sodium hydroxide ratio (SS/SH = 2.0, 2.5, and 3.0), sodium hydroxide molarity (10, 12 M, and 14 M), and a further amount of water in order to enhance workability. FS-GPC combinations were created for general concreting requirements such as columns, beams, and foundations. The findings of this investigation can be used to develop a specific strength blend of FA and SG combined GPC. All mix design elements can be employed to regulate the needed fresh and strength attributes of FS-GPC. This study will help building experts get the desired fresh and mechanical properties of FS-GPC by adjusting various mix design factors. Furthermore, mathematical formulae based on compressive strength were suggested to predict the splitting tensile strength, flexural strength, and static modulus of elasticity of ambient cured FS-GPC. The following formulas can be used for predicting the tensile, flexural, and modulus of elasticity of FS-GPC composites with compressive strengths ranging from 30 to 60 MPa after 28 days.

2. LITERATURE REVIEW

M. Sofi et al. (2007) tested the engineering properties of Inorganic Polymer Concrete (IPC) using various sources of Class-F flyash together with GGBS in the mixes. The mix designs and testing were carried out

in accordance with the applicable Australian Standards, and the findings were found to be in accordance with the Standards' projected results. As reported by X. Guo et al. (2010), shortly after 7 days of initial heat curing and subsequent 28 days of ambient curing, a geopolymer made with class-C flyash, an alkali activator (sodium hydroxide and sodium silicate solution) ratio of 1.5, and a sodium hydroxide to flyash ratio of 10% generated a compressive strength of literally 63 MPa. K. Somna et al. (2011) studied the compressive strength performance of a geopolymer paste that utilized ground fly ash (GFA) activated by NaOH solutions ranging from 4.5 to 14M in molar concentration. After 28 days, the compressive strength was 20 to 23 MPa at molar concentrations of 9.5-14M, with each increase in concentration significantly decreasing the paste strength due to aluminosilicate product precipitation. N.K. Lee et al. (2013) studied the mechanical and setting attributes of room-temperature alkali-activated flyash/slag concrete. The setting time decreased as the total amount of slag and NaOH solution rose, corresponding to the test results. The optimal slag content was maintained at 15-20% of total binder weight, giving in a faster setting time and increased compressive strength. However, the alkali-activated flyash/slag concrete's split tensile strength and modulus of elasticity were slightly reduced than those specified by the ACI and Euro codes. A.M. Rashad (2014) investigated Alkali Activated Fly Ash (AAFA) as a potential alternatives binder material to Portland Cement (PC). When comparison to the manufacturing process of Portland cements, the benefits of AAFA include lower energy consumption, lower greenhouse gas emissions, and less exploration of natural resource material. Additionally, the AAFA showed potential resistance to strong acids, sulfate attacks, alkali-aggregate reaction, and high temperatures. The inclusion of fibers, chemical compounds, admixtures of minerals, and additives will improve the particular characteristics of the AAFA system. J.G. Jang et al. (2014) reported on the characteristics of fresh and hardened characteristics of alkali-activated flyash/slag pastes made using a variety of slag-binder ratios and combined with different percentages with two types of superplasticizer (polycarboxylate-based and naphthalene-based). The results of the experiments demonstrated that autogenous shrinkage resulted in enhanced compressive strength, faster setting, and the development of cracks. In terms of preventing effect, heat of hydration, and workability, polycarboxylate-based superplasticizer exceeded naphthalene-based superplasticizer. W.C. Wang et al. (2015) investigated the intrinsic nature of geopolymer materials derived from industrial waste disposal as an alternative, eco-friendly, and cost-effective material when compared to traditional concrete materials derived from natural resources. The geopolymer was created using both fixed and variable parameters. The liquid-solid ratio was kept constant, while the other parameters, such as flyash replacement with slag, alkali-activator solution ratio, and number of days of specimen curing, were adjusted as suggested. The main conclusion drawn from the test findings was that increasing the alkaline solution enhanced the workability (in terms of slump and flow values), compressive strength, and ultrasonic pulse velocity. However, lowering the alkalinity always resulted in a shorter setting time. Y. Zhou et al. (2015) conducted an experimental investigation as well as an analytical study on the variables that influence the mechanical characteristics (prismatic compressive strength (f_c), static modulus of elasticity (E_c), and dynamic modulus of elasticity (E_d)) of concrete (volume content of aggregates, maximum size and type of coarse aggregates, water-to-cement ratio, and curing temperature).

Using multiple regression analysis, an expression consisting of coefficients of linear connection linking compressive strength and elastic moduli was obtained in the analytical investigation. The results demonstrated that aggregate volume content had a significant impact on the relationship between compressive strength and elastic moduli. S. Saha et al. (2017) made an ongoing effort to develop a flyash-based geopolymer as an effective and efficient replacement for the cement binder used in Portland cement concrete. As a result, it was discovered that flyash requires longer time to set. To address this practical issue, different percentages of flyash were replaced with slag elements. The results of the tests revealed improved performance in both setting and compressive strength. Guohao Fang et al. (2018) studied the workability and mechanical characteristics of freshly mixed Alkali Activated Flyash Slag (AAFS) concrete cured at room temperature to identify the appropriate mix concentration for engineering properties. According to the new concrete test results, as slag content and molar concentration of Sodium Hydroxide (NaOH) increased, it also improved workability and setting time. According to the hardened concrete test findings, increasing the slag content and NaOH molar concentration increased compressive strength while decreasing the alkaline activator to binder ratio.

3. MATERIALS

3.1 Binder Materials

The ordinary Portland cement of 53 grade according to IS 8112-2013 with an average particle size of 10 microns was used as a binding agent in the production of Ordinary Portland Cement concrete (OPC). Flyash (Class-C type / high-calcium) according to IS 3812, Ground Granulated Blast Furnace Slag (GGBS) according to IS 12089, Metakaolin, and Silica fume were utilized as binder components in the creation of Geo Polymer Concrete (GPC) to replace traditional Portland cement. The manufacturer's binder materials are evaluated in various amounts and combinations, as stated in Table 1.

Table 1. Binder Mixture (BM)

BM-1 = 25% Flyash+25% GGBS+25% Metakoline+25% Silicafume
BM-2 = 30% Flyash+30% GGBS+20% Metakoline+20% Silicafume
BM-3 = 35% Flyash+35% GGBS+15% Metakoline+15% Silicafume
BM-4 = 40% Flyash+40% GGBS+10% Metakoline+10% Silicafume

Table 2 provides the attributes of flyash reported by the manufacturer. Depending on the proportion of CaO in the flyash, it can be classified as high-calcium or low-calcium. High-calcium class-C flyash was chosen as the Pozzolona binder material in this investigation, which is sufficient with ambient or room curing (30°C). This class-C flyash, which includes more than 10% CaO, is frequently created by burning lignite or sub-bituminous coal. The microscopic structure of flyash reveals that solid spherical particles, specifically silica glass, have particle sizes ranging from 1m to 100 m. The surface area of the particles ranges between 300 and 400 m²/kg. The use of flyash is encouraged due to its durability, economy, and energy-saving properties. The use of high-quality flyash reduces the amount of water necessary for the projected collapse. When the water content of the fabric is reduced, bleeding and drying shrinkage are reduced. Furthermore, because flyash is a largely non-reactive mineral, the heat of hydration is minimized. When employed as a binder material in concrete, flyash produces strength due to its pozzolanic reactivity, however not immediately rather over time through a continual reaction process. As a result, longer curing times are required. The pozzolanic reaction is responsible for the dense texture of concrete, which reduces water and gas permeability. The use of flyash concrete has been found to help under water structures by improving long-term strength and water-tightness.

Table 2. Properties of Flyash Class-C

[Source: www.astrrachemicals.in]

Physical Properties	Results	Chemical Composition	Results
Specific Gravity	1.92	SiO ₂	35.7%
Fineness	372 m ² /kg	Al ₂ O ₃	15.8%
Initial Setting Time	35 mints	Fe ₂ O ₃	16.1%
Final Setting Time	548 mints	CaO	34.85%
		Na ₂ O	0.46%
		K ₂ O	1.85%
		TiO ₂	0.16%
		MgO	0.19%
		SO ₃	0.04%
		LOI	1.11%

Table 3 lists the parameters of silicafume supplied by the manufacturer. The most frequent mineral addition in high strength concrete is microsilica or silicafume. Densified silica fume or micro silica is a very reactive and potent pozzolanic material due to its small particle size and high purity of SiO₂ (99.5%) composition. Adding to the concrete mix improves workability, compressive strength, and impermeability while making the concrete resistant to chemical assaults, abrasion, and reinforcing corrosion. It is utilized in the manufacture of high strength and high performance concrete, such as bridges, where both strength and durability are required. It can be used to construct marine constructions because it decreases the damage produced by the reaction of chloride and other chemicals. It protects steel from rust and corrosion and extends the life of the construction. 7-10% of the cement weight applied to the concrete is the appropriate dosage.

Table 3. Properties of Silicafume

[Source: www.astrrachemicals.in]

Physical Properties	Results	Chemical Composition	Results
Physical state	Micronized powder	(SiO ₂)	99.886%
Odour	Odourless	(Al ₂ O ₃)	0.043%
Appearance	White color powder	(Fe ₂ O ₃)	0.040%
Colour	White	(TiO ₂)	0.001%
Pack density	0.76 gm/cc	(CaO)	0.001%
pH of 5% solution	6.90	(MgO)	0.000%
Specific gravity	2.63	(K ₂ O)	0.001%
Moisture	0.058%	(Na ₂ O)	0.003%
Oil absorption	55 ml/100gms	Loss on Ignition	0.015%
		Lead (Pb) Heavy	0.000%
		Arsenic (As) Metals	0.000%

Table 4 shows the characteristics of metakaolin furnished by the manufacturer. Metakaolin formed from the calcination of clay appears white or cream in color, with significant pozzolanic reactivity, and the reduction in Ca (OH)₂ occurs as soon as possible. It is ground so finely that it obtains a fineness of 700-900 m²/kg.

Table 4. Properties of Metakaolin-Grade A

[Source: www.astrachemicals.in]

Physical Properties	Results	Chemical Composition	Results
Colour brightness	93.5%	(SiO ₂)	52.0%
Yellowness	2.1%	(Al ₂ O ₃)	46.0%
-2 Micron w/w (min)	90%	(Fe ₂ O ₃)	0.60%
+500 Mesh w/w (max)	0.028%	(TiO ₂)	0.65%
Moisture w/w (max)	-	(CaO)	0.09%
pH (10% suspension)	5.5-6.5	(MgO)	0.03%
Bulk density	0.4-0.5 kg/lit	(K ₂ O)	0.03%
Specific surface area	10-12 m ² /g	(Na ₂ O)	0.10%
Oil absorption	45-55 g/100g	Loss on Ignition	0.50%
Specific gravity	2.6		
Retained on 500 mesh	0.05%		

Table 5 lists the attributes of GGBS as supplied by the manufacturer. GGBS is utilized in the construction of long-lasting concrete buildings when combined with normal Portland cement and/or other pozzolanic additives. GGBS has been widely used in many nations throughout Europe, Asia, and America due to its greater concrete durability, expanding the lifespan of constructions from fifty to hundred years. The most common uses of GGBS include the production of high-quality upgraded slag cements (Portland Blast Furnace Cement-PBFC and High Slag Blast Furnace Cement-HSBFC) with GGBS contents ranging from 30 to 70%, as well as the production of ready-mixed or site-batched durable concrete. GGBS concrete requires longer to set than conventional cement concrete made with Portland cement, depending on the amount of GGBS in the cementitious ingredient. However, in industrial settings, it continues to gain strength over time. As a result, the heat of hydration is lowered and temperature rises are controlled, making it simpler to avoid the formation of cold joints. Nonetheless, it has an impact on construction schedules if a quick installation is required. The use of GGBS reduces the risk of alkali-silicate reaction damage, increases resistance to chloride infiltration, decreases the risk of reinforcing corrosion, and increases resistance to sulphate and other chemical-based attacks.

Table 5. Properties of Ground Granulated Blast Slag (GGBS)

[Source: www.astrachemicals.in]

Characteristics	Unit	Requirement as Per BS:6699	Test Result
Fineness	m ² /kg	276 (min)	391
Specific gravity	-	-	2.86
Cumulative particle size	%	46 micron	97.10
Insoluble residue	%	1.6 (max)	0.49
Magnesia content	%	15 (max)	7.73

Sulphide sulphur	%	2.1 (max)	0.50
Sulphite	%	2.6 (max)	0.38
Loss on ignition	%	3.1 (max)	0.26
Manganese	%	2.1 (max)	0.12
Chloride	%	0.11 (max)	0.009
Glass	%	68 (min)	91
Moisture	%	1.1 (max)	0.10
Chemical Moduli			
a. CaO + MgO + SiO ₂		66.66 (min)	76.03
b. [CaO + MgO] / SiO ₂		> 1.0	1.30
c. CaO / SiO ₂		< 1.40	1.07

3.2 Aggregates

The fine aggregate characteristics used in the manufacturing of OPC complied with IS 383:1970. The fine aggregate was created using a locally available natural river sand with a specific gravity of 2.67, particle size ranging from 75 μ m to 5 mm, and grading zone II. For the production of GPC, M-sand from local stone quarries was used, which had characteristics comparable to river sand. The coarse aggregate parameters employed in this investigation for both OPC and GPC were in compliance with IS 383:1970. The crushed granite stone aggregate had a specific gravity of 2.63 with particle sizes ranged from 7 to 20 mm.

3.3 Water

According to IS 456:2000, water used for mixing and curing must be pure and devoid of hazardous ingredients such as oils, acids, alkali salts, sugar, organic compounds, or other chemicals that may be harmful to concrete or steel. Water should also be free of non-filterable residue, volatile and fixed residue, acidity, alkalinity, sulphate, and chloride, according to IS: 3025 standards. As a result, potable water with a pH of 6.5 was used in the manufacture of OPC.

3.4 Alkali-Activator Solution (AAS)

The Alkali-Activator Solution (AAS) was made with a 14M molar concentration of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solution in a 1.0 ratio. This solution was first combined with the binder components to create the geopolymer paste, and then with the aggregates to create the geopolymer concrete. Table 6 shows the parameters of sodium hydroxide as determined by the supplier's test findings.

Table 6. Properties of Sodium Hydroxide (NaOH)

[Source: www.astrachemicals.in]

Constituents	Unit	Test Result	Limits
Sodium Hydroxide as NaOH by mass	%	99.77	99.6 min
Sodium Carbonate as NaCO ₃ by mass	%	0.22	0.41 max
Chlorides as NaCl by mass	%	0.03	0.11 max
Sulphates as NaSO ₄ by mass	%	0.005	1.11 max
Silicate as SiO ₂ by mass	%	0.005	0.03 max
Iron as Fe	ppm	7	21 max
Copper as Cu	ppm	BDL	2.1 max
Manganese as Mn	ppm	BDL	1.1 max
Chlorates and percolates as NaCO ₃	ppm	1.1	11 max
Matter insoluble in water by mass	%	0.02	0.06 max

Table 7 shows the parameters of sodium silicate liquid (alkaline) as determined by the supplier's test findings.

Table 7. Properties of Sodium Silicate Liquid (Na₂SiO₃)

[Source: www.astrachemicals.in]

Constituents	Unit	Test Result	Limits
Total soluble Na ₂ O	-	14.21	13.7-14.3
Total soluble SiO ₂	-	31.13	28-33
Specific gravity	-	1.55	1.47-1.56
Viscosity	CPS	185	150-200
pH	-	11	11 min

Cl	-	0.02	0.05 max
Molar ratio	-	2.19	2.1-2.3
Technical Specification	Unit	Neutral Grade	Alkaline Grade
Appearance		Hazy colourless	Viscous translucent
Total alkalinity expressed as Na ₂ O by mass	%	9.00 +/- 1.00	15.00 +/- 1.00
SiO ₂ soluble silicate		29	33
Total soluble silicate by mass	%	38.00 +/- 1.00	48.00
Total alkalinity (Na ₂ O) to total soluble silica (SiO ₂) ratio i.e. (Na ₂ O : SiO ₂)		1:3.2	1:2.2
Specific gravity		40 +/- 1	50 +/- 1

3.5 Workability admixture

An additive for mortar or concrete that imparts extremely high workability or allows for a significant reduction in water content for a given workability. Superplasticizer-CONPLAST'430 was utilized at 0.60% by weight of total binder material to minimize water content and provide desired workability with projected slump values ranging over 100 mm.

4. METHODS

4.1 Mix Design

The compressive strength of 30 MPa was the goal of the concrete mix design. In order to obtain promising outcomes regarding the degree of workability and compressive strength of GPC, appropriate ingredients such as fly ash quantity and fineness, water quantity, fine aggregate grading, and fine to total aggregate ratio were thoroughly analysed and incorporated into the mix design process. These criteria aided in the design of flyash-based GPC to match the mix design of OPC as specified in IS 456-2000 [20]. When the setting time and compressive strength were controlled by the water-to-solid ratio, the amount of paste volume, water content, and precursor blend all had a substantial impact on the GPC mix, and the addition of GGBS content resulted in higher strength [21]. In this investigation, several percentages and combinations of pozzolanic (Flyash, Metakaolin, Silicafume) and slag (GGBS) binders were coupled to forecast their performance in terms of workability and strength. In this work, the mix design guidelines for pozzolanic and slag binders [20-21] were merged to produce a new formulation of mix proportions and quantities required for the test concrete specimens. To increase the workability of the GPC mix with a lower liquid-binder ratio, an appropriate superplasticizer was added as a percentage of the binder content to allow for easy flow of the concrete mixture. Table 8 summarizes the categorization of concrete mix types used in this investigation.

Table 8. Concrete Mix Types Categorization

Mix Type	Ingredient Mixture
OPC	Cement +FA(River sand)+CA+Water
GPC1	[25%FA+25%GGBS+25%MK+25% SF] + FA(M sand)+CA+Water+AA+SP
GPC2	[30% FA +30%GGBS+20% MK +20% SF] + FA(M-sand)+CA+Water+ AA + SP
GPC3	[35% FA +35%GGBS+15% MK +15% SF] + FA(M-sand)+CA+Water+ AA + SP
GPC4	[40% FA +40%GGBS+10% MK +10% SF] + FA(M-sand)+CA+Water+ AA + SP

Note: FA- Flyash, GGBS-Ground Granulated Blast Furnace Slag, MK- Metakoline, SF- Silicafume, FA-Fine Aggregate, CA-Coarse Aggregate, AA- Alkali Activator, SP- Superplasticizer

The mix proportions and quantities of OPC are given in Table 9.

Table 9. OPC Mix Proportions and Quantities

Material	Binder: Cement	FA: Sand	R.	CA: Stone	Gravel	Water @ 0.45 W/c	Superplasticizer
Quantity (kg/m ³)	426	648		1183		192	-Nil-
Proportion	1	1.86		3.0		.	.

The mix proportions and quantities of GPC are given in Table 10.

Table 10. Mix proportions and quantities of GPC

Material	Binder: FA+MK+SF+ GGBS	FA: M- Sand	CA: Gravel Stone	Sodium Hydroxide Solution (NaOH)	Sodium Silicate Solution (Na ₂ SiO ₃)	Extra Water @0.35	Super plasticizer CONPLAS T'430
Quantity (kg/m ³)	406	683.10	1268.70	70.98	70.98	29.56	2.44
Proportion	1	1.69	3.13

Note:

1. Molarity or Molar concentration of NaOH = 14M
2. Alkali Activator Solution (AAS) ratio = Na₂SiO₃ / NaOH = 1.0
3. AAS / Binder ratio = 0.35
4. Water to Binder ratio = 0.35 (added extra to the mix on moisture requirement)
5. Superplasticizer = 0.60% Wt. of Binder (added to the mix on workability criteria)

4.2 Casting and curing of specimens

Fresh concrete was put into well-prepared standard cube, cylinder, and prism moulds, compacted adequately, and kept in the moulds for 24 hours before demoulding. The samples were subjected to suitable curing conditions for 7 and 28 days. On OPC specimens, water curing was utilized. GPC samples were cured at room temperature (30°C) using class-C flyash binder combinations.

4.3 Testing of specimens

4.3.1 Fresh concrete workability properties test

To determine the workability of both OPC and GPC, a slump test for fresh concrete was performed for the specified design mixtures. According to IS 456-2000, the workability of concrete is always dependent on the concrete mix proportions that satisfy the parameters of compaction and placement of concrete. Concrete workability is tested in line with IS 1199-1959. The degree of workability assessed for structural components in this mix design of OPC and GPC, as per IS 456-2000, falls into the "Medium" category, with a slump value ranging between 75-100 mm.

4.3.2 Mechanical properties of hardened concrete testing

Concrete compressive strength was tested using cube specimens 150 x 150 x 150 mm, tensile strength was tested using cylinder specimens 150 x 300 mm, and flexural strength was tested using prism specimens 150 x 150 x 750 mm. A total of 120 specimens were evaluated (40 cubes, 40 cylinders, and 40 prisms). The concrete samples were held in the curing tank for 7 and 28 days to achieve maximum strength. The test technique for determining the compressive strength of hardened concrete was carried out in accordance with IS 516-1959, with regard to apparatus, age at test, number of specimens, procedure, calculation, and report. IS 5816-1999 was used to measure the indirect tensile strength of hardened concrete with regard to apparatus, age at test, number of specimens, process, calculation, and report. The test technique for determining the modulus of rupture of toughened concrete was carried out in

accordance with IS 516-1959, taking into account the apparatus, age at test, number of specimens, procedure, calculation, and report. The scope, apparatus, test specimens, test technique, bond stress calculation, and documentation of results for assessing the bond strength of toughened concrete were all carried out in accordance with IS 2270 (Part I)-1967. The test technique for determining the elasticity modulus of hardened concrete with extensometer attachment was carried out in accordance with IS 516-1959, with regard to specimen size, preparation of test specimens, age at test, apparatus, procedure, calculation, and report. IS 13311 (Part 1)-1992 was used to establish the concrete quality grading by cross probing pulse velocity on hardened concrete specimens subjected to varied curing conditions. Figure 2 displays hardened concrete specimen testing.



Figure 2. Test setup on Compressive strength, Split tensile strength, Flexural strength, Pull-out test and Modulus of Elasticity of concrete

5. TEST RESULTS AND DISCUSSIONS

The workability of fresh concrete obtained through slump measurements is presented in Table 11.

Table 11. Slump test results of fresh concrete

Mix Type	Slump Value (mm)
OPC	76
GPC1	74
GPC2	71
GPC3	75
GPC4	72

Table 12 displays the mechanical parameters of hardened concrete test results.

Table 12. Hardened concrete mechanical properties test results

Specimen- ID	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)		Bond Strength (MPa)		Elastic Modulus $\times 10^4$ (MPa)		UPV (km/s)	
	7D	28D	7D	28D	7D	28D	7D	28D	7D	28D	7D	28D
OPC	23.50	36.84	0.78	3.10	0.93	3.72	6.03	7.86	1.23	2.73	2.25	2.79
GPC1	18.22	22.37	1.42	5.66	0.30	1.20	7.62	9.91	1.73	2.82	2.43	2.86
GPC2	22.52	35.26	2.55	10.19	0.31	1.25	9.21	12.04	1.83	2.91	2.51	2.95
GPC3	28.15	48.77	3.18	12.73	0.38	1.53	10.5 8	14.30	2.78	3.10	3.22	3.76
GPC4	27.70	47.11	4.10	16.41	0.52	2.07	9.87	12.69	1.93	2.82	2.55	2.62

Note: D – No. of days of curing

5.1 Workability

The slump values of fresh concrete obtained through slump cone test is shown in Figure 3.



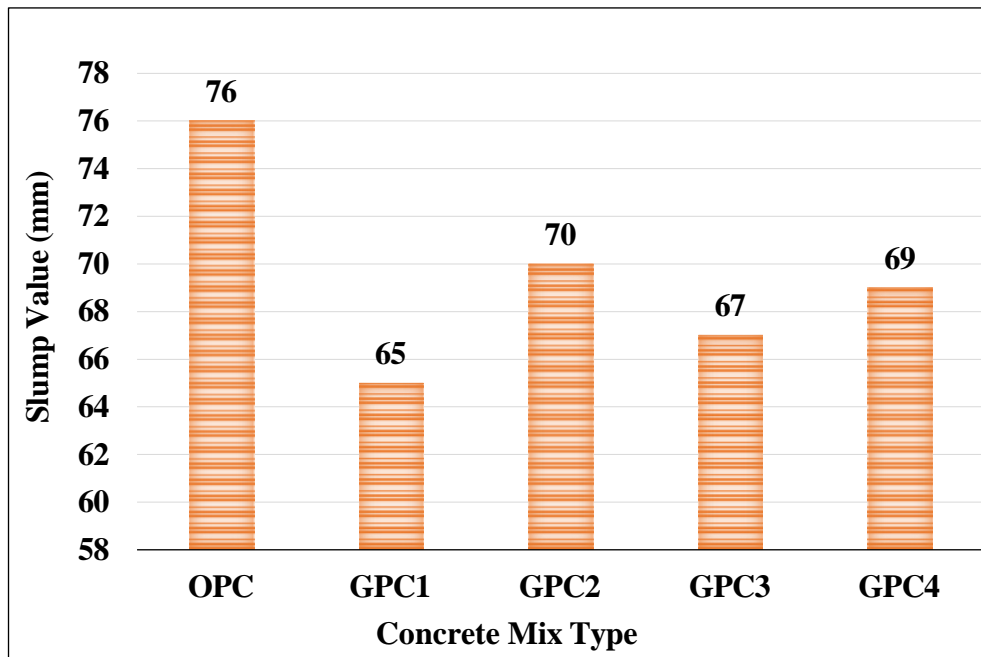


Figure 3. Slump test results

According to Figure 3, the slump value of OPC was 76 mm, which was within the degree of workability "Medium Workability" predicted in the mix design. Lower slump was seen in GPC mixtures because the binder mix included pozzolanic mineral and slag material. One explanation was the fast hardness of the GPC mixture, and the other was most likely owing to the lower amount of superplasticizer 0.60%. Furthermore, the activator to binder ratio of 0.35 in GPC may have contributed to lower slump readings when compared to OPC. Increase the proportion of superplasticizer to overcome the difficulties in workability of GPC mix. As a result, several parametric trial modifications must be used to achieve the desired workability and setting of concrete.

5.2 Compressive Strength

The compressive strength values of hardened concrete determined by compression testing on cube specimens are shown in Figure 4.



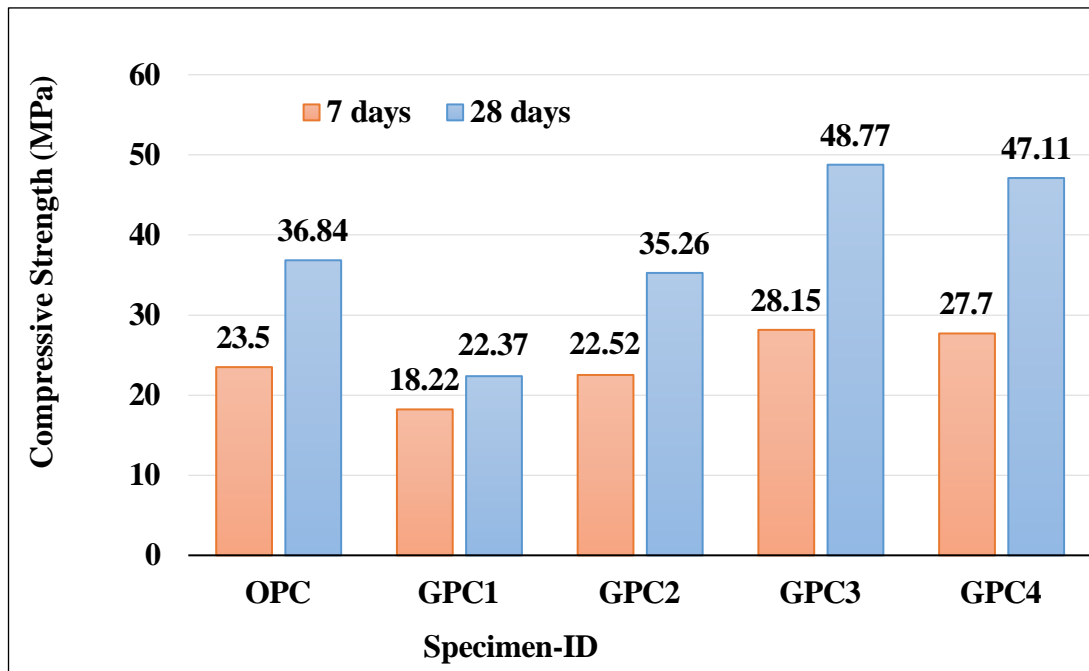


Figure 4. Concrete failure specimen compressive strength and test results

These values represent the ability of each concrete mix to withstand compressive forces at different curing times. The data provides insights into the development of strength over time for different cement formulations. Generally, higher compressive strength values indicate better performance in terms of the concrete's ability to support loads. Except for GPC1, the compressive strength of GPC mixes was virtually equivalent to that of OPC mixes (Figure 2). GPC3 had the highest compressive strength of the four GPC mixtures after 7 and 28 days of curing. GPC3's 7-day strength was 28.15 MPa, which was higher than OPC's strength of 23.5 MPa, resulting in a 19.78% increase in strength above OPC. Similarly, the 28-day strength of GPC3 was 48.77 MPa, which was greater than the 36.84 MPa strength of OPC, and so the percentage increase in strength of GPC3 was 32.38% when compared to OPC.

5.3 Split Tensile Strength

Figure 5 depicts the indirect tensile strength values of hardened concrete acquired from split tension tests on cylinder specimens.



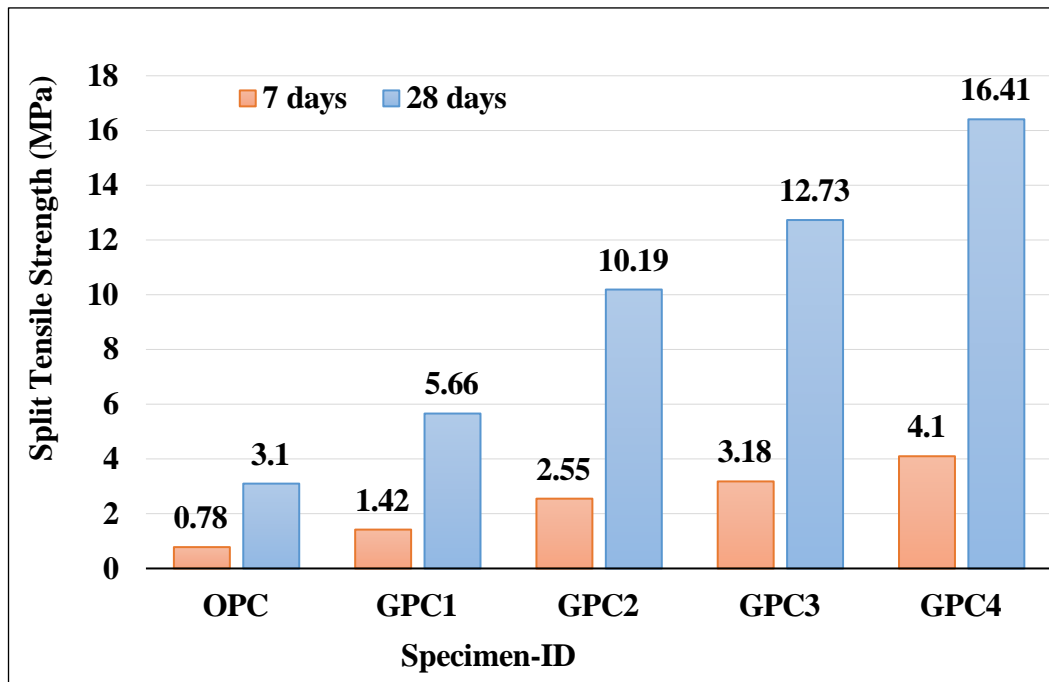


Figure 5. Concrete failure specimen split tensile strength and test results

Figure 5 indicates that the indirect tensile strength of GPC mixes gradually increased as compared to OPC mixes over 7 and 28 days. After 7 and 28 days of curing, GPC4 exhibited the highest tensile strength of the four GPC mixes. GPC4's 7-day strength was 4.1 MPa, which was higher than OPC's strength of 0.78 MPa, resulting in a 425.64% increase in strength when compared to OPC. Similarly, the GPC4 28-day strength was 16.41 MPa, which was higher than the OPC strength of 3.1 MPa, and so the percentage increase in strength of GPC4 was 429.35% when compared to OPC.

5.4 Flexural Strength

Figure 6 depicts the modulus of rupture of hardened concrete achieved from flexure testing on prism specimens.



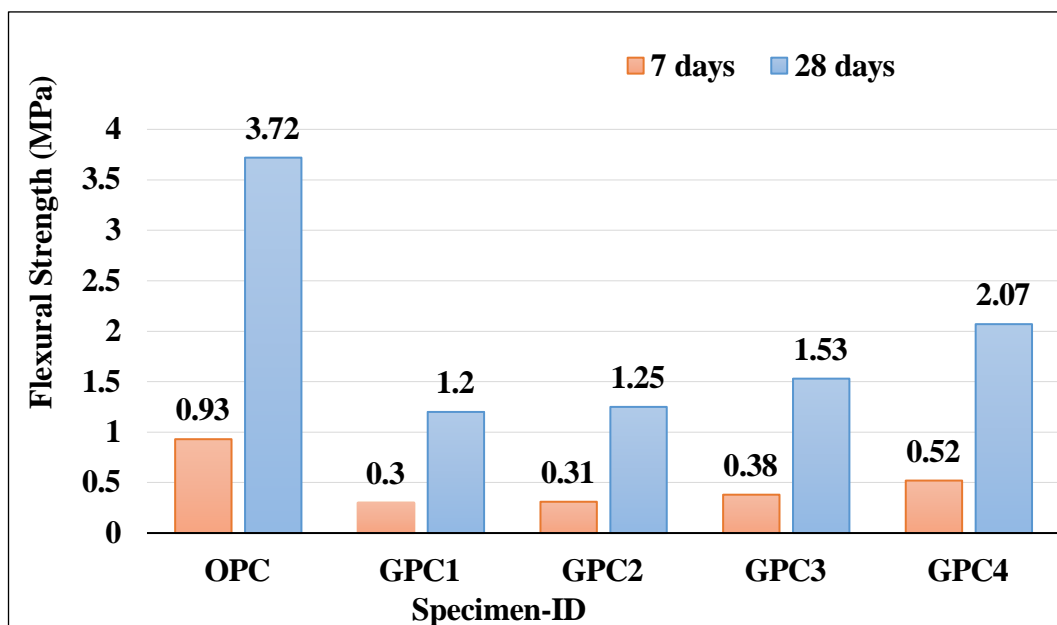


Figure 6. Flexural strength of concrete failure specimen and test results

Figure 6 shows that the flexural strength of GPC mixes is much lower than that of OPC mixes at both 7 and 28 days' strength. Flexural strength is lowered in all four types of GPC mixtures. The flexural strength of OPC after 7 and 28 days was 0.93 MPa and 3.72 MPa, respectively, whereas the strength of GPC mixes ranges between 0.30-0.52 MPa and 1.2-2.07 MPa. The GPC mix, which increased compressive strength, was plainly brittle and less ductile, and hence failed miserably to achieve higher flexural strength.

5.5 Bond Strength

Figure 7 displays the hardened concrete bond strength as assessed by a pull-out test on implanted rod cube specimens.



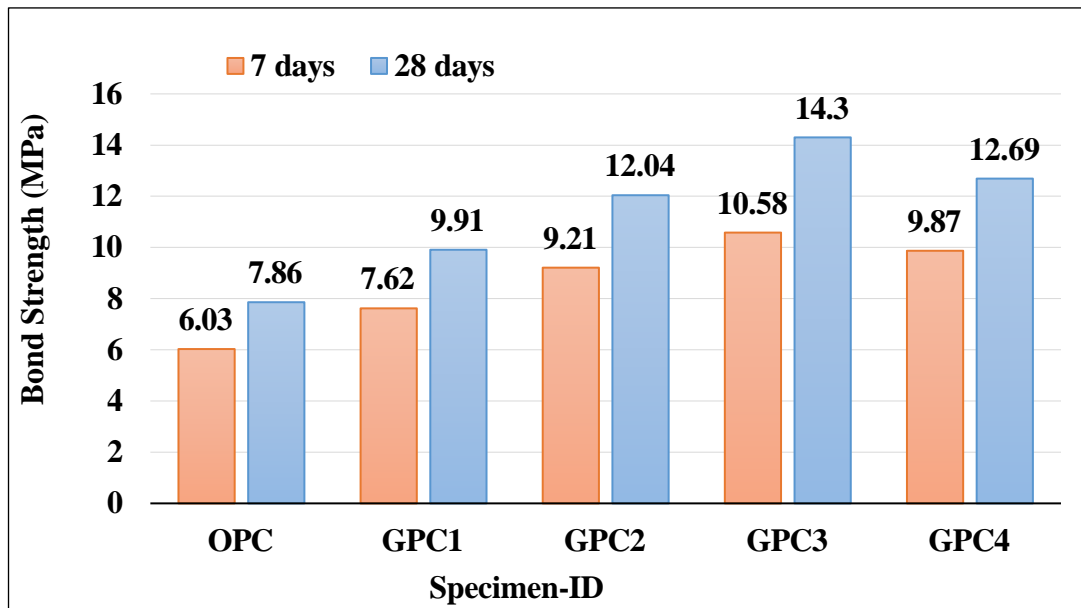


Figure 7. Bond strength of concrete failure specimen and test results

Figure 7 shows that the binding strength of GPC mixes was higher than that of OPC mixes after 7 and 28 days. GPC3 had the highest binding strength of the four GPC mixtures after 7 and 28 days of cure. GPC3's 7-day strength was 10.58 MPa, which was higher than OPC's strength of 6.03 MPa, resulting in a 75.46% increase in strength when compared to OPC. Similarly, the GPC3 28-day strength was 14.30 MPa, which was higher than the OPC strength of 7.86 MPa, and so the percentage increase in strength of GPC3 over OPC was 81.93%.

5.6 Elastic Modulus

The modulus of elasticity of hardened concrete determined from compression tests on cylinder specimens is depicted in Figure 8.



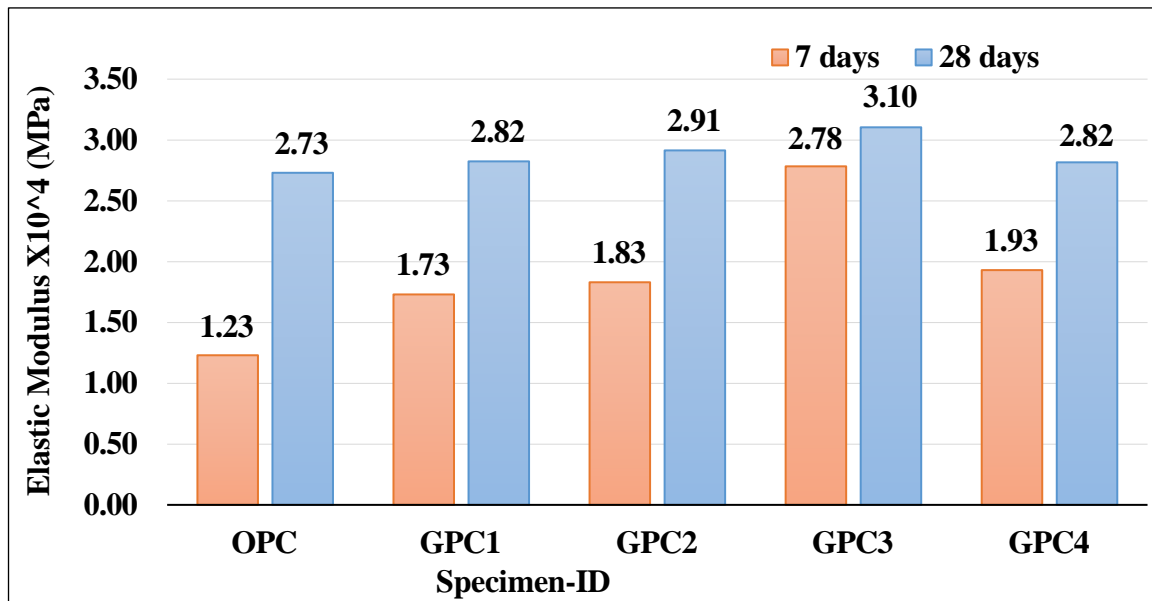


Figure 8. Elastic Modulus of concrete failure specimen and test results

Figure 8 shows that the elastic modulus of GPC mixes was greater than that of OPC mixes after 7 and 28 days of strength. GPC3 had the highest elastic modulus among the four types of GPC mixtures. GPC3's 7-day strength was 2.78×10^4 MPa, which was greater than OPC's strength of 1.23×10^4 MPa, resulting in a 126% increase in strength over OPC. Similarly, the strength of GPC3 after 28 days was 3.10×10^4 MPa, which was greater than the strength of OPC, which was 2.73×10^4 MPa, and therefore the percentage increase in strength of GPC3 was 13.55% when compared to OPC.

5.7 Ultrasonic Pulse Velocity

The velocity criterion of hardened concrete obtained through UPV test on cube specimens is shown in Figure 9.



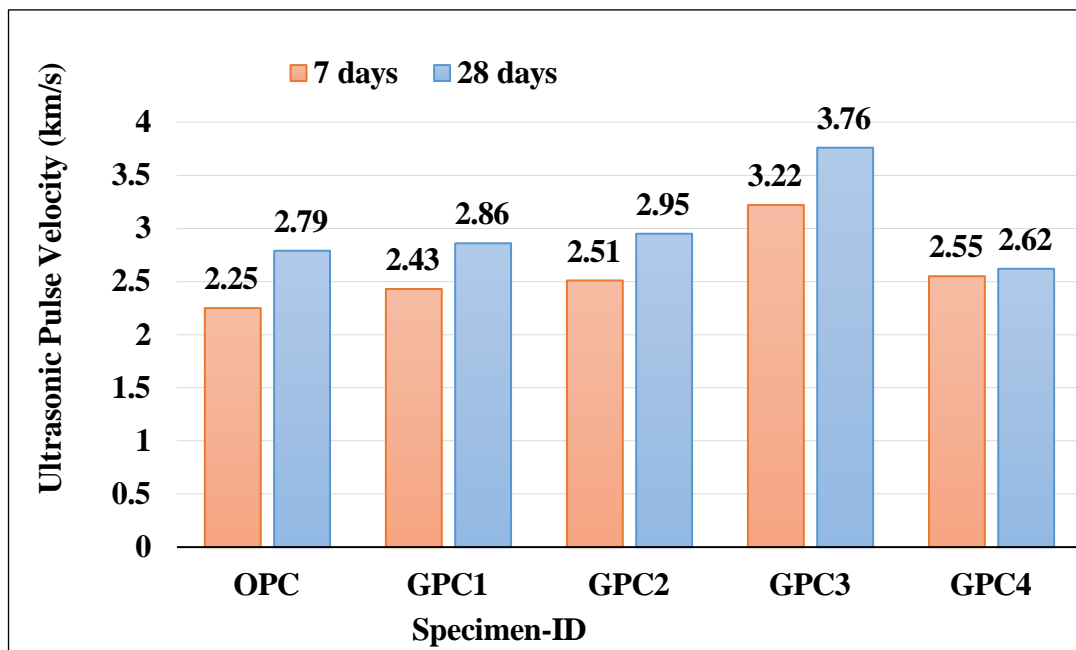


Figure 9. Concrete failure specimen UPV and test results

Figure 9 shows that, with the exception of GPC4, the pulse velocity of GPC mixes was almost twice that of OPC mixes in both 7 and 28 days' strength. Table-2 of IS 3311(Part 1)-1992 shall be used to determine the equivalent concrete quality grade for the pulse velocity experienced by each concrete specimen. GPC3 had the highest pulse velocity of the four GPC mixes in both 7 and 28 days' strength. The pulse velocity of the 7 days' strength GPC3 mix was 3.22 km/s, with the accompanying concrete quality grade of "Medium," whereas the pulse velocity of the OPC mix was 2.25 km/s, with the corresponding concrete quality grading of "Doubtful." Similarly, the pulse velocity of the 28-day strength GPC3 mix was 3.76 km/s, with the associated concrete quality grading of "Good," but the pulse velocity of the OPC mix was 2.79 km/s, with the corresponding concrete quality grading of "Doubtful." As a consequence of the UPV test findings, it was determined that at least one of the GPC mixes (GPC3) was able to achieve a concrete quality grading of "Good" as compared to the OPC mix, which remained "Doubtful."

6. CONCLUSIONS

The workability and mechanical properties of various combinations of GPC mixes using Pozzolona and slag as binder components were thoroughly examined in the current investigation. The performance of classified GPC mixes was compared to that of an OPC mix for numerous metrics such as slump, compressive strength, tensile strength, flexural strength, bond strength, elastic modulus, and concrete grading in an M30 grade concrete. The following findings have been obtained based on the results of the experimental tests:

- GPC mix slump values were slightly lower than OPC mix slump values, indicating a need for enhanced slump in GPC mixes, which is associated with better workability and ease of placement.
- At 7 and 28 days, the compressive strength of GPC3 mix was higher than that of OPC mix, indicating that GPC is developing stronger.
- The GPC4 mix's 7 and 28 day split tensile strength was higher than the OPC mix's, indicating that GPC4 had stronger tensile strength.
- At 7 and 28 days, the flexural strength of all GPC mixes was lower than that of the OPC mix, indicating that GPC may be less resistant to bending stresses.
- The bond strength of GPC3 mix was higher than OPC mix after 7 and 28 days, demonstrating improved bond characteristics in GPC3.
- The elastic modulus of GPC3 mix at 7 and 28 days was higher than that of OPC mix, indicating that GPC3 has greater stiffness and modulus of elasticity.
- The 7 and 28 days velocity requirement of GPC3 mix resulted in appreciable concrete grading as compared to OPC mix, showing favorable performance in terms of concrete quality.

- When compared to ordinary OPC concrete, geopolymer concrete displayed substantial performance in workability and mechanical parameters, with the exception of bending behaviour.
- The usage of geopolymers, which are made from industrial waste/byproducts, is promoted as an eco-friendly/green material in the construction industry. This option contributes to environmental protection by lowering carbon emissions connected with typical cement manufacture. In conclusion, the study reveals that geopolymer concrete made from industrial waste materials is a promising option with desirable qualities, offering both technical and environmental advantages over standard OPC concrete.

REFERENCES

- [1] Mehta, P. K. 2002 “Greening of the Concrete Industry for Sustainable Development”, ACI Concrete International, 24(7): pp.23-28.
- [2] Cembureau “Cement in Cembureau Countries Statistics 2005-2007” available at <http://www.cembureau.be/Documents/KeyFacts/STATISTICS/Cement%20in%20CEMB%20countries.pdf>.
- [3] Mehta, P. K. 2001 “Reducing the Environmental Impact of Concrete”, ACI Concrete International 23(10): pp. 61-66.
- [4] Min-Hong Zhang, Alain Bilodeau, V. Mohan Malhotra, Kwang-Soo Kim, and Jin Choon Kim, Concrete Incorporating Supplementary Cementing Materials: Effect on Compressive Strength and Resistance to Chloride-Ion Penetration, ACI Materials Journal/March-April 1999, 181-189.
- [5] Portland Cement Association 2006 “World Cement Consumption Growth Expected to Continue” in Portland Cement Association Executive Report, available at <http://www.cement.org/exec/10-23-06.htm>.
- [6] Davidovits, Properties of Geopolymer Cements, Proceedings First International Conference on Alkaline Cements, Scientific Research Institute on Binders and Materials, Kiev State Technical University, Kiev, Ukraine, 1994, pp131-149.
- [7] Davidovits, J. 1991 “Geopolymers: inorganic geopolymeric new materials” Journal of Thermal Analysis, 37, pp. 1633-1656.
- [8] Rangan, B.V. 2008 “Low-Calcium Fly Ash-Based Geopolymer Concrete” Chapter 26, Concrete Construction Engineering Handbook, Second Edition, Editor-in-Chief: E.G. Nawy, CRC Press, New York, pp. 26.1-26.20;
- [9] Sumajouw, M. D. J. and Rangan, B.V. 2006 “Low-Calcium Fly Ash-Based Geopolymer Concrete: Reinforced Beams and Columns” Research Report GC3, Faculty of Engineering, Curtin University of Technology.
- [10] M. Sofi, J.S.J. van Deventer, P.A. Mendis, G.C. Lukey, Engineering properties of inorganic polymer concretes (IPCs), Cem. Concr. Res. 37 (2) (2007) 251–257.
- [11] X. Guo, H. Shi, W.A. Dick, Compressive strength and microstructural characteristics of Class-C fly ash geopolymer, Cem. Concr. Compos. 32 (2) (2010) 142–147.
- [12] K. Somna, C. Jaturapitakkul, P. Kajitvichyanukul, P. Chindaprasirt, NaOH activated ground fly ash geopolymer cured at ambient temperature, Fuel 90 (6) (2011) 2118–2124.
- [13] N.K. Lee, H.K. Lee, Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature, Constr. Build. Mater. 47 (2013) 1201–1209.
- [14] A.M. Rashad, A comprehensive overview about the influence of different admixtures and additives on the properties of alkali-activated fly ash, Mater. Des. 53 (2014) 1005–1025.
- [15] J.G. Jang, N.K. Lee, H.K. Lee, Fresh and hardened properties of alkali-activated fly ash/slag pastes with super plasticizers, Constr. Build. Mater. 50 (2014) 169–176.
- [16] W.-C. Wang, H.-Y. Wang, M.-H. Lo, The fresh and engineering properties of alkali activated slag as a function of fly ash replacement and alkali concentration, Constr. Build. Mater. 84 (2015) 224–229.
- [17] Y. Zhou, J. Gao, Z. Sun, W. Qu, A fundamental study on compressive strength, static and dynamic elastic moduli of young concrete, Constr. Build. Mater. 98 (2015) 137–145.
- [18] S. Saha, C. Rajasekaran, Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag, Constr. Build. Mater. 146 (2017) 615–620.
- [19] Guohao Fang, Wing Kei Ho, Wenlin Tu, Mingzhong Zhang, “Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature”, Construction and Building Materials, 172 (2018), pp 476–487.
- [20] Subhash V. Patankar, Yuwaraj M. Ghugal and Sanjay S. Jamkar, “Mix Design of Fly Ash Based Geopolymer Concrete”, Advances in Structural Engineering, 2015, 1619-1634.
- [21] A. Rafeet, R. Vinai, M. Soutsos, W. Sha, Guidelines for mix proportioning of fly ash/GGBS based alkali activated concretes, Constr. Build. Mater. 147 (2017) 130–142.
- [22] ASTM C143-15a, Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM International, West Conshohocken, PA, 2015.
- [23] BS E.N 12390-2:2009, Testing Hardened Concrete Part 3: Compressive Strength of test Specimens, BSI Standards Publication, 2009.
- [24] ASTM C496-11, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2011.
- [25] ASTM C78-16, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, West Conshohocken, PA, 2016.
- [26] IS 383-1970: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, Bureau of Indian Standards, New Delhi, India.
- [27] IS 456-2000: Plain and Reinforced Concrete - Code of Practice, Bureau of Indian Standards, New Delhi, India.
- [28] IS 516-1959: Method of Tests for Strength of Concrete, Bureau of Indian Standards, New Delhi, India.
- [29] IS 1199-1959: Methods of Sampling and Analysis of Concrete, Bureau of Indian Standards, New Delhi, India.
- [30] IS 2270 (PART-1)-1967: Methods of Testing Bond in Reinforced Concrete, Part 1: Pull-Out Test, Bureau of Indian Standards, New Delhi, India.

- [31] IS 3812 (PART-1)-2003: Specification for Pulverized Fuel Ash, Part 1: For use as Pozzolana in Cement, Cement Mortar and Concrete, Bureau of Indian Standards, New Delhi, India.
- [32] IS 5816-1999: Method of Test Splitting Tensile Strength of Concrete, Bureau of Indian Standards, New Delhi, India.
- [33] IS 8112-2013: Specification for 43 Grade Ordinary Portland Cement, Bureau of Indian Standards, New Delhi, India.
- [34] IS 10262-2009: Concrete Mix Proportioning Guidelines, Bureau of Indian Standards, New Delhi, India.
- [35] IS 3025 (Part 22/23): Specification for Water for Concrete, Bureau of Indian Standards, New Delhi, India.
- [36] IS 9103-1999: Specification for Admixtures for Concrete, Bureau of Indian Standards, New Delhi, India.
- [37] IS 2386 (Part 3)-1963: Methods of Test for Aggregates for Concrete: Specific Gravity, Density, Voids, Absorption and Bulking. Bureau of Indian Standards, New Delhi, India.
- [38] IS 13311-1 (1992): Method of Non-Destructive Testing of Concrete, Part 1: Ultrasonic Pulse Velocity, Bureau of Indian Standards, New Delhi, India.
- [39] SP 23-1982: Handbook on Concrete Mixes, Bureau of Indian Standards, New Delhi, India.