



Study of various properties of geopolymer concrete – A review

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ABSTRACT

Cement, being a key material of concrete, experiencing a rise in global demand. It has a massive carbon footprint having a contribution of about 8% to the global CO₂ emissions. Geopolymer concrete has a huge potential to replace ordinary Portland concrete. An overview of geopolymer concrete is presented in this paper. Discussion includes constituents and their mix proportions, mechanical and rheological properties of geopolymer concrete (GPC), the interfacial transition zone (ITZ), bond strength for steel reinforcement. Along with the change in properties with different blends of GGBS in fly ash-based GPC, the effects of constituents on the properties are outlined. This paper also highlighted comparisons between ordinary Portland cement concrete (OPCC) and GPC based on the work of different researchers. GPC has better mechanical properties and has a lower carbon footprint making it a potential material for the construction sector in the near future.

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1. Introduction

Urbanization, rapid development in technologies, industrialization were intended to make our life easier and better. But for everything we need to pay a price and in this case, it is pollution. Pollution is taking its toll on the global population, deteriorating the air, the water, and the land of this beautiful planet.

With the increasing need for infrastructure, the demand for concrete is increasing globally. Consequently, demand for cement is rising as it acts as a binder material in ordinary portland cement concrete. Fig. 1 shows the increasing trend of cement production across the globe. Calcination of limestone and fossil fuel-based rotating kiln for high heat generation for production contributes to high CO₂ emission, which is the major concern of using Ordinary Portland cement and amount of CO₂ emitted is about “one ton for every ton of OPC” being manufactured [1]. The world’s construction sector is contributing nearly 40% to global emissions, with the number of buildings being built increasing every passing year. It is estimated that only 40% of the infrastructure needed for the world by 2050 is there at present and the rest 60% is yet to be built [2,3,4]. Thus it is high time that we shift our dependency from cement to some other alternatives.

“Fly ash also known as pulverized fuel ash in some countries, is a coal combustion product that is composed of the particulates (fine particles of burned fuel) that are driven out of coal-fired boilers together with the flue gases” [6]. It is a waste product from thermal power plants. In 2016 the total global CCPs (Coal Combustion Product) generation was estimated to be nearly 1.2 billion tonnes [7]. In the year 2016–17, the fly ash generation in India was reported to be 169.25 Million tons [8]. “Ground-granulated blast-furnace slag (GGBS or GGBFS) is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder” [9]. Disposal of these wastes into landfills possesses problems because of land scarcity and they pollute soil, water, air which is a threat to human lives and the whole ecosystem in the near vicinity. These materials were found to have cementitious properties and can replace cement, solving both the problems of CO₂ emissions and waste disposal at the same time.

“The term geopolymer was first introduced by Davidovits in 1979 to describe a family of mineral binders” possessing an amorphous microstructure and chemical composition like zeolites [10]. Geopolymerization is a polycondensation reaction between aluminosilicate materials and alkali metal silicates under strongly alkaline conditions resulting in the formation of polymer “– Si–O–Al–O– bonds”, which lead to the formation of geopolymers [1]. Geopolymers derives its structural strength from this

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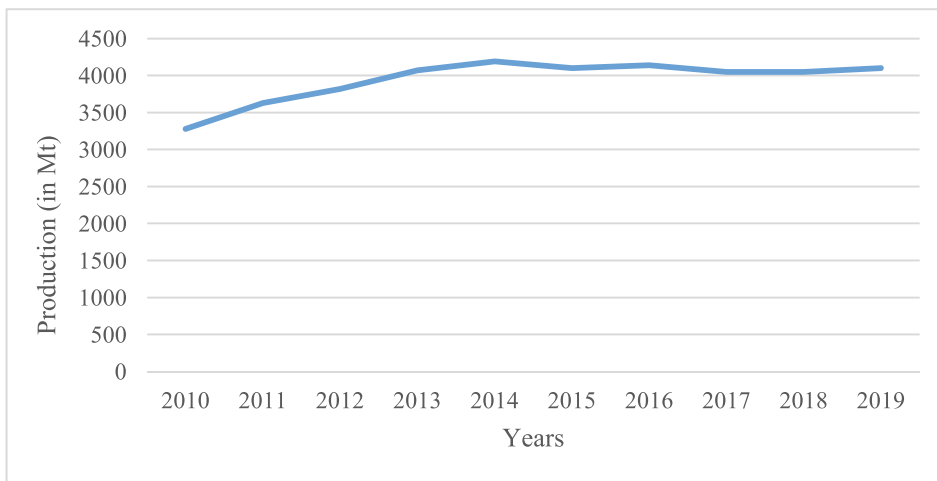


Fig. 1. Global cement production trend, 2010–2019 [5].

polycondensation not from the development of Calcium Silicate Hydrate gel unlike in OPC. According to Davidovits, “around 0.184 tons of CO₂ per ton of binder” is generated in the case of geopolymers [11]. It was reported, compared to OPC an 80% reduction in CO₂ emission is witnessed in geopolymers [10]. Though the setting and hardening mechanisms of GPC are still under the scope of research, the formation of a geopolymer can be shown with the help of the following equations [12].

Equations showing the formation of Geopolymer.

2. Constituents of geopolymer concrete

The constituents of geopolymer concrete consist of a binder material, activators, aggregates, and necessary admixtures. Fig. 2 shows the constituents of the geopolymer concrete and some of their examples that are often used.

2.1. Cementitious materials

Materials with high alumina and silica content are preferred as raw materials for the binder. Fly ash and GGBS are more preferred because of their availability and desired properties.

2.1.1. Fly Ash

It is a by-product that is generated in thermal power plants. it is being separated from the flue gases produced during the combus-

tion of coal. Mainly it contains SiO₂, Al₂O₃, CaO with small amounts of MgO, SO₃, Na₂O, K₂O. The shape of the fly ash particle is spherical glassy, with a specific surface area of 2500–5000 cm²/g and a density of 2.2–2.8 g/cm³. There are two types of fly ash: Type F, having < 7% of CaO, and Type C, having greater than 20% of CaO [11]. Fig. 3 shows the microstructure of fly ash under a scanning electron microscope.

2.1.2. Ground Granulated Blast Furnace Slag

The furnaces in iron industries are fed with iron ore, coke, limestone, and operate at a very high temperature. In that high temperature, the iron ore is being reduced and converted to iron and the remaining materials form a slag. This slag is rapidly quenched to obtain Blast furnace slag which is being grounded to a fine powder to obtain GGBS. It mainly contains CaO, silica, alumina, and small amounts of magnesia and has a “bulk density of 1200 Kg/m³ and fineness 350 m²/Kg” [13]. Fig. 4. Shows the microstructure of GGBS for a better comprehension of its shape and structure.

2.2. Alkaline activators

The alkaline activators, another important material for the production of geopolymers. A vital role is being played by the alkaline activators in the rate of the polymerization reaction and thus, in the strength gain of the concrete. Sodium hydroxide/potassium hydroxide along with sodium silicate/potassium silicate is generally used as alkaline activators. The addition of soluble silicate like

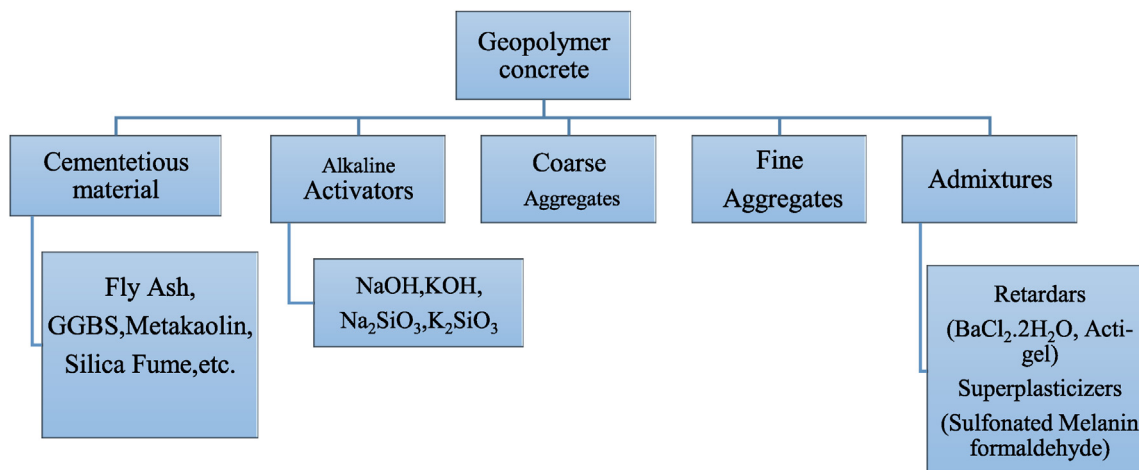


Fig. 2. Constituents of a geopolymer concrete [1,11].

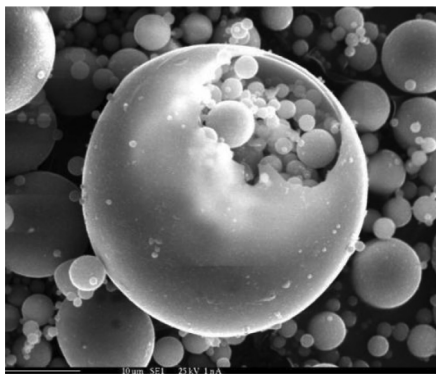


Fig. 3. The microstructure of fly ash [11]

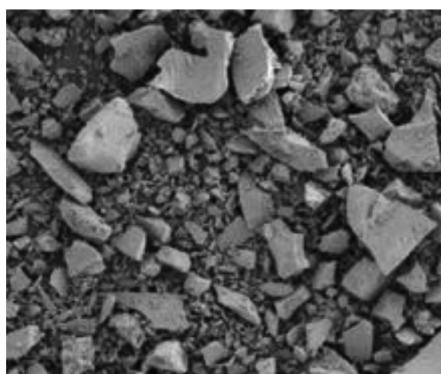


Fig. 4. The microstructure of GGBS [14]

sodium silicate with sodium hydroxides enhances the rate of reaction. Compared to KOH, NaOH solution was seen to cause a higher extent of dissolution of minerals, thus NaOH is preferred over KOH [1].

2.3. Coarse aggregate and fine aggregates

Aggregates occupy almost 70% of concrete volume, where the mass proportion of coarse aggregate and fine aggregate usually used is 65% and 35%. Locally available aggregates can be used and will be economical. Tests like sieve analysis, impact test, etc. should be done for fine aggregates and coarse and coarse aggregates conforming to IS 2386–1963(part 1) and IS 383–2016 [15,16].

2.4. Admixtures

Admixtures are the material used to change certain rheological properties of fresh concrete. Superplasticizers are used to enhance the slump value and thus the workability of concrete. Some commonly used superplasticizers are Sulfonated melamine formaldehyde, Sulfonated naphthalene formaldehyde. Retarders are the materials used for increasing the setting time of concrete. Actigel is one of the anti-setting materials used for geopolymers [1,11].

3. Mix proportion of geopolymer concrete

Guidelines, standards, codes for designing a mix of geopolymer concrete are yet to develop, but we get some idea from the literature based on previous research works by different researchers. Table 1 shows the mix proportion used by different researchers which helps us to understand the ratios in which the constituents

can be mixed. Fly ash to GGBS ratio ranges from 9 to 4 and Na_2SiO_3 to NaOH ratio varies from 2 to 2.5, 2.5 being the optimum ratio.

4. Mechanical properties of geopolymer concrete(GPC)

4.1. Compressive strength

Compressive strength of geopolymer concrete is governed by several factors and ratios of the constituents, still, it can be said that the compressive strength of geopolymer concrete is high or similar compared to Ordinary Portland cement concrete. Guo et al. [21] reported the compressive strength of 63.4 MPa for a class C fly ash-based GPC. Alike OPC concrete, the compressive strength decreases when there was an increase in the water- geopolymer solids ratio. Nath et al. [17] reported an increase in compressive strength with the increase of GGBS blends in fly ash based GPC, which is shown in Fig. 5, and the change in compressive strength (28 days) with varying GGBS percentage is tabulated in table 2 which shows a percentage increase of compressive strength with increase in GGBS percentage. Castel et al. [22] suggested an optimum blend of 14.8% of GGBS for enhancement of compressive strength of low calcium class F fly ash-based GPC.

4.2. Modulus of elasticity

Young's modulus of elasticity of geopolymer concrete was found to be 90% of that of an ordinary portland cement concrete possessing the same compressive strength. The modulus of elasticity of a GPC gets enhanced because of the presence of silicate ions in the activator solutions [23]. GPC was found to have a reduced modulus of elasticity of 14.9%–28.8% compared to OPC concrete of the same compressive strengths [24]. Although during the first 14 days the static modulus of elasticity of geopolymer concrete remains low compared to an OPCC, in the long-term tests the values observe an increase of about 5%–20% [25].

4.3. Flexural strength

When similar grades of OPC concrete and GPC are compared, the flexural strength of GPC is found to be 1.4 times higher and split tensile strength 8%–12% greater than that of OPC concrete and applies to both ambient and heat cured geopolymer concrete. With the blending of GGBS in fly ash based GPC, the flexural strength increases, and up to 20% increase in split tensile strength was observed [23,24]. The compressive strength of geopolymer concrete that can be achieved is as high as 80 Mpa, the flexural strength of 12 Mpa was achieved and the modulus of elasticity achieved is 42 Gpa as shown in table 3.

4.4. Durability

Durability is another important and desirable property of hardened concrete. Interfacial transition zone (ITZ) as shown in Fig. 6, is a zone that develops between the matrix and the aggregate. ITZ is the weakest link in a block of concrete. Under load, the microcracks start developing in these zones and propagates further. ITZ of geopolymer concrete is less microstructurally distinct and dense, thus resists the penetration of external agents like chlorides, sulphates, etc. making the structure more durable. High bond strength and tensile strength of the GPC is because of the stronger ITZ [21,28].

4.4.1. Alkali-silica reaction

Due to the hydrolysis of silica in aggregate by hydroxyl ions in the concrete matrix, the formation of alkali-silica gel takes place,

Table 1
Mix proportions of geopolymer concrete (in kg/m³).

	Nath et al. [17]		Prabir k. Sarker [18]	Stengel et al.[19]	Sumajouw et al.[20]	
fly ash	360	320	408	408	408	404
GGBS	40	80	-	-	-	-
Na ₂ SiO ₃	106.7	114.3	103	103	103	102
NaOH	53.3	45.7	41	41	41	41
water	-	-	15	22.5	26	16.5
superplasticizer	0	0	5.6	6	6	6
Coarse aggregates	1209	1209	1202	1294	1202	1190
sand	651	651	647	554	647	640
Concrete mass(kg/m ³)	-	-	-	2428.5	2433	2400

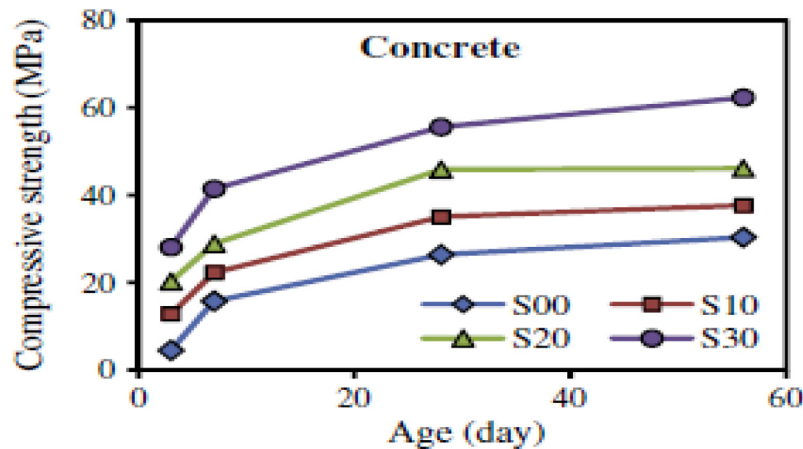


Fig. 5. Variation of compressive strength with different blendings of GGBS, S00, S10, S20, S30 being 0%, 10%, 20%, 30% blend respectively [17].

Table 2
variation of compressive strength with varying GGBS content [17].

	Fly ash (in %)	GGBS (in %)	SS/SH	%CS
1	90	10	2.5	33 ↑
2	80	20	2.5	74 ↑
3	70	30	2.5	110 ↑

SS = sodium silicate, SH = Sodium hydroxide, %CS = percentage change in Compressive strength .

resulting in the absorption of water, and thus the volume increases [21]. The fly ash-based geopolymer mortars do not show significant expansion and surface cracking. However, due to the formation of “sodium calcium silicate hydrate with rosette-type morphology”, the slag-based GPC shows expansion [30].

4.4.2. Acid attack

The degree of degradation of a concrete structure by acid attack depends on the concentration of acid solutions and the period of exposure. The performance of fly ash based GPC was found to be better than OPCC when exposed to 5% acetic acid and 5% H₂SO₄

[21]. Table 4 shows the performance of GPC and OPCC when exposed to acids and GPC was found to be more acid-resistant.

4.5. Fire resistance

Concrete shows a good fire resistance capacity. Firing an OPC concrete between 800 °C and 1000 °C, the maximum residual strength was found out to be 20% – 30% due to the lack of moisture and destruction of CSH and other crystal hydrates. A high-temperature gradient develops between the outer and inner layers resulting in the separation and spalling of the outer layer from the

Table 3
Properties of geopolymer concrete mixes [21,26,27].

Sample No.	Molarity (M)	activator/binder ratio	Curing temp. and period	Compressivestrength (in MPa)	SplittingTensilestrength (in MPa)	Flexuralstrength(in MPa)	ModulusOf elasticity (in GPa)
1.	10–16	0.35–0.40	60–80 °C for 24hrs	30–80	3.74–6	5–12	23–31
2.	8 & 12.5	0.40 & 0.55	85 °C for 20hrs	29–43.5	-	6.86	10.7–18.4
3.	-	0.45–0.59	23 °C till testing	47–56.5	2.8–4.1	4.9–6.2	23–39
4	14	0.40–0.94	60 °C for 72hrs	10–80	-	2.24–6.41	1.9–42
5	8	0.40–0.65	60 °C for 24 hrs	65.1–77.9	2.8–5.1	-	11.2–41.2
6	8 & 12.5	0.55	85 °C for 20hrs	45	-	6.85	13.4

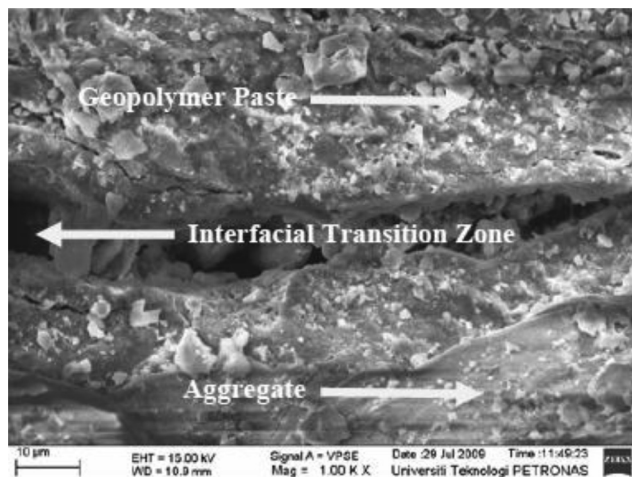


Fig. 6. SEM image of GPC showing ITZ[29]

interior layer. On the other hand, the presence of highly distributed nano-pores in the structure of geopolymers allows the migration and evaporation of water that is physically and chemically bonded to the structure, rescuing the aluminosilicate network from any damage. Kong et al. observed a 34% loss and a 6% gain in the compressive strength of metakaolin-based and fly ash-based geopolymer paste after being exposed to 800 °C temperature. The unreacted fly ash particles follow sintering reaction and are primarily responsible for the increase in strength. No spalling was found after exposing the fly ash-based geopolymer concrete to 850 °C. GPC possesses higher spalling resistance compared to that of OPC Concrete under fire [21,32].

4.6. Bond strength

Slag blended fly ash based GPC was found to have a 10% higher bond strength with steel reinforcement compared to OPCC of equivalent compressive strength [22]. Comparing bond strength of concretes having different compressive strengths may lead to an inappropriate conclusion, thus to avoid this a normalized factor is used to give normalized bond strength value. For both OPCC and GPC, an increase in the concrete cover shows an increase in the normalized bond strength of both 20 and 24 mm steel bars, which is presented in Fig. 7a and 7b. From Fig. 8 it is evident that for the same cover/diameter ratio, the geopolymer concrete shows better bond strength than OPC concrete. Fig. 9a and 9b show that for both the types of concrete with the increase of compressive strength, the bond strength increases [18].

Table 4
Performance of OPCC and GPC when exposed to different acids [21,31,32].

Binder material	Acid and its Strength	Period of exposure	Loss of weight	Decrease in compressive strength
Fly ash	0.5% H ₂ SO ₄	12 months	–	20%
	1% H ₂ SO ₄		–	52%
	2% H ₂ SO ₄		–	65%
Fly ash + palm oil ash	2% H ₂ SO ₄	18 months30 days	8%	35%
OPC	2% H ₂ SO ₄		20%	68%
slag	CH ₃ COOH(pH 4)	12 months	–	33%
OPC	CH ₃ COOH(pH 4)		–	47%
slag	2% H ₂ SO ₄	3 months	–	11%
OPC	2% H ₂ SO ₄		–	36.2%
Fly ash	5% Na ₂ SO ₄ & 5% MgSO ₄	3 months	2.4%	2% – 29%
OPC	5% Na ₂ SO ₄ & 5% MgSO ₄		–	38%

5. Rheological properties of geopolymer concrete

5.1. Workability

The value of slump values and flow values gives the measure of workability. Higher the slump value, the concrete is considered more workable. In fly ash-based GPC, increasing the blend of slag results in a decreased slump and flow values. At a higher percentage of the blend, the phenomenon becomes more significant. Fig. 10 shows a variation of slump value and flow value with the change in the slag content in the mixture, where S00, S10, S20, S30 denotes the mixture having slag content of 0%, 10%, 20%, 30% respectively [17].

5.2. Setting time

The slower rate of reaction at a low ambient temperature of 21–23 °C, fly ash-based geopolymer paste requires more than 24 h before it starts setting. However, the blending of slag improves both the initial and the final setting time significantly. Inclusion of 10% slag in the binder results in decreasing the initial setting time to 290 min, which was further reduced to 94 min and 41 min after increasing the slag content to 20% and 30%. Increasing the slag content in geopolymer pastes reduces the difference between the initial and the final setting time. Thus it can be said that the more the percentage of slag, the faster the setting will be, which is evident from Fig. 11. Fig. 11 represents the change in initial setting time and final setting time and the period of difference between the two with the increase in slag content. Here S00, S10, S20, S30 depicts the incorporation of the slag blend of 0%, 10%, 20%, 30% respectively [17].

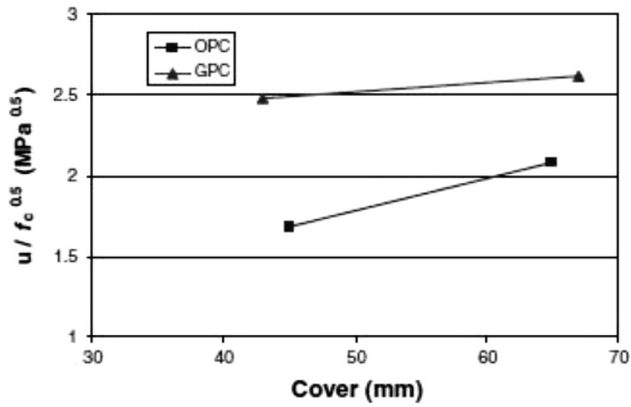
6. Effect of constituents on properties of GPC

6.1. Effect of activator dosage

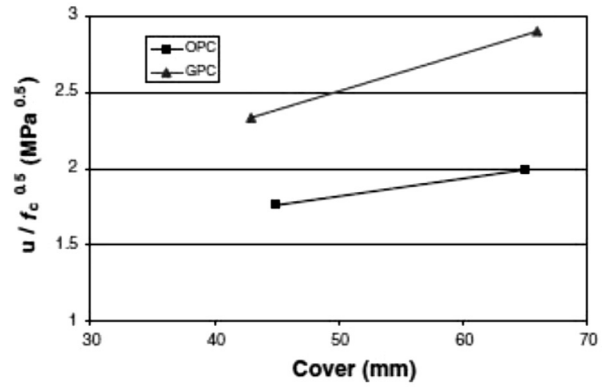
In fly ash based GPC, the pores developed at high activator dosage(30%) were lesser in size and showed a narrow distribution pattern compared to a lower activator dosage(18%) showing larger pores and had a broader distribution which is evident from Fig. 12. Increased particle dissolution and development of reaction product are witnessed because of pore refinement. Thus due to reduced porosity, an increase in strength of geopolymer paste can be observed [21]. “SiO₂/Al₂O₃ ratio of 3.0–3.8 and Na₂O/Al₂O₃ ratio of 1” were reported to give the optimum strength in a GPC [33,34].

6.2. Effect of NaOH concentration

Increasing the molarity of the sodium hydroxide solution decreases the workability of fly ash based GPC. Fig. 13a depicts a



(a)



(b)

Fig. 7. Change in the bond strength with the variation of concrete cover for (a) 20 mm bar, (b) 24 mm bar [18]

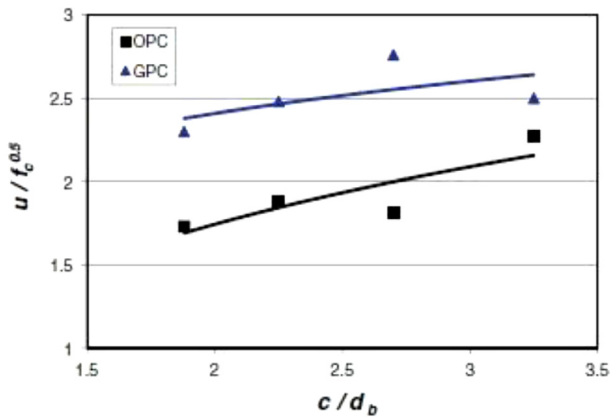


Fig. 8. Change in the bond strength with the variation of c/d_b ratio, where c - cover, d_b - diameter of the bar [18].

reduction in slump values of 10.5% when 16 M and 20% when 18 M NaOH solution was used in place of 12 M NaOH solution. The change in compressive strength with changing the concentration of NaOH for fly ash based GPC that was cured for 48 h at 50 °C is shown in Fig. 13b. It was observed to have increased compressive strength when the NaOH concentration was increased from 12 M

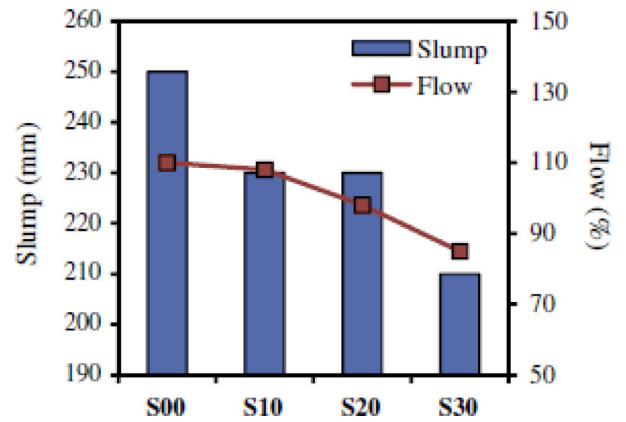
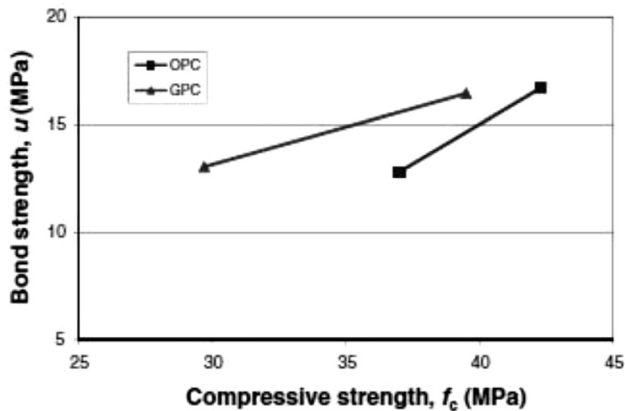


Fig. 10. Variation of slump values and flow values with changing slag content [17].

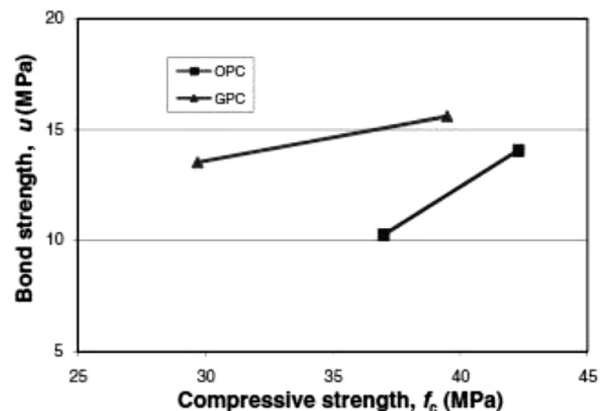
to 16 M but beyond 16 M the compressive strength saw a gradual drop in its value [35].

6.3. Effect of NaOH/Na₂SiO₃ ratio

The NaOH/Na₂SiO₃ ratio's effect on workability is shown in Fig. 14a. An increase in NaOH/Na₂SiO₃ ratio increases the slump



(a)



(b)

Fig. 9. Change in the bond strength with the variation of compressive strength for 20 mm bar and cover of (a) 65 mm, (b) 45 mm [18].

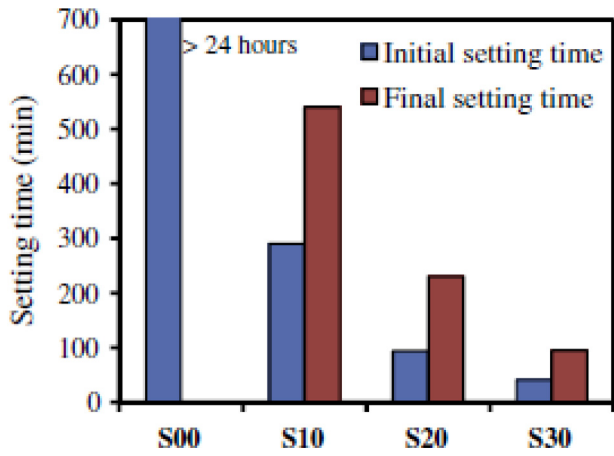


Fig. 11. change in the setting times with the variation of slag [17].

value and thus enhances the workability of fly ash based GPC. Compared to a mix having 0.3 NaOH/Na₂SiO₃ ratio, an increase of 28.6% and 57.1% in slump value was reported for mixes having 0.4 and 0.5 NaOH/Na₂SiO₃ ratio respectively. However, Fig. 14b shows that the compressive strength of GPC decreases with an

increase in NaOH/Na₂SiO₃ ratio. The 28 days compressive strength of GPC witnessed a drop of 22.5% for the mix with 0.4 NaOH/Na₂SiO₃ ratio and 29.5% for the mix with 0.5 NaOH/Na₂SiO₃ ratio with respect to the mix with 0.3 NaOH/Na₂SiO₃ ratio [35].

6.4. Effect of admixture

Citric acid increases setting time in OPC but acts as an accelerator in fly ash based GPC, shortening the setting time by 9 and 16 mins [36]. Polycarboxylate based superplasticizers increases workability, but a 29% reduction in compressive strength was reported [37]. In comparison to naphthalene based superplasticizers, polycarboxylate based superplasticizers show significant enhancement in workability but also acts as retarders in the ash-slag blended mix [38].

7. Conclusion

The carbon emission due to the use of ordinary portland cement concrete is affecting the whole ecosystem. The geopolymer concrete is one of the eco- friendly solutions for the future of the construction industry. Geopolymer having a blend of GGBS shows upto 110% increase in percentage compressive strength. The modulus of elasticity was found to be greater than OPC concrete by 5%- 10%. The flexural strength of GPC is found to be 1.4 times higher and

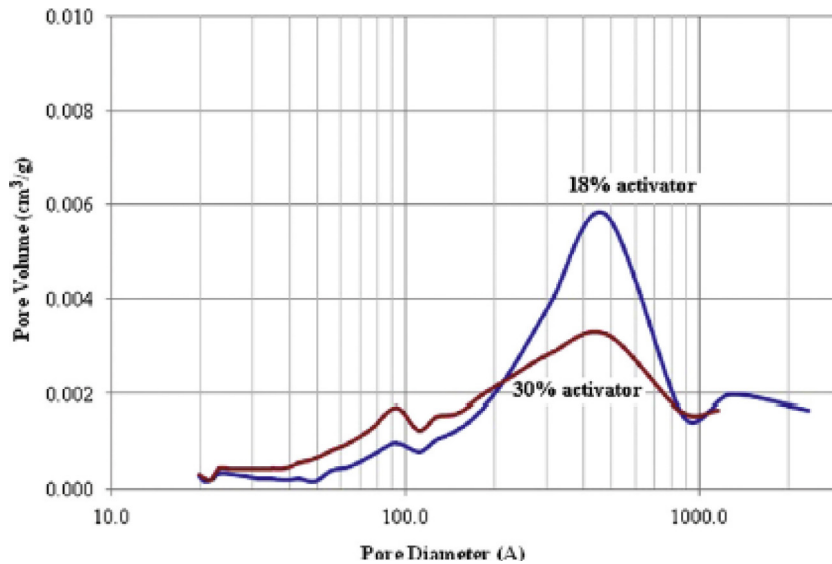


Fig. 12. Effect of activator dosage on the pore size distribution of fly ash-based geopolymer [21].

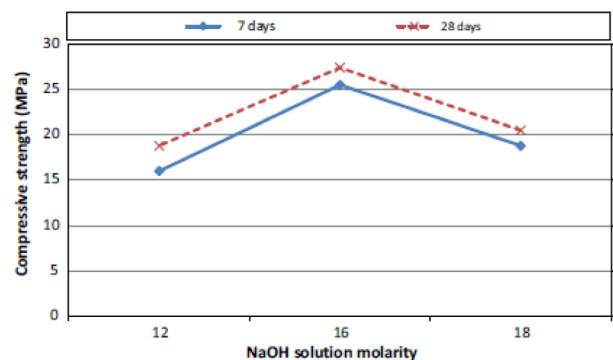
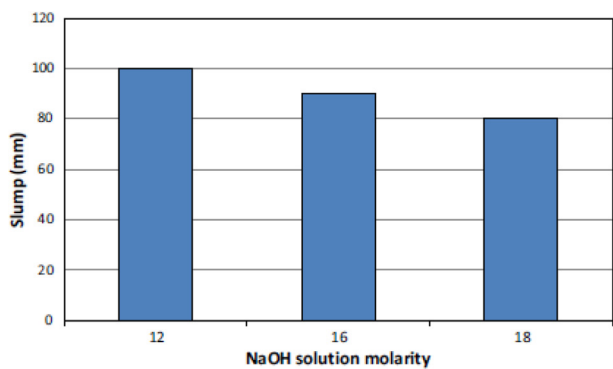


Fig. 13. Effect of concentration of NaOH on (a) slump (b) compressive strength [35].

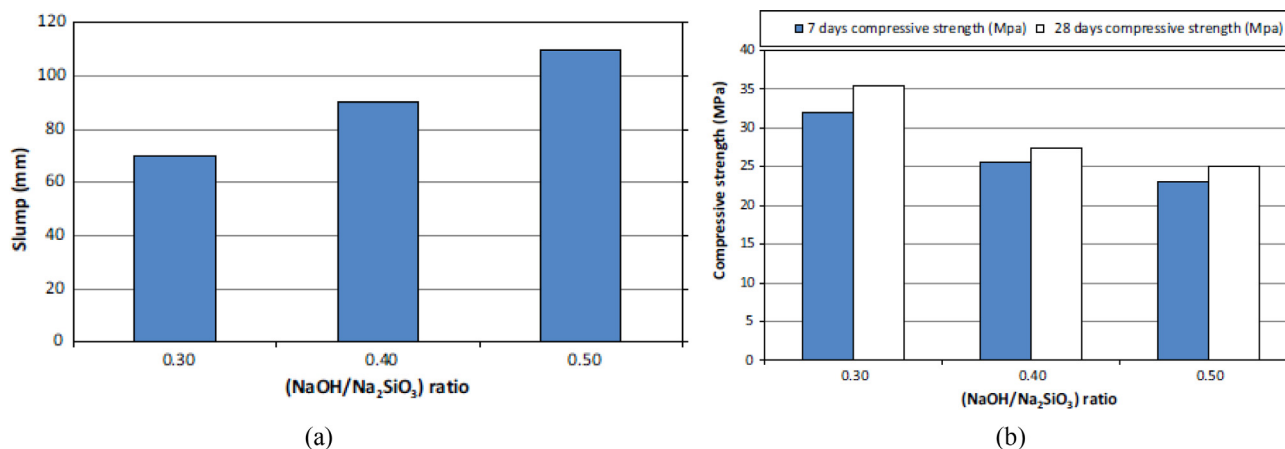


Fig. 14. Effect of NaOH/Na₂SiO₃ ratio on (a) slump (b) compressive strength [35].

split tensile strength 8%–12% greater than that of OPC concrete. GPC having a blend of slag with fly ash was found to have a 10% higher bond strength with steel reinforcement compared to OPCC of equivalent compressive strength. Compared to ordinary Portland cement concrete, the geopolymer has better durability, fire resistance, and acid resistance. The setting time of GPC is found out to be more, so as of now, GPC is more dependent on heat curing, and that narrow its spectrum of use. Though many experimental data are presented by different authors helping us to understand the mix proportions of geopolymer concrete, lack of standard codes is inhibiting its mass adaptation. Moreover, the hardening mechanism of GPC is still under the purview of research. Thus, efforts have to be made in the direction of ambient curing and different blendings of fly ash, GGBS, silica fume, etc. to enhance setting time, workability, and other mechanical properties of geopolymer concrete. However, geopolymer concrete is a potential material that can replace OPC concrete in future and can become the backbone of the construction industries.

CRediT authorship contribution statement

Subhankar Chowdhury: Writing - original draft, Writing - review & editing. **Subhashree Mohapatra:** Literature Review. **Ambar Gaur:** Gaurav Dwivedi: Final drafting. **Archana Soni:** Writing - review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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