Research Article

Effect of curing condition on the mechanical properties of fly ash-based geopolymer concrete

Amer Hassan[1] · Mohammed Arif[2] · M. Shariq[1]

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Abstract
In the present study, the mechanical properties of geopolymer concrete (GPC) has been investigated. GPC represents a novel technology that is giving significant concern in industrial construction, especially in term of the current emphasis on sustainability. In this study, the NaOH and Na_2SiO_3 solutions were used as an alkaline solution in all GPC mixes. Na_2SiO_3 with 10 concentration of molarity, activator-to-FA ratio of 0.4, Na_2SiO_3/NaOH ratio of 1.75, and two curing regimes viz., ambient curing, and heat curing at 75 °C for 26 h were employed. The experimental results indicated that the geopolymer concrete strengths, modulus of elasticity, and other mechanical properties increased with heat curing as compared to ambient temperature curing. The elastic modulus of GPC was associated with the compressive strengths and similar to those of OPC concrete. Furthermore, the geopolymer concrete mixture requires proper mix proportion and temperature-controlled curing conditions to accomplish good results.

Keywords Geopolymer concrete · Sustainable materials · Mechanical properties · Flexural strength · Modulus of elasticity · Fly ash

1 Introduction

The manufacture of ordinary Portland cement (OPC) contributes about 10% of CO_2 emission to the environment and because of a significant demand for construction in various sector of industries such as, buildings, transportation, dams, tunnels, and sewage, etc., there is an urgent need for an alternate material binder which can replace OPC for a cleaner and sustainable construction [1–6]. Geopolymer materials are a novel construction technology that could be employed for green construction purposes [7–9]. There are two significant ingredients of geopolymer concrete, namely the source material with rich Alumina–Silica content such as fly ash (FA), metakaolin or GGBFS), and alkali activator, which consists of sodium silicate and sodium hydroxide solutions [10–13]. The raw material which is rich in Aluminium (Al) and silica (Si) such as GGBFS, fly ash, or metakaolin reacts with an alkaline solution to produce alumina silicate gel [14–16]. This gel behaves as a binder which binds unreacted materials (sand and coarse aggregates) to manufacture geopolymer concrete (GPC) [17].

The geopolymer concrete is considered as an ideal choice not only because it is a sustainable material, but because it utilizes waste materials from industries as a source material contrast OPC which uses virgin materials [9, 18].

Although usage of geopolymer concrete is still in the beginning stage, however, recently, many structures have been successfully constructed utilizing geopolymer concrete [19]. Some of these geopolymer composites are reinforced box culverts, concrete pipes, pavements, structural

✉ Amer Hassan, ameralburay@gmail.com | [1]Department of Civil Engineering, Zakir Husain College of Engineering and Technology, Aligarh Muslim University, Aligarh 202002, India. [2]Department of Civil Engineering, College of Engineering, Qassim University, Buraidah 51452, Saudi Arabia.

elements, precast concrete such as railway sleeper and electric power pole and marine construction, reinforced box culverts, precast footway panels, the airport in south-east Queensland, Australia, etc. [20].

In the production of geopolymer concretes, fly ash is considered the primary source materials due to its availability in the industry. According to the chemical composition, fly ash is categorized as either class F or class C. The previous studies on the GPC reported that the use of F class of FA on the production of GPC has comparable or superior mechanical properties to the OPC concretes [21, 22]. In India, the manufacture of clay bricks requires 540 million tonnes of clay for manufacturing 180 billion tonnes of clay brick per year, makes 26,800 hectares of land barren, and requires 30 million tonnes of coal equivalent, generates around 27 million tonnes of CO_2 [19, 23, 24]. Annually, a 10–12% replacement with fly ash will consume 30–32 million tonnes of fly ash, save coal and environment and yield a benefit of 310 crores by decrease cost in the production of blocks [24].

To fill the gap on the mechanical behaviour of GPC, long-term engineering properties of GPC such as flexural strength elastic modulus and compressive strength, in addition to the effect of types of curing (heat and ambient) have been investigated in the study. We also recommended more researches on geopolymer concrete for a better understanding of the performance behaviour of GPC before introducing this concrete to the industrial construction as an alternative to OPC concrete. The cost analysis and economic benefits of GPC and OPC concrete also have been compared to find out the economic aspect of GPC along with the environmental potentials for a clean technology option.

In the present study, the elastic modulus, E_C, of geopolymer concrete was calculated at the stress level equal to 40% of cylinder compressive strength (f'_c). For each mixture, three concrete cylinders of 100 × 200 mm were cast.

In term of elastic modulus, the experimental values are compared with the elastic modulus calculated using the equations proposed by some researchers and equations recommended in various code standards.

Australian Standard AS3600 [25] suggests Eqs. (1) and (2) for the elastic modulus of concrete (± 20%) at the proper age.

$$E_{cj} = \left(\rho^{1.5}\right) \times \left(0.043 \times \sqrt{f_{cmi}}\right), \quad f_{cmi} \le 40 \text{ MPa} \tag{1}$$

$$E_{cj} = \left(\rho^{1.5}\right) \times \left(0.024 \times \sqrt{f_{cmi}} + 0.12\right), \quad f_{cmi} > 40 \text{ MPa} \tag{2}$$

where E_{cj} elastic modulus in MPa, f_{cmi} site compressive strength (90% of cylinder strength (f_{cm}) tested at laboratory), ρ the concrete density in kg/m^3.

American Concrete Institute the ACI 318-14 code [26] recommends Eq. (3) for calculating the elastic modulus of concrete.

$$E_c = \left(\rho^{1.5}\right) \times 0.043 \times \sqrt{f'_c} \tag{3}$$

where ρ the density of concrete kg/m^3, f'_c the compressive strength of concrete after 28 days of curing in MPa, and E_c the elastic modulus in MPa.

Diaz-Loya et al. [27] suggested Eq. (4) for predicting elastic modulus of GPC depending on the experimental results of heat-cured fly ash GPC.

$$E_c = \left(\rho^{1.5}\right) \times 0.037 \times \sqrt{f'_c} \tag{4}$$

where E_c the elastic modulus (MPa); f'_c compressive strength of heat-cured GPC after 3 days curing. For the reason that the GPC specimens cured at elevated temperature develop strength approximately equal to the ultimate strength after few days curing, the f'_c in Eq. (4) indicates the ultimate strength of the GPC. Furthermore, geopolymer concrete specimens cured in normal condition (room temperature) gain strength slowly with the time [21, 28]. Lee and Lee [29] proposed Eq. (5) for predicting the elastic modulus of GPC. While Nath and Sarker [30] proposed Eq. (6) to calculate the elastic modulus of GPC.

$$E_c = 5300 \times \sqrt[3]{f'_c} \tag{5}$$

$$E_c = 3510 \times \sqrt{f'_c} \tag{6}$$

where E_c the elastic modulus (MPa) and f'_c the compressive strength of GPC.

From the values of compressive strengths, various standard codes have proposed equations to evaluate the flexural strength of concrete. In this study, the equations suggested in the American and Australian standard codes were employed to assess the flexural strength of GPC and compared with the obtained values by experimental test.

Australian Standard code The flexural strength of concrete ($f'_{ct.f}$) at 28 days can be computed employing Eq. (7) as proposed by AS 3600 [25].

$$f'_{ct.f} = 0.6 \times \sqrt{f'_c} \tag{7}$$

where f'_c 90% of cylinder compressive strength (f_{cm}) prepared and tested at a laboratory.

American Concrete Institute The ACI Code 318-14 [26] suggested Eq. (8) for calculating the flexural strength of concrete using the values of compressive strength.

$$f'_{ct.f} = 0.62 \times \sqrt{f'_c} \tag{8}$$

The relationships between the specified (f'_c) and measured compressive strengths (f_{cm}) are given by Eqs. (9)–(11).

$$f_{cm} = f'_c + 7.0 \text{ for } f'_c < 21 \text{ MPa} \tag{9}$$

$$f_{cm} = f'_c + 8.3 \text{ for } 21 < f'_c \leq 35 \text{ MPa} \tag{10}$$

$$f_{cm} = 1.1 \times f'_c + 5.0 \text{ for } f'_c > 35 \text{ MPa} \tag{11}$$

Indian standard code The IS 456-2000 code [31] recommended the following Eq. (12) for predicting the flexural strength of concrete using the compressive strength of the corresponding specimen.

$$f_r = 0.7 \times \sqrt{f_{ck}} \tag{12}$$

where f_r is the flexural strength of concrete and f_{ck} is the compressive strength at 28 days.

Diaz-Loya et al. [27] suggested the following Eq. (13) to calculate the flexural strength of geopolymer concrete based fly ash;

$$f_r = 0.69 \times \sqrt{f_c} \tag{13}$$

where f_r the flexural strength of fly ash-based GPC and f_c compressive strength of heat-cured GPC after 3 days.

2 Experimental details

2.1 Materials

2.1.1 Fly ash

Fly ash from Dadri thermal power station, Uttar Pradesh (U.P.), India, was utilized in this experimental investigation. The fly ash was greyish colour and comprised of 51.86% SiO_2, 1.66% MgO, 1.08% K_2O, 9.15% Al_2O_3, 33.98% Fe_2O_3, and 2.26% CaO, which as analysed by X-ray fluorescence (XRF). As per ASTM C618 [32], according to the chemical composition analysis, the FA had a low Ca content and classified as class F.

2.1.2 Aggregates

Limestone aggregates available on the market have a specific gravity of 2.67, and 16 mm was the maximum size of coarse aggregates used. The sand utilized in this experimental work was river sand with a specific gravity of 2.58. The fineness analysis of coarse and fine aggregates has been done according to IS 383 [28] guidelines, and the results of the fineness analysis curve were in the limitation of IS 383 [28].

2.1.3 Alkaline solution

An alkaline solution prepared by mixing the solutions of NaOH and Na_2SiO_3 with 10 molarity, the composition of Na_2SiO_3 was 15.35% Na_2O, 32.85% SiO_2, and 51.80% water. However, for preparing the sodium hydroxide solution, sodium hydroxide in flakes form and 10 molarity were dissolved on water, i.e., 314 grams of sodium hydroxide flakes dissolved in 1 L of water. After that, the sodium hydroxide solution was mixed with sodium silicate and then left for at least 6 h before use.

2.2 Methodology

2.2.1 Mixing proportions

The weight of coarse and fine aggregates was 70% of the total mix. For all combinations, the ratio of activator-to-FA was constant and equal to 0.4. The NaOH molarities were 10 M in all mixes, and the ratio of Na_2SiO_3-to-NaOH by weight was 1.75. Table 1 gives the mix proportions of GPC mixtures used in this study.

2.2.2 Mixing procedure

The mixing technique was achieved according to the guidelines reported from previous works on the geopolymer concrete [27, 29]. The process was initiated by mixing Na_2SiO_3 with NaOH solution for 4 min. After that, the fly ash was added to the mixer with sand and coarse aggregate and mixed for 4–6 min. Then, the alkaline solution was added to the dry materials mixture and mixed for an extra 4 min.

2.2.3 Casting of specimens

For compressive strength tests, GPC was cast into 150 mm cube moulds according to ASTM C192 [30]. For the elastic modulus test, GPC was cast into 100 × 200 mm cylindrical steel moulds. For the flexural strength test, GPC was cast into 100 × 100 × 500 mm prism moulds.

2.2.4 Curing of specimens

In this experimental work, two curing conditions were employed. The first type of curing was heat (oven) curing

Table 1 Mixing proportion of GPC (kg/m^3)

Mixes	Aggregates		FA	NaOH (molar)	Na_2SiO_3	Extra water	Water/solid	Activator/FA	Curing	Age (days)
	Coarse	Fine								
GPC-7H	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Oven-75 °C	7
GPC-7A	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Ambient	7
GPC-28H	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Oven-75 °C	28
GPC-28A	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Ambient	28
GPC-56H	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Oven-75 °C	56
GPC-56A	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Ambient	56
GPC-90H	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Oven-75 °C	90
GPC-90A	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Ambient	90
GPC-180H	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Oven-75 °C	180
GPC-180A	1044.4	530.6	410	67.1 (10 M)	117.4	79.2	0.4	0.4	Ambient	180

at 75 °C for 26 h after a 2–3 days delay time. The delay time was the time from the casting of specimens into the moulds till unmoulds the specimens. The delay time lets concrete to accomplish initial setting time before being shifted to the curing room or curing oven. The other curing condition was in ambient temperature conditions. For heat curing, all GPC specimens were moved from the oven after 26 h curing and cured in ambient temperature until testing.

3 Results and discussions

3.1 Scanning electronic microscopy test (SEM)

For a proper understanding of the microstructure of GPC, the SEM test was performed on the raw materials of GPC. Sodium silicate, fly ash, and sodium hydroxide have been tested to understand the real shape of material particles that would assist in anticipating the behaviour of the composition materials when they mixed during the production of a geopolymer binder. Figure 1a–c shows the SEM testing images of the materials used in the production of GPC. As can be seen in Fig. 1a, the fly ash material has a circular and rounded shape, while the silicon particles on the sodium silicate solution are finer than the silicon particles on the fly ash, as shown in Fig. 1b. Moreover, The SEM images of sodium hydroxide show that the particles of sodium (Na) are organized in a hydrargillite-like layer structure (Fig. 1c).

3.2 Compressive strength

The experimental results of the compressive strength of the GPC of this study are summarized in Fig. 2. The compressive strengths of GPC at 28 and 7 days were in the range of 10.50–31.11 MPa for heat curing (75 °C) while the compressive strengths of GPC at 7 and 28 days for ambient curing were 4.50–10.00 MPa for ambient curing, respectively. It can be noted that the heat curing temperature influenced the early strength of GPC due to the geopolymerisation process, which required heating for accelerating the reaction between alkali activator and fly ash. For GPC cured at 75 °C, the compressive strength

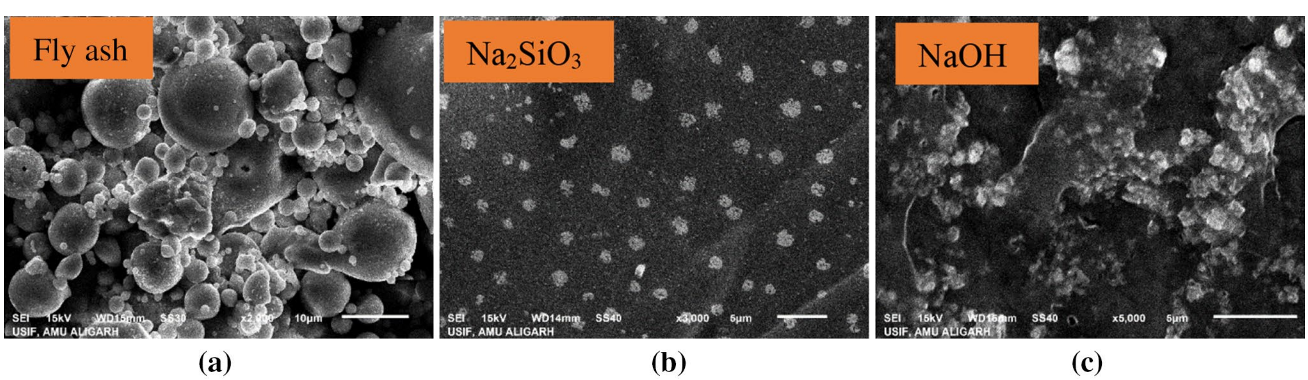

Fig. 1 SEM images; **a** FA, **b** Na_2SiO_3 and **c** NaOH

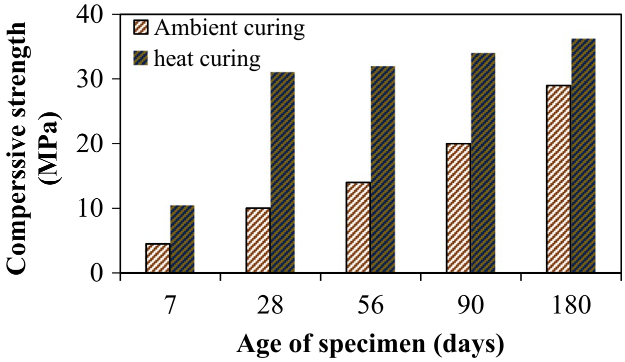

Fig. 2 Compressive strength of GPC specimens at different ages cured at heat and ambient temperatures

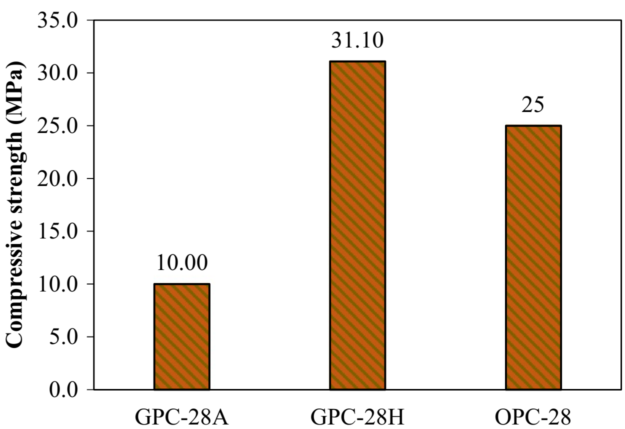

Fig. 3 Compressive strength of GPC and OPC concrete at 28 days

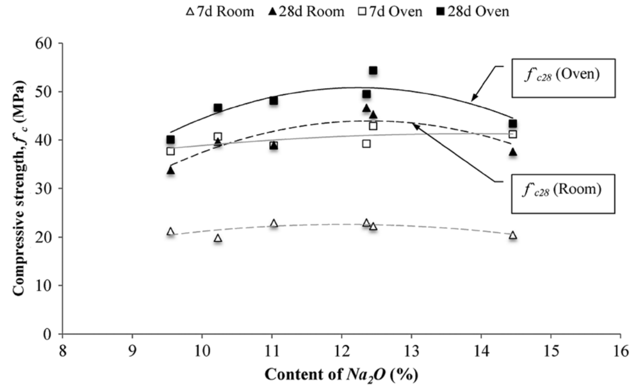

Fig. 4 Effect of Na_2O (%) content on the compressive strength of GPC

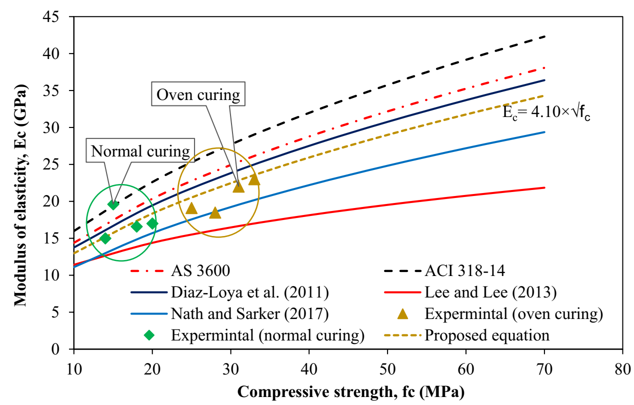

Fig. 5 Elastic modulus of geopolymer concrete verse compressive strength

increased by 57% at 7 days as compared to ambient curing. The strengths of heat-cured specimens at 28 days increased with 67% as compared to the same samples cured at room temperature. Furthermore, from Fig. 3, it can be observed that the compressive strengths of heat curing specimens of GPC were higher than the compressive strength of OPC at the age of 28 days.

Figure 4 shows the experimental test results of 7- and 28-day compressive strengths of GPC against the Na_2O/FA ratio in the geopolymer concrete mixture. For both curing regimes, the maximum compressive strengths were given with approximately 12% of Na_2O/FA. The compressive strength of GPC at 28 days could be expressed as a function of total moles of Na_2O as given in Eqs. (14) and (15).

For 25 °C and 24 h curing

$$f'_{c28} = -1.13\left(M_{Na_2O}\right)^2 + 28.1\left(M_{Na_2O}\right) - 130 \quad (14)$$

For 60 °C and 24 h curing

$$f'_{c28} = -1.27\left(M_{Na_2O}\right)^2 + 31.2\left(M_{Na_2O}\right) - 140 \quad (15)$$

where f'_{c28} the compressive strength of GPC at 28 days; MNa_2O mass proportion of Na_2O-to-fly ash (%).

3.3 Modulus of elasticity

The experimental results of this study have been analyzed to develop an appropriate equation using the generally utilized term, square root of compressive strength $(f'_c)^{0.5}$. The analysis gave Eq. (16) for predicting the elastic modulus of GPC:

$$E_c = 4100 \times \sqrt{f'_c} \quad (16)$$

where f'_c is the compressive strength of GPC in MPa. Values calculated using Eq. (16) are also presented in Fig. 5. From Fig. 5, it can be observed that Eq. (16) matches well with Eq. (4) proposed by Diaz-Loya.

Table 2 Elastic modulus of various mixtures

Mix ID	Curing	E_c (GPa)			Test/AS 3600	Test/ACI 318-14
		Test	AS 3600	ACI 318-14		
GPC-7A	Ambient curing	16.60	19.30	21.45	0.86	0.77
GPC-28A		19.62	17.62	19.58	1.11	1.00
GPC-56A		15.01	17.03	18.92	0.88	0.79
GPC-90A		17.20	20.35	22.61	0.84	0.75
GPC-180A		22.08	24.50	27.23	0.90	0.81
GPC-7H	Heat curing (75 °C)	22.00	25.33	28.15	1.14	1.03
GPC-28H		23.01	26.14	29.04	1.31	1.17
GPC-56H		19.11	22.75	25.28	1.21	1.01
GPC-90H		18.50	24.08	26.75	0.91	0.82
GPC-180H		24.67	27.38	30.42	1.01	0.91

The experimental results of the elastic modulus of GPC specimens and proposed Eq. (16) are presented in Fig. 5 and compared with the values calculated by previous Eqs. (1)–(6). The experimental results of elastic modulus were in the range (24 to 15 GPa). From Fig. 5, It can be concluded that the elastic modulus of GPC commonly increased with the increase of compressive strength, which that is comparable to the existing standard codes, ACI 318-14 and AS 3600 [25, 26]. The experimental results of elastic modulus of GPC are lower than those predicted using suggested equations of ACI 318-14 and AS 3600. Since the prediction equations proposed by ACI 318-14 and AS 3600 are developed for the elastic modulus of conventional concrete, some modifications on those equations are required to match the elastic modulus of GPC. The proportion between the experimental values of GPC and the values calculated as per ACI 318-14 and AS 3600 are 0.77–1.17 and 0.84–1.31, respectively, as shown in Table 2. Figure 5 shows that the equation suggested by Diaz-Loya et al. [27] matched well with the experimental findings of this investigation, while the equation presented Lee and Lee [29] drew a lower model line than the model plotted by experimental values. This variation might be attributed to the difference of the FA type, curing condition, and temperature used in those particular works and different mixture compositions and so on.

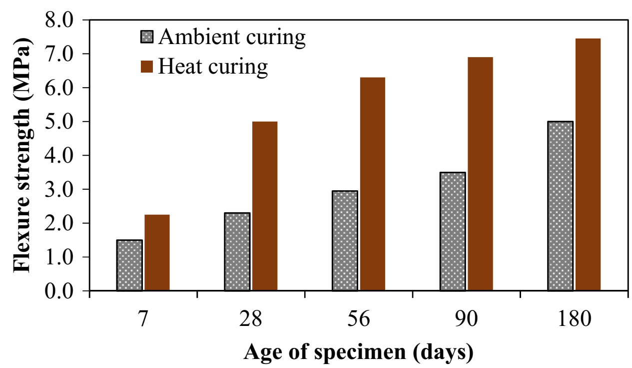

Fig. 6 Flexural strength of GPC specimens at different ages, cured at heat and ambient temperatures

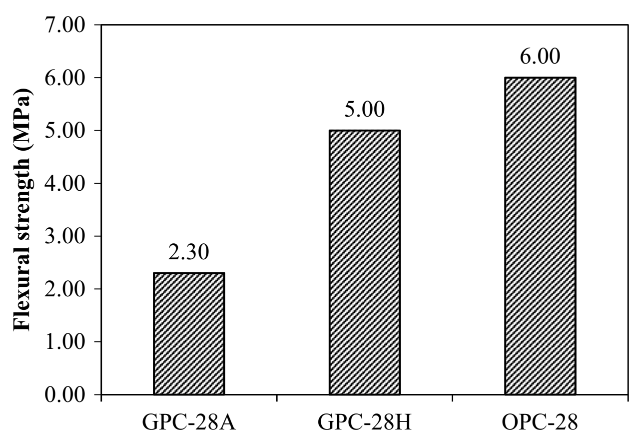

Fig. 7 Flexural strength of OPC concrete and GPC at 28 days

3.4 Flexural strength

The flexural strengths of geopolymer concrete were affected by the curing condition, a finding similar to those other mechanical properties where the heat curing improves the strength of geopolymer concrete. Figure 6 compares the flexural strengths of the GPC at various ages for both types of curing (oven @ 75 °C and room temperature). It can be observed that flexural strength increased when the specimen age was raised. However, the flexural strength of GPC at ambient-cured was lower than that those specimens at heat-cured. When compared with OPC concrete at 28 days, OPC concrete exhibited higher flexural strength than GPCs with 16.5% for heat-cured specimens and 60% for normal-cured samples, as shown in Fig. 7.

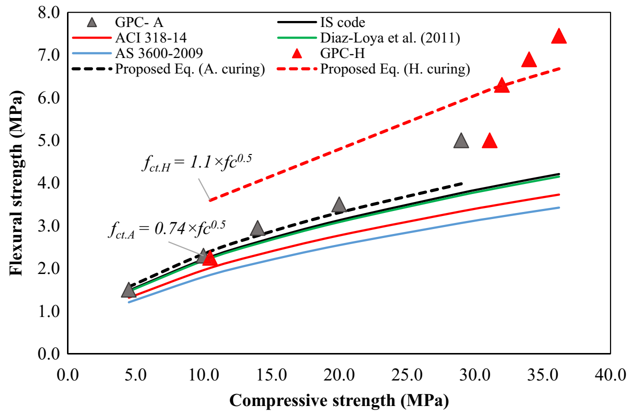

Fig. 8 Experimental and predicted flexural strengths of geopolymer concrete

In Fig. 8, it can be observed that approximately all of the experimental values of this work fall in the above equations given by ACI 318-14, AS 3600, and Diaz-Loya et al. [27]. In this study, a model was developed using regression analysis by employing the experimental values. The following Eqs. (17) and (18) for heat-cured and ambient cured respectively have been proposed to fit the experimental results best, as shown in Fig. 8.

$$f_{ct.H} = 1.10 \times \sqrt{f_c} \quad \textit{for heat-cured} \tag{17}$$

$$f_{ct.A} = 0.74 \times \sqrt{f_c} \quad \textit{for ambient-cured} \tag{18}$$

where $f_{ct.H}$ and $f_{ct.A}$ is the heat-cured and ambient cured flexural strengths of GPC, respectively. f_c is the compressive strength of GPC (MPa). It also should be noted that the proposed Eqs. (17) and (18) give about 5–7% higher flexural strength than predicted values calculated according to the Eq. (13) that suggested by Diaz-Loya et al. [27] and 20–28% higher values than the flexural strength as per ACI Code 318-14 [26].

3.5 Cost analysis and economic benefits of GPC

A raw material cost comparison was carried out to produce GPC and OPC concrete on the assumption that the concrete producer has to buy in all raw materials from outside. The price for the reference year 2019 was requested at the terms for a significant purchaser in India. The cost estimation of the raw materials for production of GPC is presented in Table 3, and the cost estimation of the raw materials for production of OPC concrete is presented in Table 4. The significant differences between the minimum and maximum production costs for GPC and OPC concrete are shown in Fig. 9.

Table 3 Cost estimation of GPC for 1 m^3

Material	Price (INR)	Unit	M-30		M-40		M-50	
			Quantity (kg)	Price (INR)	Quantity (kg)	Price (INR)	Quantity (kg)	Price (INR)
FA	300	MT	378	189	395	119	408	204
Fine agg.	800	MT	554	443	647	518	647	518
Coarse agg.	650	MT	1294	841	1201	781	1201	781
Na_2SiO_3	8	kg	124	992	130	1040	138	1104
NaOH	25	kg	50	1250	55	1375	63	1575
Electricity	600	PC/m^3	–	600	–	600	–	600
Total		INR	4315		4433		4782	

INR Indian rupee, *MT* 1000 kg, *PC* power consumed

Table 4 Cost estimation of OPC concrete for 1 m^3

Material	Price (INR)	Unit	M-30		M-40		M-50	
			Quantity (kg)	Price (INR)	Quantity (kg)	Price (INR)	Quantity (kg)	Price (INR)
OPC	300	50 kg	350	2100	480	2880		
Fine agg.	800	MT	642	514	450	360	647	518
Coarse agg.	650	MT	1270	826	1059	688	1201	781
SP	100 or 200*	kg	7.5	750	8	800	8*	1600
Total		INR	4190		4728		5538	

SP superplasticizer (type I = 100 INR and type II* = 200 INR)

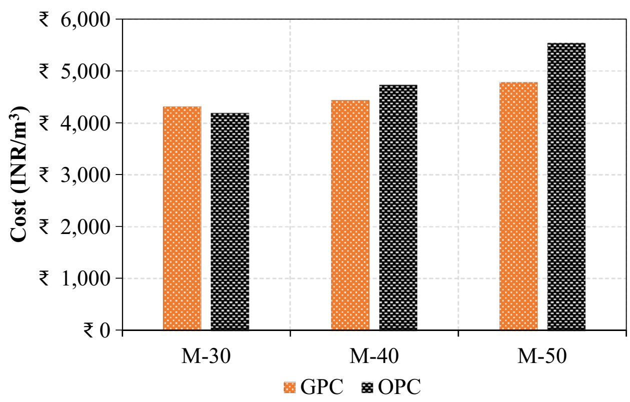

Fig. 9 Cost estimation of GPC and OPC concrete

Despite the wide range of costs, Fig. 9 shows that, in principle, geopolymer-based concretes can be economically competitive with Portland-cement-based systems. In addition to the aggregate (sand, gravel) as the main component (approx. 75% by mass) in both mixes, the cement is the main cost driver in the OPC concrete. On the other hand, in the geopolymer concrete all components contribute to a different extent to the total costs, while, i.e. the activator sodium hydroxide contributes noteworthy to the overall costs, the solid component hard coal fly ash contributes only to a lesser extent. The activator sodium silicate solution adds with the highest specific costs considerably to the total costs.

Based on the cost analysis, it might be concluded that the cost of production of M-30, normal strength concrete, is marginally 2.9% higher than OPC concrete, whereas the cost-saving in GPC production of M-40 is 6.67% and 15.8% M-50 as compared with OPC concrete. Therefore, it can be concluded that cost-effectiveness can be achieved in the production of high strength of geopolymer concretes.

Moreover, GPC promotes early strength development, which has the potential to facilitate early project completion. Compared to traditional project construction, the project completion time can be reduced by at least 30% with the use of GPC.

4 Conclusions and remarks

Based on the analytical and experimental test results on the mechanical properties of GPC, the following remarks can be drawn.

- Since the main constituent of GPC is an industrial by-product (fly ash), GPC is relatively inexpensive to produce. Moreover, the geopolymer binder production does not cause harmful greenhouse gas emissions and is consequently considered environmentally friendly.
- The fresh GPC had a long setting time of 234–247 min due to the low calcium content in the matrix of GPC. The heat-curing of GPC specimens at 75 °C at the oven for 26 h enhanced the strength development. However, the strength of ambient-cured GPC continued to develop with time comparable to conventional concrete. In general, heat curing and curing temperature play a significant role in the geopolymerisation process.
- The ratio of Na_2O-to-Si_2O molar has no significant effect on the compressive strength of fly ash-based geopolymer concrete.
- SEM images enabled the assessment of reaction product formation and microstructural evolution in the specimens of GPC. The images show a less dense structure as compared with OPC concrete.
- The elastic modulus of GPC increased when the compressive strength increased, and the equation proposed by Diaz-Loya et al. for the modulus of elasticity of fly ash-based GPC gave the best fit with elastic modulus values calculated in this study.
- The cost-effectiveness can be achieved in the production of high strength of geopolymer concretes.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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