Research Article

Exploration of mechanical and durability characteristics of fly ash-GGBFS based green geopolymer concrete

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Abstract
In this paper, the use and effect of Ground Granulated Blast Furnace Slag (GGBFS) addition to fly ash (FA) on the performance of Geopolymer Concrete was presented. A reference of Ordinary Portland cement concrete (OPC) mix was used to compare with geopolymer concrete. The effect of different proportions of GGBFS addition, ambient curing, and curing age on the properties of geopolymer concrete was reported. The concentration of sodium hydroxide solution with 8 M and solution to binder ratio as 0.4 were taken for all the mixes of geopolymer concrete. This paper reported an investigation data on the mechanical and durability characteristics of fly ash-GGBFS based geopolymer concrete and that data was compared with the control mix (OPC). SEM analysis was done on selected samples to estimate the microstructural characteristics. The results concluded that a geopolymer concrete mix containing 60% GGBFS and 40% fly ash at 28 days of ambient temperature achieved maximum compressive strength (55.63 MPa) and further performed durable under severe environmental conditions.

Keywords Fly ash · GGBFS · Cement · Geopolymer concrete · Ambient curing · Mechanical properties · Durability

1 Introduction

A massive quantity of raw materials and energy is being consumed while manufacturing of cement. Aside from this, a lot of stable waste and vaporous discharges, especially Carbon Dioxide (CO_2), are being emitted into the atmosphere [1]. Therefore, a decrease in the quantity of utilized cement can give to a cutback of CO_2 liberations. The cement industry is supposed to turn out 0.83 kg of CO_2 per kilogram Cement production, which leads to 12% of total worldwide CO_2 emission by 2020 [2, 3]. Geopolymer binder has an imaginative designing alternative substance with the possibility to shape standard ordinary Portland cement (OPC) for both auxiliary and non-basic applications. French Professor Davidovits introduced "Geopolymer" to the world [4]. That can be produced from numerous industrial by-products/wastes, together or alone with fly ash (FA), Silica fume, and GGBFS [2, 5]. The industrial waste like fly ash, GGBFS, red mud, and silica fume are used as source materials in geopolymer concrete. The alkaline solution is prepared from potassium/sodium-based soluble solutions [6–13]. The Alkaline-activation on these wastes like fly ash will be end product in the development of geopolymer Resin/Binder [14, 15]. Geopolymer Concrete is produced by mixing of geopolymer binder with fine and coarse aggregates in the presence of alkaline solution [16]. Polymerization has taken place when receptive alumino-silicates are quickly broken down, and free SiO_4 and AlO_4 tetrahedral units are discharged in solution. On the other hand, the tetrahedral units are going with polymeric antecedents by the dispersion of oxygen molecules to set up unstructured geopolymers [17]. Chi and

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Huang [18] reported the mechanical properties and binding mechanism of FA-GGBFS based geopolymer mortars. The test data showed that both fly ash significantly influenced the mechanical properties and binding mechanism of FA-GGBFS based geopolymer mortars to slag ratio and the dosage of sodium oxide (Na_2O). Besides, SEM and XRD images reveal the polymerization process in FA-GGBFS based geopolymer mortars. Mainly consist of amorphous alkaline aluminosilicate and low crystalline C–S–H gel.

The deterioration of OPC concrete over time due to sulphate attack has been broadly observed and documented [19]. The presence of inadequately mineralized/acidic water in concrete; the acid leaches into the concrete. It reacts with concrete chemical components, which are known as diffusion–reaction and cause degradation of structural elements [20]. The pH levels play a significant role in the decomposition of calcium hydroxide ($Ca(OH)_2$) and calcium sulphoaluminate i.e., calcium hydroxide decomposes at a pH value under 12. In contrast, calcium sulphoaluminate decomposes at a pH value under '11' [21]. Several researchers reported the behavior of geopolymer concrete under extreme environmental conditions, and the studies revealed the superior characteristics of GC over conventional cement concrete mixes [6–11, 17, 19–22].

Fly ash and GGBFS-based geopolymer concrete have attracted attention due to the virtue of its usage without a supply of any external energy. Ambient curing process was adopted for fly ash-GGBFS based geopolymer concrete to estimate mechanical and durability properties. It has been concluded from the previous research that geopolymer concrete has comparable mechanical properties to that of OPC control mix. However, the present study explores the strength properties of Geopolymer Concrete mixes with a combination of fly ash and GGBFS as a binder under ambient temperature. Further, a comprehensive assessment of their durability characteristics has been evaluated for making geopolymer concrete into practical applications. For durability assessment, all the samples were fully immersed for 30 and 60 days in 5% sodium chloride (NaCl), 5% sodium sulphate (Na_2SO_4) and sulphuric acid (H_2SO_4) solutions at room temperature.

Table 2 Physical properties of aggregates

Physical properties	Aggregates	
	Fine	Coarse
Specific gravity	2.63	2.8
Fineness modulus	2.56	7.40
Bulk density (gm/cc)	1.46	1.40
Water absorption %	1.22	0.79

2 Materials and methods

2.1 Materials

The binders used in this data are Fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS), conforming to ASTM C 618-08 [23] and ASTM C 989-18 [24], respectively. FA obtained from a coal-based thermal power station, Vijayawada, India, and commercially available GGBFS were taken from JSW Cements Ltd., India. OPC 43 grade cement, according to ASTM C 150-19 [25], was used for conventional concrete reference mix and taken from UltraTech Cement, India. The XRF test was conducted to determine the oxide composition of FA, GGBFS, and cement; the data is presented in Table 1. To active the source materials, the alkaline solution was used. In this data, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as an alkaline solution to activate the binders, and these chemicals are obtained from local chemical stores. The composition of Na_2SiO_3 by weight ratio is $Na_2O = 14.50\%$, $SiO_2 = 29.60\%$ and water = 55.90%. Coarse aggregates used in the making of GC were taken from stones derived from the granite of the local area. Locally available river sand was used as fine aggregate. Categorization of coarse aggregate was passed through 20 mm, and 12 mm IS sieve and sand passed through 4.75 mm IS sieve. The properties of aggregates used in this paper are shown in Table 2.

2.2 Preparation of alkaline liquid

The alkaline liquid was prepared 24 h before the cast of GC samples. This procedure concerned in estimating the essential mass of NaOH, which was then added to the calculated quantity of water to compose the require molarity (8 M). This liquid was prepared in a 100 kg capacity bucket

Table 1 Oxide conformation of binders

Material	Al_2O_3	Fe_2O_3	SiO_2	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	SO_3	TiO_2	LOI
Fly ash	25.08	4.56	58.23	2.87	1.21	0.41	0.87	2.94	0.2	1.16	0.83	1.59
GGBFS	12.14	1.10	32.25	44.7	4.23	0.87	–	1.96	–	0.84	–	1.98
Cement (OPC)	4.18	3.10	21.47	65.15	1.97	0.63	1.01	–	–	1.96	–	0.37

in an ice bath to advance cooling as the excessive reaction of NaOH liquid liberates a lot of heat. After this, NaOH liquid was mixed with a calculated amount of Na_2SiO_3 solution. The Na_2SiO_3 has taken 2.5 times more than that of NaOH as recommended in previous literature [26–28] indicating to be the most favorable ratio to obtain desired results.

2.3 Mix proportioning of GC

The mix proportioning of GC was done according to previous reports by considering the density as 2400 kg/m^3 [6, 7, 10, 17, 19–22]. The mix proportion details for GC M1 to M7 and control mix are presented in Table 3. The aggregate proportions used in different GC mixes are about 73–76% by mass of the concrete. However, the control mix (OPC) was taken according to similar binder content as well to get a specific 28 days strength.

2.4 Mixing and curing of GC samples

The mixing process followed for GC was comparable to that of conventional concrete [27]. Initially, the binders (FA and GGBFS) were mixed well for 2–3 min. After that, fine and coarse aggregates were added to the binders and mixed further 3–4 min. Then the alkaline liquid was introduced into the dry material mix, allowed for an additional 5–6 min to obtain a uniform blend. The fresh GC mixture was used to test the degree of workability, and then this concrete was cast in moulds. All the GC specimens were cured under ambient temperature (open-air curing), while OPC concrete (control mix) samples were immersed in water for specified age of curing.

2.5 Method of testing

Experiments were conducted to determine the engineering properties of GC like compressive, splitting tensile and flexural strengths. The compressive strength of geopolymer and OPC concrete were tested according to BS EN 12390-03 [29]. While, the splitting tensile and flexural strengths tests were conducted according to ASTM C496/C496M-17 [30] and ASTM C78/C78M-18 [31], respectively. The resistance of GC against chemical attacks was conducted according to ASTM C267-01 [32].

X-Ray Diffraction (XRD) analysis was performed for the structural characterization of GC samples. XRD-6000 RIGAKU XRD with Cu-Ka radiation initiated less than 15 mA and 40kv at room heat condition was used to study 4 elected samples. The XRD test was conducted at a scanning angle 2θ from 3 to 91°. A scanning electron microscope (SEM) VEGA 3 SBH (TESCAN Brno S.R.O) equipped with an Energy Dispersive Spectroscopy (EDS) analyzer (EDAX-EDS-SDD) with the high energy of 10–30 kV was adopted for morphological study assessed with a low-vacuum approach. The samples selected for SEM analysis were taken from broken pieces of GC specimens after testing.

3 Result and discussions

3.1 Workability

Figure 1 identifies that OPC concrete shows better workability compared to all other mixes of GC. Mix M1 has higher slump value, i.e., 82 mm compared to all remaining GC mixes, while less workability was observed for Mix M7 (contains 60% GGBFS), i.e., 53 mm. It was observed that the addition of GGBFS had shown much influence on the workability values of fresh geopolymer concrete. An increase of GGBFS content in FA-based geopolymer concrete mixes decreased the workability values [33].

Table 3 Mix proportioning of GC in kg/m^3

Mix Id	Binders			Aggregates		Alkaline solution		W/B (or) S/B ratio[a]
	FA	GGBFS	Cement	Fine	Coarse	Na_2SiO_3	NaOH	
M1	407	–	–	610	1220	116.28	46.51	0.4
M2	366.3	40.7	–	610	1220	116.28	46.51	0.4
M3	325.6	81.4	–	610	1220	116.28	46.51	0.4
M4	284.9	122.1	–	610	1220	116.28	46.51	0.4
M5	244.2	162.8	–	610	1220	116.28	46.51	0.4
M6	203.5	203.5	–	610	1220	116.28	46.51	0.4
M7	162.8	244.2	–	610	1220	116.28	46.51	0.4
OPC	–	–	407	610	1220	–	–	0.4

[a]W/B (or) S/B ratio = water/solution to binder ratio

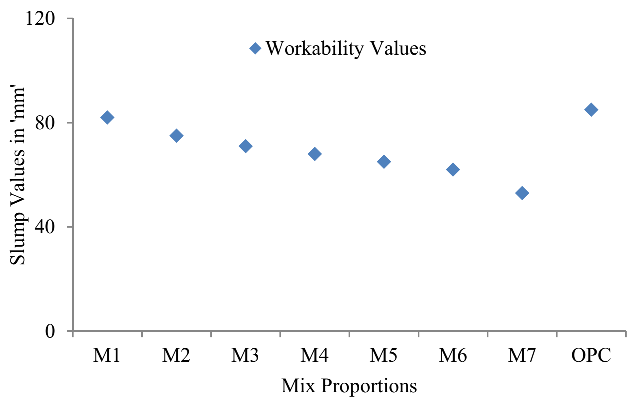

Fig. 1 Slump cone values of geopolymer and OPC concretes

3.2 Compressive strength

The compressive strength of GC and OPC concretes was presented in Fig. 2. Mix M1 did not attain proper strength because of the improper polymerization process. It was observed due to ambient curing, 100% FA based GC requires oven curing. Figure 2 depicted that mix M7 attained the highest compressive strength at 28 days of ambient curing compared to all other mixes. The compressive strength of OPC at 28 days of water curing was found as 37.51 MPa. Whereas for GC mixes, M1, M2, M3, M4, M5, M6, and M7 were 21.41, 35.76, 38.85, 42.58, 45.41, 49.75 and 55.63 MPa, respectively at ambient curing for 28 days. It was observed that higher GGBFS content led to the formation of extra C–A–S–H gel, and it enhanced the strength properties of GC.

In comparison to OPC concrete, GC attained superior strength characteristics for the mixes containing a minimum 30% replacement of FA with GGBFS. With the increase in the age of the curing period, the strength values were also increasing [33, 34]. The variances of strengths from 14 to 28 days are presented to Fig. 2.

3.3 Splitting tensile strength

Figure 3 depicts the experimental data on splitting tensile strengths of different mixes based GC for 14 and 28 days of curing. Similar to compressive strength values, mix M7 achieved higher splitting tensile strength values at 28 days of ambient curing. It was found from the experimental data that the indirect tensile values are very high compared to OPC for the mixes containing equal or more than 30% replacement of FA with GGBFS. From Fig. 3, it can be recognized that with the rise in GGBFS levels, the splitting tensile strength was also increased drastically. The compressive strength values are evident that GC has good engineering properties, and that was proving by splitting tensile strength values. It was apparent from Fig. 3 that the 100% FA blended GC has not attained desired strength because of insufficient supply external energy, and it was found that pure fly ash blended GC samples required a minimum of 24 h oven curing at specified temperatures [35]. With the addition of little quantities of GGBFS to FA, the oven curing can be avoided, and the desired strength can be attained at ambient curing conditions. Figure 4 was evident that the increases of GGBFS content in the mixes the strength values were also increasing [33, 34, 36]. The higher values were attained for 60% replacement of GGBFS at 28 days of ambient curing. It was observed for both compression and splitting tensile strengths as shown in Fig. 4.

3.4 Flexural strength

Figure 5 indicates the flexural strengths of GC and reference OPC concrete at 14 and 28 days of curing. Mix M7 shows a higher flexural strength at 28 days of ambient

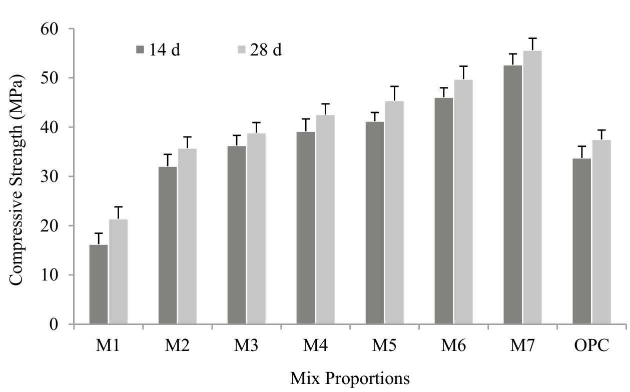

Fig. 2 Compressive strength of dissimilar concrete mixes for 14 and 28 days of curing

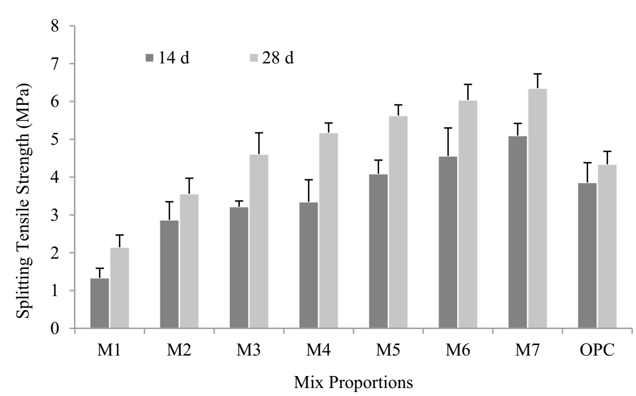

Fig. 3 Splitting tensile strength of dissimilar concrete mixes for 14 and 28 days of curing

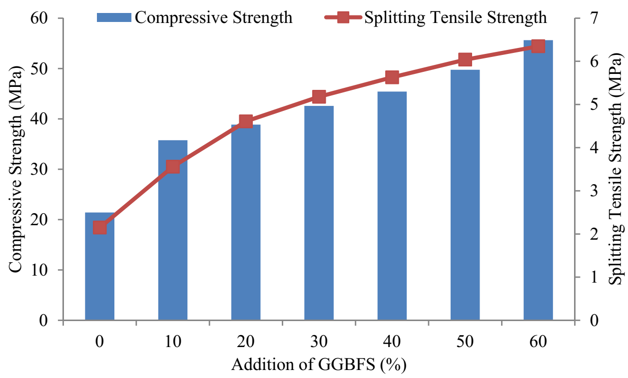

Fig. 4 Effect of GGBFS on compressive and splitting tensile strengths of GC for 28 days

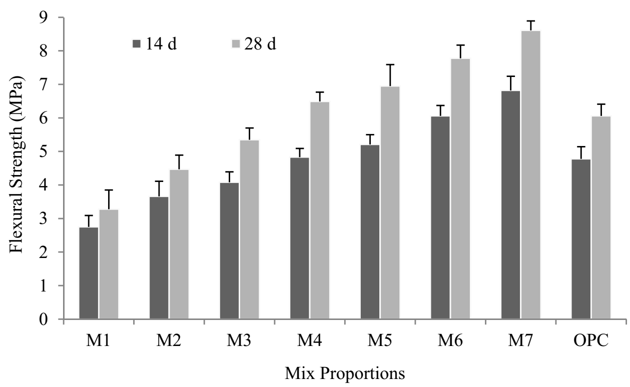

Fig. 5 Flexural strength of dissimilar concrete mixes for 14 and 28 days of curing

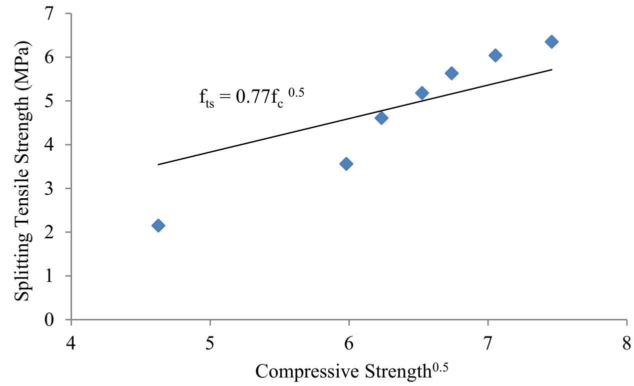

Fig. 6 Predicted splitting tensile strength of geopolymer concrete

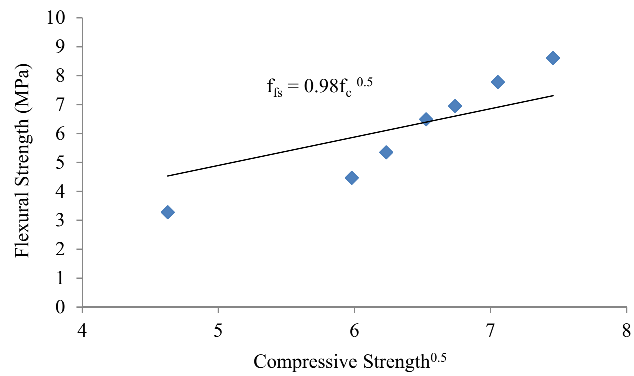

Fig. 7 Predicted flexural strength of geopolymer concrete

curing. The addition of 60% GGBFS attained superior strengths at all ages of curing compared to all other mixes. Figure 5 indicated that an increase of GGBFS content in GC mixes enhances the flexural strength values, and a similar trend was repeated in case of compressive and split tensile strength values. Except for 100% FA based mixes of GC remaining, all shown good results compared with OPC concrete. The flexural strength of GC compared with reference OPC mix 20–30% strength enhancement was found with experimental data. The trend line drawn for 28 days flexural strength values of GC mixes to identify the strength enhancement with the increase of GGBFS content. The highest value was attained for mix M7 = 8.61 MPa for 28 days of ambient curing, and this mix contains 60% replacement of FA with GGBFS.

3.5 Correlative study on mechanical properties

A correction can be established between compressive strength (f_c), split tensile strength (f_{ts}), and flexural strength (f_{fs}) values of GC mixes as per ACI363R-92 [37] and ACI 318-99 [38]. Figure 6 shows that split tensile strength is 0.77 times the square root value of compressive strength results, which is in correlation with ordinary cement concrete specimens [39]. At the same time, flexural strength is 0.98 times the square root value of compressive strength results (Fig. 7). Concerning ACI codes, the proposed correlation for compressive strength and flexural strength is on the higher side for GC mixes.

3.6 SEM and XRD analysis

The SEM images of FA based GC with different proportions of GGBFS additions are shown in Fig. 8. It is clear from SEM analysis that the GC with 40% FA and 60% GGBFS depicts the most completely reacted index with fewer FA particles and a denser structure. Figure 8b reveals that the existence of C–S–H and C–A–S–H gels, which were mostly formed from the reaction of 60% GGBFS, interacts with FA. GGBFS sourced an extra quantity of calcium and contributed to a further binding agent, which in turn affects the hardening properties of geopolymer. It is also evident from Fig. 8b that the 60% GGBFS and 40% FA based GC attained enhanced strength, which is due to the formation of

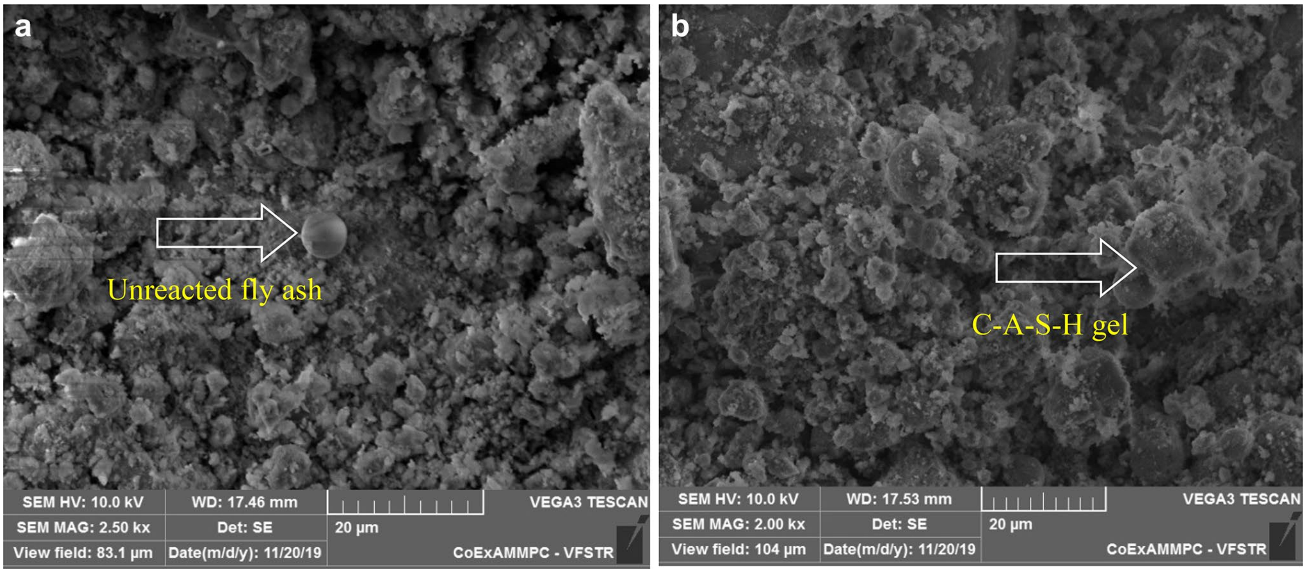

Fig. 8 SEM images **a** 100% FA, **b** 60% GGBFS and 40% FA

additional C–A–S–H gels and a closed pack of microstructure. Figure 8a shows that few FA particles are unreacted, and the micro-cracks were also observed. Development of less geopolymeric gel and no denser microstructure was observed in Fig. 8b; these are the significant reasons that the strength attainment is less in 100% FA based GC compared to all other GGBFS addition mixes.

The XRD images presented in Fig. 9 shows that the significant recognized peak in FA was the quartz with a high potency of 2θ = 27°, which is strengthened by the XRF data where 58.23% of SiO_2 was identified in FA. Mullite was the second significant peak identified in FA at different ranges of 2θ (17, 32, 33, 42, 50, and 61°). The critical peaks found in GGBFS were calcite and quartz at 28, 35, 37° and 21, 42°, correspondingly, and is commanded by the XRF results where 44.7% of calcium oxide was diagnosed in GGBFS. Alite and Belite are major peaks detected in cement at different ranges of 2θ (A = 29, 32, 33, 42° and B = 32, 33°). Pentlandite was another peak identified in cement at 2θ = 52° and 58°.

Fig. 9 XRD patterns of fly ash, GGBFS and cement

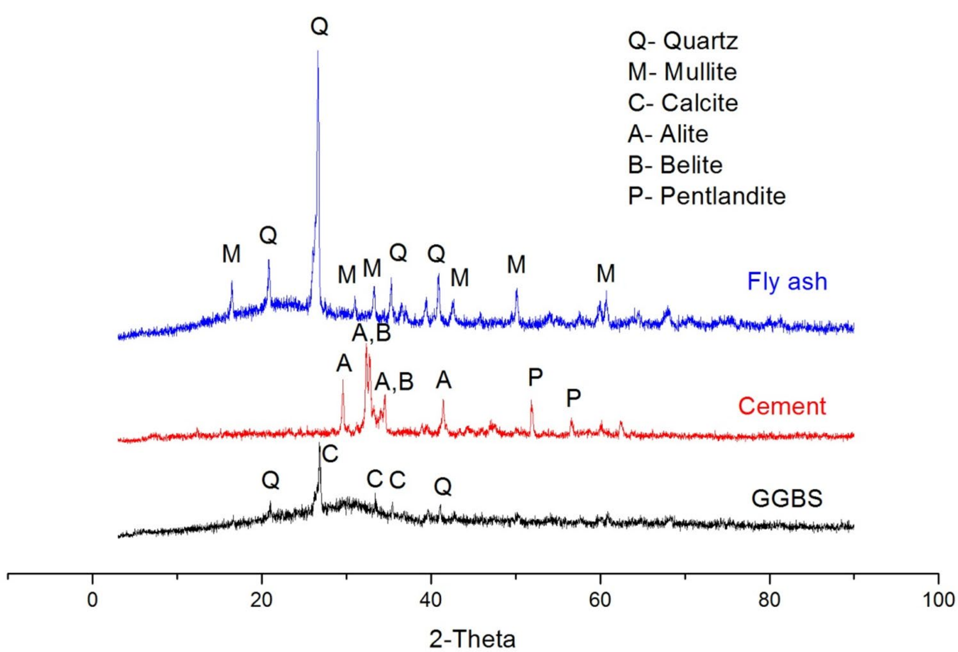

Table 4 Mass loss in % for 60 days immersion in 5% H_2SO_4 solution

No. of days	Loss of mass (%)							
	M1	M2	M3	M4	M5	M6	M7	OPC
30 days	7.58	5.74	5.05	4.33	3.97	3.14	2.41	3.5
60 days	9.37	7.65	6.8	5.76	5.08	4.7	3.56	6.76

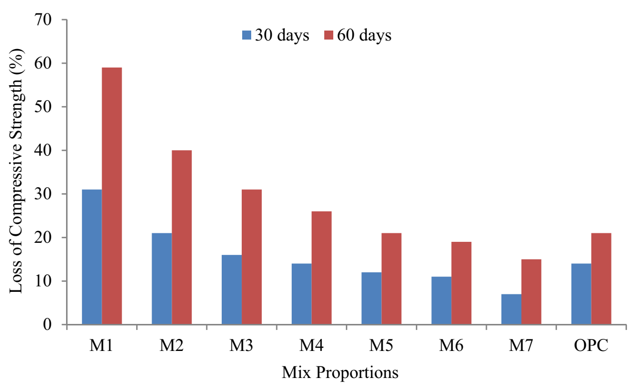

Fig. 10 Loss of compressive strength after immersion in 5% H_2SO_4 solution

3.7 Resistance to sulphuric acid

After 28 days of curing period, the specimens of each batch were taken and their surfaces were cleaned with a soft brush to remove weak reaction products and loose materials from the specimen. The initial mass was measured and the samples were immersed to chemical attack. The mass loss of GC by immersion of samples in 5% H_2SO_4 solution up to 60 days was presented in Table 4. The arrangement was placed at room temperature and standard with a specific end goal to keep up the centralization of the mechanism through the trial, the consistent substitution must be finished. Indeed, even following 60 days stretches of submersion in sulphuric acid, a similar impact is reflected. It was identified from Table 4 that the durability of geopolymer concrete against destructive chemical conditions was excellent, compared to OPC [40]. The mass loss due to the immersion of specimens in 5% of the H_2SO_4 solution for 60 days was 6.76 for OPC and 3.56 for GC, respectively. It demonstrates that mass diminution is a smaller amount in geopolymer concrete contrasted with OPC [41]. The dissolution of Geopolymer specimens in the acid solution indicates the loss of mass due to the contact is only 0.5% compared to ordinary Portland concrete when dissolved in sulphuric acid solution [42].

Figure 10 makes evident that the mix M7 shows the superior compressive strength even after immersion in the acid solution for 30 and 60 days when compared to OPC concrete. GC has excellent resistance against the acid attack, and no deterioration was observed on the surfaces of the specimens. The loss of compressive strength for 30 and 60 days immersion 5% H_2SO_4 solution was 7 and 15%, respectively for mix M7.

3.8 Resistance to sodium chloride

FA-GGBFS based GC exhibits superior protection from the chloride solution. There was no deterioration found on the specimen surface in the presence of sodium chloride arrangements for both 30 and 60 days. It was also observed that there was no significant change in mass and compressive strength. Whereas, the change of mass was obtained by subtracting the mass of cube before immersion in NaCl and mass after immersion. This outcome demonstrates that the use of GC in the construction is excellent in the seawater zone. At the point when contrasted with OPC concrete, GC has incredible mechanical properties and solidness. Table 5 shows the mass loss % of OPC after 30 and 60 days immersion in 5% NaCl solution was 2.5 and 4.1, respectively. Similarly, for GC it was observed as 1.83 and 2.22, respectively. These values are clear evidence that the GC sample has excellent chemical resistance against NaCl solution compared to the reference mix (OPC).

Figure 11 shows that the loss of compressive strength of GC (M7) after immersion in 5% NaCl solution was 5.5 and 11.3% for 30 and 60 days, respectively. While the loss of strength values low for OPC concrete say 8.5 and 17% for 30 and 60 days of NaCl solution curing.

Table 5 Mass loss in % for 60 days immersion in 5% NaCl solution

No. of Days	Loss of mass (%)							
	M1	M2	M3	M4	M5	M6	M7	OPC
30 days	6.14	5.57	5.01	4.26	3.43	2.5	1.83	2.5
60 days	7.5	6.86	6.3	5.17	4.52	3.68	2.22	4.1

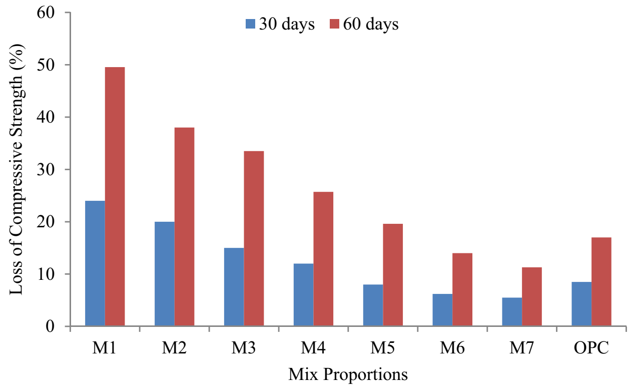

Fig. 11 Loss of compressive strength after immersion in 5% NaCl solution

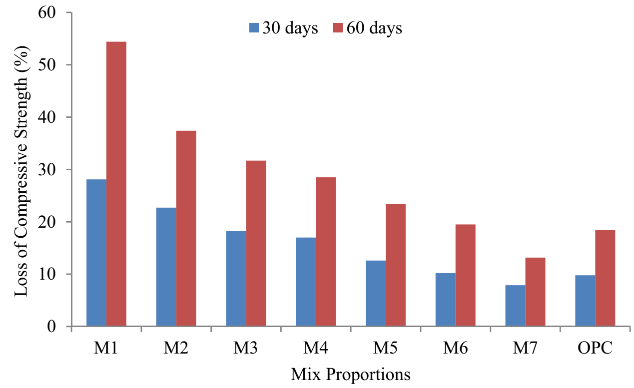

Fig. 12 Loss of compressive strength after immersion in 5% Na_2SO_4 solution

3.9 Resistance to sulphate solution

Table 6 illustrates the performance of FA-GGBFS based GC subjected to aggressive chemical environments; the results showing that the GC was good resistant to sulphate environment. Indeed, after the introduction of these specimens for 60 days to 5% sodium sulphate arrangement, there was no deterioration to the surface. When specimens are exposed to sodium sulphate solutions from 7 to 38%, then the loss of compressive strength was observed [3]. The compressive strength of both GC and OPC is decreasing on disclosure of 30 and 60 days in sulphate and chloride salts, but compared to GC, OPC has more deterioration; GC has significant resistance to sulphate attack. Loss of mass because of samples immersion in Na_2SO_4 liquid for 30 and 60 days were 1.23 and 2.46 in GC as well as 2.1 and 3.6 for OPC, individually; it shows that mass reduction is less for GC contrasted with OPC [42].

The strength loss values were low for GC (M7) when compared OPC for both 30 and 60 days immersion in 5% Na_2SO_4 solution, as shown in Fig. 12. The loss of compressive strength values after 30and 60 days were 9.8 and 18.42%, respectively, for control mix OPC. Whereas, for the GC mix M7, these values are 7.9 and 13.17%, respectively.

4 Conclusions

The following conclusions are drawn from the experimental work conducted on both OPC and GC,

- The geopolymer concrete samples attained superior mechanical properties compared to similar grade of OPC concrete for 28 days of ambient curing.
- The correlation between compressive strength, split tensile strength, and flexural strength for GC mixes is as $f_{ts} = 0.77 \times \sqrt{f_c}$, and $f_{fs} = 0.98 \times \sqrt{f_c}$.
- SEM images depict denser microstructure, thus leading to superior strength attainment for GGBFS added FA-based GC samples.
- The resistance of GC against chemical attack was also superior for the mixes M5 to M7 compared to OPC concrete for 60 days immersion in 5% NaCl, Na_2SO_4, and H_2SO_4 solutions.
- The experimental values are proving that GC has enough ability to replace that OPC concrete in all kinds of Civil Engineering works.

There were a lot of future investigations required on GC to evaluate the microstructural and durability characteristics to improve the practical applications of GC. The

Table 6 Loss of mass in % for 60 days immersion in 5% Na_2SO_4 solution

No. of days	Loss of mass (%)							
	M1	M2	M3	M4	M5	M6	M7	OPC
30 days	7.14	6.47	5.75	4.48	3.6	2.86	1.23	2.1
60 days	8.69	7.2	6.34	5.13	4.17	3.34	2.46	3.6

sustainable utilization of industrialized by-products in the making of GC will help to decrease the environmental problems being caused by cement production. This can be achieved by implementing alternative cementitious materials (like GC) in practical construction applications.

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Compliance with ethical standards

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

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