

The Effect on Mechanical and Microstructure Properties by Varying GGBS Content and NaOH Solution Concentration in Alkaline Solution of Fly-Ash-Based Self-compacting Geopolymer Concrete



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Abstract In this research, mechanical and microstructural properties of Fly-ash-based self-compacting geopolymer concrete (SCGC) were investigated for shear strength and impact strength by substituting Fly Ash with Ground Granulated Blast Furnace Slag (GGBS) by 0, 30, 50 and 70% and by using alkali solutions such as sodium hydroxide and sodium silicate in the ratio 1:2.5 for different NaOH solution molarities like 8, 10 and 12 M. An iterative procedure was utilized to arrive at the SCGC design mix by completing workability tests like slump flow in compliance with European Federation of National Associations Representing for Concrete (EFNARC) criteria. After obtaining the requisite flow, the concrete was poured into the moulds and cured for 24 h at 70 °C in the oven, with ambient treatment occurring for the remainder of the test days. A constant binding content of 400 kg/m³ and a fluid to binder ratio of 0.47 by mass have been maintained for all molarities, while the superplasticizer dosage of 3% has remained constant. And by compromising on strength, the extra water content was adjusted to provide the desired flow. With increasing molarity and GGBS, the slump flow was reduced. As GGBS content and molarity increased, engineering properties such as shear and impact strength increased, and this was justified with microstructure analysis. As compared to the other replacement level, the replacement of 70% of the Fly Ash with GGBS at 12 M showed higher structural strength. Hence, fly ash and GGBS in a ratio of 50:50 could be a better CO₂-reducing alternative to traditional OPC concrete in connection to cost and sustainability.

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Keywords High calcium fly-ash geopolymer concrete (HCFGC) · Fly ash (FA) · Self-compacting geopolymer concrete (SCGC) · Molarities (M) · Specific gravity (S.G.) · Water absorption (W.A.) · Fluid-to-binder ratio (F/B) · Fineness modulus (F.M.)

1 Introduction

Concrete is a potential resource for a variety of projects owing to its structural capabilities and strength. The total consumption is about twenty billion tons, which for every living human being is equal to two tones [1]. In such enormous amounts, human beings ingest. Most construction activities in India are done with concrete, as it is easily available and moulding can be done even by unqualified labour. Therefore, for every human being, concrete becomes a very important material. Cement is a binder that forms a protective bind with other compounds. India is the world's second-largest cement major exporter, factoring for 6.9% of global cement output. India has approximately 420 million tons (MT) of cement production capacity (as of July 2017), which is expected to reach 550 million tons by 2025, according to Indian cement industry research. The cement industry has realized the necessity to reduce concrete creation's ecological consequences while also taking into account the issues that come with it. Cement processing is responsible for over 80% of overall greenhouse gas emissions in concrete, according to Flower and Sanjayan [2]. Portland cement production accounts for around 7% of global emissions [3, 4] and global greenhouse gas emissions are about 50 Gt per year [5] (6.6 tonnes per person). This is the result of kiln calcination and fossil fuel combustion throughout the manufacturing process, according to Roy et al. [6]. Furthermore, according to Berry et al. [4], Portland cement production is a high-energy operation.

The use of alkaline and aluminosilicates to make cement is known as geopolymer by French research scientist Davidovits. As a cement matrix, geopolymer technology performs similarly, but with significantly lower greenhouse gas pollutants, boosted fire and chemical tolerance, and easier scrap disposal. A recent development is the use of geopolymers in modern industrial applications, becoming increasingly popular due to their intrinsic environmental and technical advantages.

Geopolymer concrete, which uses Fly Ash and alkali as the binding agent instead of OPC, is springing up as new material that is friendly to the environment for sustainable development. This effort yields two benefits: reduced CO₂ emissions from OPC processing and more effective operation of industrial waste in the form of Fly Ash, slag and other materials. OPC replacement levels need to be increased and industrial by-products used as supplementary cementing materials should be maximized. SCGC is a new group of non-traditional, modern free binders and self-compacting materials that do not segregate and flow into locations and obstructions by themselves, hence self-compacting geopolymer concrete is a potential field in this approach.

2 Literature Review

In geopolymer concrete, superplasticizer is a key component. On the other hand, Topark-Ngarm et al. [7] have studied HCFGC at room temperature and analysed the effect of extra water, superplasticizer (SP), retarders on the mix to study flow, setting time and compressive strength. The ratio of Alkali liquid to the Fly Ash was 0.5, and the ratio of Sodium Hydroxide solution to Sodium Silicate solution was 1.0, and the concentration of sodium hydroxide solution was fixed at 10 molarity. The superplasticizer used in the study was sulphonate-based and the retarder used was Sika Plastiment, and it was added to the mix by 1, 3 and 5% by mass of Fly Ash and extra water dosage added was 2, 4 and 6% by mass of Fly Ash.

The flow of geopolymer concrete was found to have ramped up when extra water and retarder admixture were added, but when SP was added the flow decreased because chemicals in SP reduced the amount of liquid in the process. Setting time increased when SP and retarder were added but decreased when extra water was added; this is because extra water reduces NaOH concentration and reacts with the calcium in Fly Ash and forms a hydration reaction instead of polymerization. The compressive strength of HCFGC cured at room temperature decreased when extra water and chemical admixtures were added. The average compressive strength ranged from 21.1 to 39.9 MPa when compared to a controlled mix without any extra water and chemical admixture.

Variables such as workability and durability of fly-ash-based geopolymer concrete have been studied in various studies by Hardjito and Rangan [8] and Wallah and Rangan [9] as well as Rangan [10]. The inclusion of a superplasticizer based on naphthalene by up to 4% of Fly Ash by mass increases the workability, and a slight degradation of compressive strength can be seen after an increase in SP dosage by 2%. The slump value also increases as the water content increases. A higher Molarity of sodium hydroxide solution and a higher ratio of sodium hydroxide solution to sodium silicate solution results in higher compressive strengths and also stressed the curing temperature that as the curing temperature increases from 30° to 90 °C the strength also increases but the strength increase from 70 °C is not that significant and also curing hours place a very important role; as the curing hours increase from 4 to 96 h, the strength also increases, but after 48 h the strength increase is not that significant. Geopolymer concrete that has been thermally cured, on the other hand, shows very little strength gain over time.

3 Materials Used

3.1 Fly Ash

The physical and chemical characteristics of the Fly-Ash sample taken for this study are provided in Tables 1 and 2. Fly-Ash samples were found to meet IS 3812: 1981 requirements.

In Fig. 1, scanning electron microscope images of Fly Ash are reproduced. Most of the Fly-Ash particles are smooth and spherical, as shown by these photos. The X-ray diffractogram analysis in Fig. 2 shows that the alumino-silicate-glass matrix has crystalline phases of quartz and mullites. The base hump denotes the existence of reactive silica, which defines fly ash's pozzolanic potential and its ability to respond rapidly with accessible calcium hydroxide to generate cementitious hydration products.

Table 1 Fly ash's physical characteristics

Colour	Grey
S.G.	2.1
Surface area	310 m ² /kg
Bulk density	1.1 gm/cc

Table 2 Chemical composition of fly ash

S. No.	1	2	3	4	5	6	7	8	9
Parameter	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SO ₃	Loss on ignition (% by mass)
Quantity (wt%)	62.63	3.93	23.35	0.46	2.04	0.032	0.03	1.34	0.39

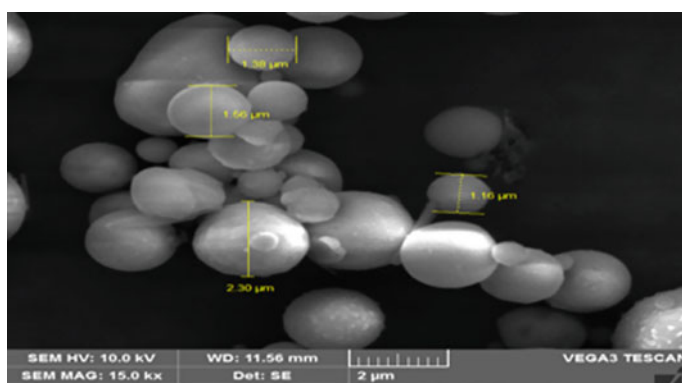


Fig. 1 SEM micrographs of fly-ash specimen

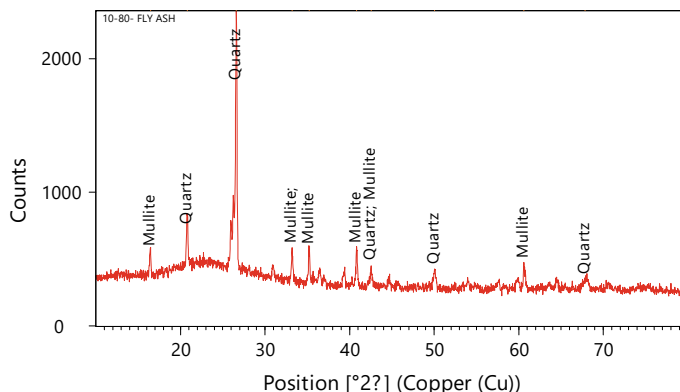


Fig. 2 X-ray diffractogram pattern of fly ash

Table 3 GGBS physical characteristics

Colour	Specific gravity	Surface area
Light grey	2.7	450 m ² /kg

Table 4 Chemical composition of GGBS

Parameter	SiO ₂	CaO	Al ₂ O ₃	MgO	Fe ₂ O ₃	Mno	Sulphide sulphur
Quantity (wt%)	33.77	33.77	13.24	8.46	0.05	0.65	2.23

3.2 Ground Granulated Blast Furnace Slag (GGBS)

The GGBS proposed to be used in the present investigation is from JSW, Ballari, Karnataka. Tables 3 and 4 display the physicochemical characteristics. The test results of the chemical composition of GGBS and the requirements are as per IS: 12089-1987 [11].

SEM micrographs of GGBS in Fig. 3 show more or less angular, flaky and elongated in shape. XRD of the GGBS. Figure 4 shows the significant amorphous phase of calcium, silica and aluminaoxides.

3.3 Alkaline Activators

As an alkaline solution, a blend of sodium hydroxide and sodium silicate was used in this study. Both of these substances are available for commercial purposes. Solvents derived from sodium, on the other hand, were cheaper than those derived from potassium. Sodium silicate aids in the dissolution of the binder components more easily. As a result, both alkalis were of industrial quality. Sodium hydroxide in pellet form

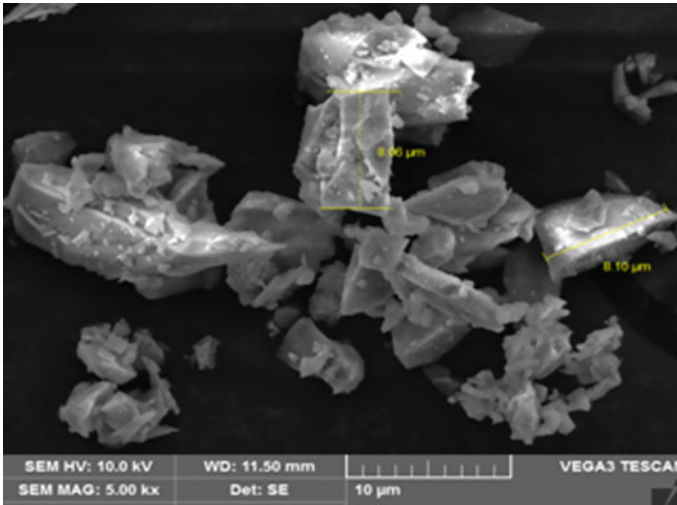


Fig. 3 SEM micrographs of GGBS specimen

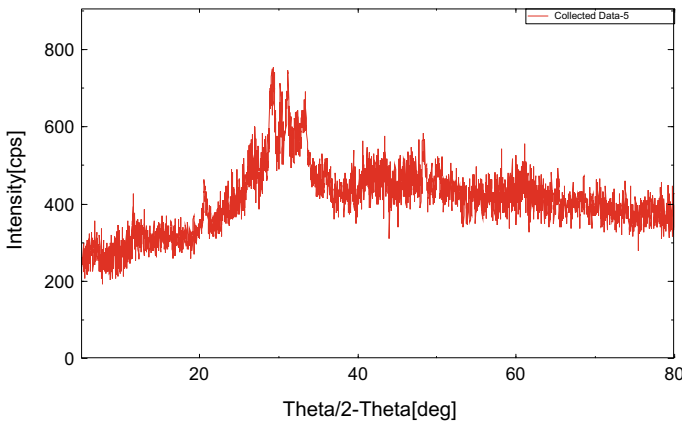


Fig. 4 X-ray diffractogram pattern of GGBS

used in the study is 99% pure and has a specific gravity of 2.11. The pH of the silicate solution is 12 and it is driven by a range of factors including the amount of silica in the solution, as shown in Table 5. The ratio of sodium hydroxide solution to sodium silicate solution is fixed at 2.5 for all of the experiments in the study.

Table 5 Composition of sodium silicate solution

Sp. gravity	Na ₂ O %	SiO ₂ %	Water %
1.55	14.34	29.55	56.11

3.4 Superplasticizer

A contemporary group of polycarboxylic ether-based additive GLENIUM B233 was used.

3.5 Aggregates

The M-sand that verified zone 2 had an S.G. of 2.57, a Water Absorption (W.A.) of 2.21%, and an Fineness Modulus (F.M.) of 2.66, while the crushed coarse aggregate had an S.G. of 2.66, a W.A. of 0.63% and an F.M. of 6.83.

3.6 Mix Proportions

Twelve Fly-Ash blends were swapped with GGBS at 0, 30, 50 and 70% by mass for this study. As stated in Table 6, mix Mix1–Mix2–Mix3–Mix4 corresponds to 8 molarity concentration, mix Mix5–Mix6–Mix7–Mix8 corresponds to 10 molarity concentration and mix Mix9–Mix10–Mix11–Mix12 corresponds to 12 molarity concentration. For all combinations, the (F/B) ratio was kept at 0.47 by mass and the maximum amount of binder was established at 400 kg/m³. The requisite working qualities of SCGC were achieved by keeping the Superplasticizer content at 3% for Mix1, Mix5 and Mix9 and 4% for the remaining combination, and Table 6 shows additional water content based on binding mass molarities.

4 Engineering Properties and Test Results of SCGC

4.1 Test Result of SCGC on Slump Flow

Slump flow must be within 650–800 mm of the acceptable threshold as given by EFNARC. Table 7 shows the results for various molarities, and Fig. 5 illustrates the same. As GGBS granules are flat, elongated and have a large surface area, as shown in Fig. 3, the rate of flow reduces as the amount of GGBS increases, leading to a high supply of water and, as a result, a loss in concrete workability; however, all readings stayed within a prescribed tolerance. The effectiveness of the SCGC decreases as the dosage of sodium hydroxide goes up from 8 to 12 M.

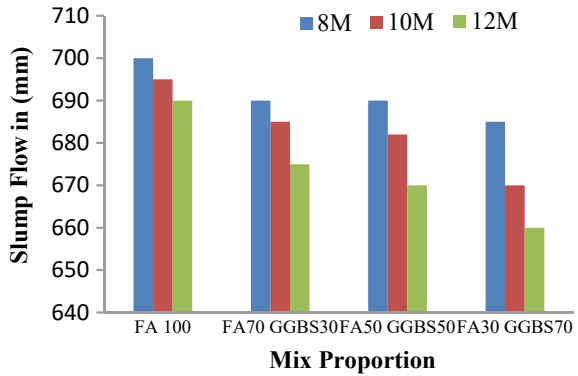
Table 6 Mix proportion

Mix proportion	Fly ash (kg/m ³)	GGBS (kg/m ³)	M-sand (kg/m ³)	Coarse aggregate (kg/m ³)	(F/B) ratio	Molarity (M)	S.P (%)	Extra water (%)
Mix1 (FA 100%)	400	0	872	706	0.47	8 M	3	1
Mix2 (FA 70% and GGBS 30%)	280	153.6	872	706	0.47	8 M	4	1
Mix3 (FA 50% and GGBS 50%)	200	256	872	706	0.47	8 M	4	4
Mix4 (FA 30% and GGBS 70%)	120	358.4	872	706	0.47	8 M	4	9
Mix5 (FA 100%)	400	0	872	706	0.47	10 M	3	2
Mix6 (FA 70% and GGBS30%)	280	153.6	872	706	0.47	10 M	4	2.5
Mix7 (FA 50% and GGBS 50%)	200	256	872	706	0.47	10 M	4	5.5
Mix8 (FA 30% and GGBS 70%)	120	358.4	872	706	0.47	10 M	4	10
Mix9 (FA 100%)	400	0	872	706	0.47	12 M	3	3.5
Mix10 (FA 70% and GGBS 30%)	280	153.6	872	706	0.47	12 M	4	4
Mix11 (FA 50% and GGBS 50%)	200	256	872	706	0.47	12 M	4	7
Mix12 (FA 30% and GGBS 70%)	120	358.4	872	706	0.47	12 M	4	12

Table 7 Workability test results

Mix No.	Mix1	Mix2	Mix3	Mix4	Mix5	Mix6	Mix7	Mix8	Mix9	Mix10	Mix11	Mix12
Slump flow (mm)	700	690	690	685	695	685	682	670	690	675	670	660

Fig. 5 Slump flow test for various molarities



4.2 Test Result of SCGC on Shear Strength

Shear strength tests on an L-shaped shear test specimen on self-compacting geopolymer concrete were done devoid of a stated code, as advised by Bairagi and Modhera [12] and Baruah and Talukdar [13]. Before the concrete was poured, a steel block with a cross-section of 90 mm × 60 mm and a height of 150 mm was inserted into 150 mm side-cube moulds. Figure 6 shows the details of shear test specimens. The sample was mounted in a CTM system and specimen failure is shown in Fig. 7 and loading was applied until the specimen failure was reached.

SCGC’s shear strength increases when the GGBS content rises and the Fly-Ash content falls, as illustrated in Fig. 8. However, the strength of all mix proportions increases gradually and marginally after 28, 56 and 90 days.

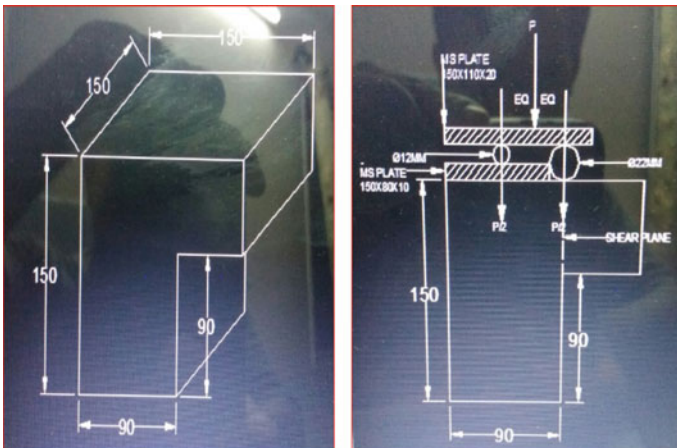
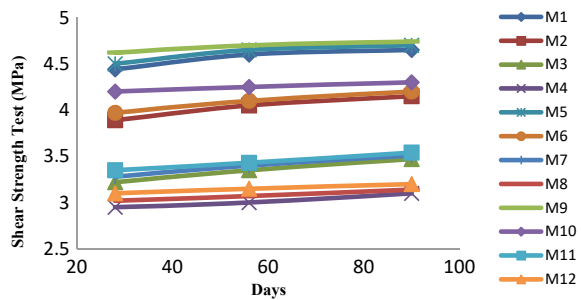


Fig. 6 Details of shear test specimen

Fig. 7 Failure of shear test specimen in CTM machine



Fig. 8 Shear strength w.r.t. different binder components and molarity



At the end of 90 days, the percentage strength gain for (30%–50%–70%) replacement of Fly Ash by GGBS for 8 M, 10 M and 12 M compared to control mix FA100 is around 4.3–18.2%–30.4%, 4.2%–18.2%–28.9% and 2.9%–8.1%–18.5%.

At the close of 90 days, the percentage boost in strength from 8 to 10 M and from 10 to 12 M for Mix1 and Mix2 series is 2.1% and 14.8%, respectively. The Mix3 and Mix4 series have a 2.2% and 5.0% boost in strength, accordingly.

The maximum concrete shear strength given in IS 456-2000 [14] is approximately 2.5 MPa for (conventional) concrete grade M20. Therefore, it can be observed from Fig. 10 that for 8 M and 10 M samples for 50% and 70% Fly-Ash replacement with GGBS, all specimens achieved strength above 2.5 MPa and for 12 M all formulations

achieved shear strengths around 2.6–3.2 MPa. In view of this, geopolymer concrete based on oven-cured Fly-Ash–GGBS can be considered to perform satisfactorily.

4.3 Test Result of SCGC on Impact Strength Test

By means of Schruder’s impact test machine, the impact strengths of self-compacting geopolymer concrete have been obtained. As a result, samples with a diameter of 150 mm and a thickness of 60 mm (high) were employed. The experiment is placed in Schruder’s impact assessment apparatus, and a 45.4 N hammer (ball) is lowered from a height of 457 mm, as shown in Fig. 9. The number of blows that must occur for the initial and final breakdown to occur is recorded. The final failure is to create cracks enough in the sample to impact at least three out of four sections of concrete on the base plate.

The compressive, tension and flexural strength test are subjected to a low-stress rate, and the behavior of concrete subjected to a high-stress rate and the energy absorption can be known by impact test. The experimentation is to study the Impact resistance of SCGC by the incorporation of mineral admixture in various proportions. Table 8 demonstrates the impact strengths and eventual failure of specimens at 28, 56 and 90 days for various replacements of Fly Ash by GGBS in SCGC, as recommended by ACI Committee 544 [15].

Table 9 displays the percentage increase in impact energy of SCGC compared to the control mix Mix1 for 8 M, Mix5 for 10 M and Mix9 for 12 M for all testing days.

Impact resistance was improved in comparison to Fly Ash, which has a surface area of around 310 m²/kg, due to its strong wrapping ability and porous structure of GGBS, which is around 450 m²/kg, as shown in Table 3. Furthermore, the SEM



Fig. 9 Impact test setup and failure of impact specimen

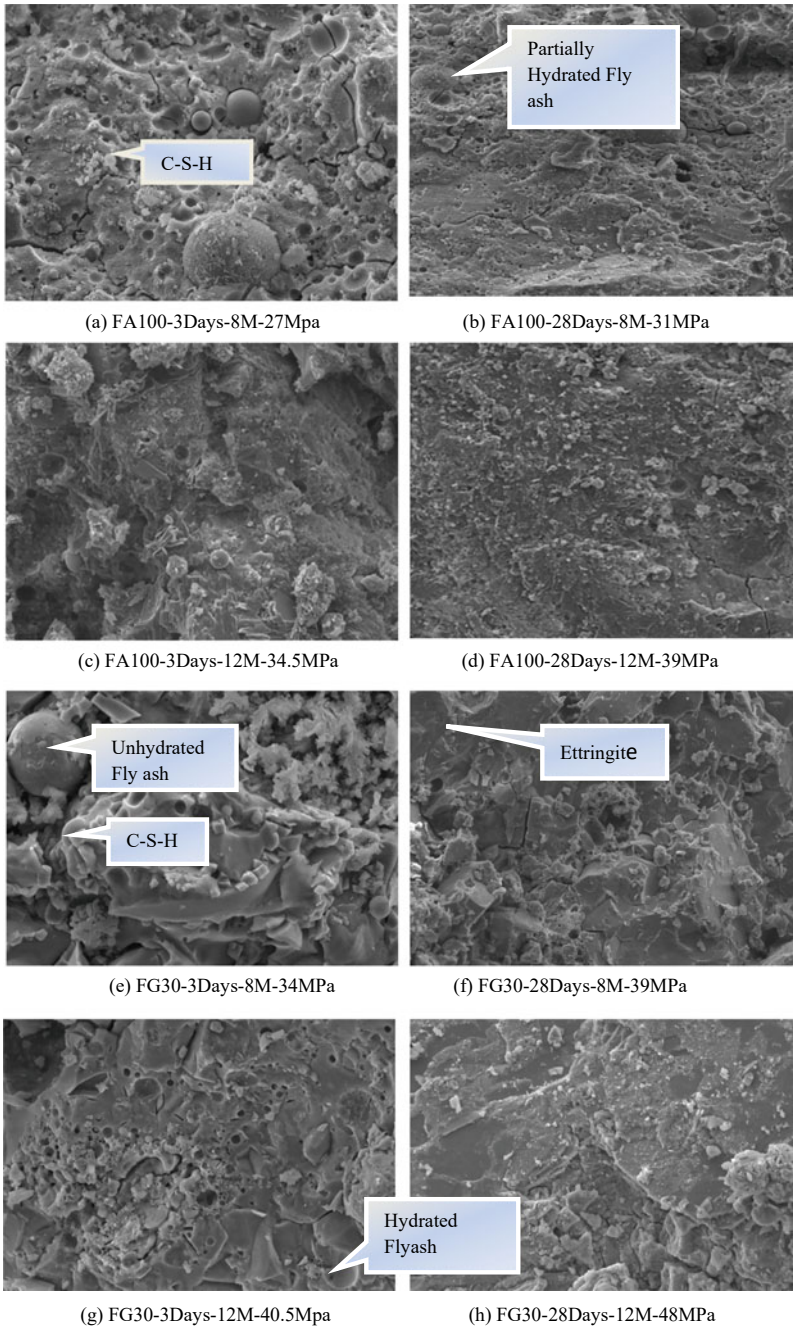


Fig. 10 SEM images of fly ash/GGBS-based SCGC w.r.t. different binder composition and molarity

Table 8 Impact energy of fly ash/GGBS-based SCGC

Mix	Molarity	28 days		56 days		90 days	
		First crack, N m	Final crack, N m	First crack, N m	Final crack, N m	First crack, N m	Final crack, N m
Mix1	8 M	1058	1141	1183	1245	1328	1390
Mix2		1141	1203	1245	1307	1411	1452
Mix3		1224	1307	1328	1369	1452	1514
Mix4		1390	1452	1432	1494	1535	1597
Mix5	10 M	1141	1224	1266	1307	1432	1494
Mix6		1203	1266	1348	1390	1514	1556
Mix7		1286	1348	1432	1473	1597	1660
Mix8		1432	1473	1514	1577	1722	1763
Mix9	12 M	1183	1245	1348	1432	1473	1535
Mix10		1266	1307	1411	1473	1535	1597
Mix11		1328	1390	1514	1577	1639	1722
Mix12		1494	1556	1618	1680	1763	1867

Table 9 % Increase (+) or % decrease (-) in impact energy

Mix	Molarity	% Increase (+) or % decrease (-) in the impact energy of SCGC at 28 days		% Increase (+) or % decrease (-) in the impact energy of SCGC at 56 days		% Increase (+) or % decrease (-) in the impact energy of SCGC at 90 days	
		First crack, N m	Final crack, N m	First crack, N m	Final crack, N m	First crack, N m	Final crack, N m
Mix1	8 M	0	0	0	0	0	0
Mix2		7.84	5.43	5.24	4.97	6.25	4.46
Mix3		15.68	14.54	12.25	9.95	9.33	8.92
Mix4		31.37	27.25	21.04	20	15.58	14.89
Mix5	10 M	0	0	0	0	0	0
Mix6		5.43	3.43	6.47	6.35	6.35	4.14
Mix7		12.70	10.13	13.11	12.70	12.70	11.11
Mix8		25.5	20.34	19.58	19.78	20.65	18
Mix9	12 M	0	0	0	0	0	0
Mix10		7	4.97	4.67	2.86	4.20	4.03
Mix11		12.25	11.64	12.31	10.12	11.26	12.18
Mix12		26.28	24.97	20	17.31	19.68	21.62

picture of GGBS in Fig. 3 reveals that flakier and longer particles make GGBS particles more packable.

Due to increased sodium hydroxide concentration, the increase in molarity increased SCGC's energy absorption. In addition, the energy absorption capacity was greater when Fly Ash was replaced with GGBS at 70%, regardless of the molarity, on all test days.

The percentage gain in strength at ultimate failure from 8 to 10 M and from 10 to 12 M for 70% substitution of Fly Ash with GGBS at 90 days is 10.39% and 5.89%, accordingly. This implies that self-compacting geopolymer concrete based on oven-cured Fly Ash–GGBS performs well in terms of impact strength.

5 Microstructure Studies

5.1 Evaluation of Microstructure and Compressive Strength with Age w.r.t. Different Binder Composition and Molarity

The micrographs (Fig. 10a, b, e, f), (8 M) and (Fig. 10c, d, g, h), (12 M) of hardened geopolymer concrete samples, taken after 3 days and 28 days of compressive strength tests, for FA100 mix (Fly Ash 100%) and FG30 mix (Fly Ash 30% and GGBS 70%), respectively, reveal microstructural morphology with respect to binder composition and molarity.

In micrograph (a) for 100% Fly Ash at 8 M when tested at 3 days, the Fly-Ash particles are spherical as shown in Fig. 1, of different sizes and dissolved to a different extent which can be seen distributed throughout. Some of the Fly-Ash particles appear to have dissolved almost completely, while large number of particles have partially dissolved. Completely un-reacted spherical particles are visible.

In micrograph (b) for 100% Fly Ash at 8 M when tested at 28 days, we can see that the un-reacted and marginally reacted Fly-Ash particles seem to be bonded in the matrix. And when compared with micrograph (a), only a few un-reacted spherical particles are visible and hence the geopolymer matrix in (b) is more compact than in (a), and the strength attained is more than 3 days at 28 days (31 MPa).

When compared to micrographs (a) and (b) in micrographs (c) and (d), the matrix appears to be more homogeneous with surface continuity. Correspondingly, the compressive strengths have also increased due to the maximum dissolution of the binder components in alkaline liquid with 12 M NaOH. The strength attained at 3 days and 28 days is of order 34.5 MPa and 39 MPa, respectively.

In image (e), a few undissolved Fly-Ash particles do exist in spite of much better dissolution and the reaction of both Fly Ash and GGBS. Voids, discontinuous micro-cracks and partially dissolved GGBS particles are also visible. The strength gained at 3 days is around 34 MPa. This is due to more CaO percentage as shown in Table 4.

However, the microstructure of micrograph (f) is far more compact because at later stages GGBS content led to the formation of higher geopolymeric and CSH gel, resulting in much higher strength development of around 39 MPa at 28 days.

In micrographs (g and h) due to the high concentration of NaOH, the un-reacted Fly-Ash particles are almost absent; dissolution of Fly Ash and GGBS is more complete and uniform. Micro-pores and semi-spherical cavities as a result of the breakdown of Fly-Ash particles at this stage can be seen in micrograph (g). Still, the matrix appears to be dense and compact giving strength in excess of 40.5 MPa and 48 MPa, respectively.

Thus, significant progressive morphological changes take place with a progressive increase in GGBS content as shown in micrographs (e)–(h) compared to micrographs (a) and (b) resulting in better strength performance.

According to Song et al. [16], the alkaline activated slag microstructure was highly smooth, uniform and interconnected-solid in all samples. Increased alkali doses, on the other hand, contributed to more degree of reactivity and more sealed pores, resulting in a less porous microstructure.

6 Conclusion

1. With the addition of GGBS and molarity concerning the reference mix (fly ash 100%), slump flow values decreased and all the values were within the limits of EFNARC guidelines.
2. With age, oven-cured SCGC centred on fly ash/GGBS gain strength for all binder fractions and molarities.
3. At all ages, shear strength increases with an increase in GGBS and a decrease in Fly Ash. Unaffected by the mix, an increase in molarity also increases shear strength. These strengths vary from 5 to 10% of the respective compressive strength.
4. The increase in GGBS and molarity increased the energy absorption and hence increased the impact resistance of SCGC, and energy absorption capacity was more for 70% replacement of fly ash with GGBS irrespective of any molarity for all the days of testing.
5. The microstructure images reveal a very dense structure and correspondingly higher strength with age. A similar observation is made with an increase in GGBS content and also with an increase in the molarity of NaOH solution.
6. From both competitiveness and cost standpoints, a Fly Ash:GGBS proportion in the spectrum of 50:50, regardless of molarity, appears to be desirable.

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