Mix Design Methodology for Fly Ash and GGBS-Based Geopolymer Concrete

G. Mallikarjuna Rao and M. Venu

1 Introduction

With the continuous increase in human population, the housing sector and construction industry have gained boom to meet the current demand. The increased usage and demand for cement production day by day lead to huge depletion of natural resources which ultimately results in environmental issues. To overcome these problems, there is a need to focus on new emerging binding materials such as industrial by-products, which will reduce the environmental pollution. Emerging technology aids for the utilization of industrial by-products into useful materials such as fly ash, GGBS, metakolin and rice husk ash. The development of alkali-activated binders with superior engineering properties as well as longer durability has emerged as an alternative to ordinary Portland cement (OPC). Geopolymer (inorganic polymer concrete) is an emerging class of cementitious material and could be the next-generation concrete for civil infrastructure applications. This innovative technology provides a new platform for the sustainable growth of our urban society in the coming decades and helps in building durable structures. These materials can be used as a replacement to the binder in concrete as a major construction material.

Davidovits, 1970, reported the use of waste materials like fly ash and GGBS as high alkaline solution activators to form geopolymer. The constituents of the commonly used alkaline solution are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The alkaline solution helps to bind the loose aggregates in mixture to form geopolymer concrete (GPC) which has high strength, durability and low creep [1]. The alkaline solution activates silica and alumina to form aluminosilicate hydrate in fly ash and forms calcium silicate hydrate (C–S–H) by reacting with calcium in GGBS. The curing conditions, especially temperature, play a significant impact on the polymerization process [2]. Researchers have [3] concluded that a combination

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of sodium hydroxide and sodium silicate solutions can be a good application for activators. High concentration of sodium hydroxide solution and curing temperature enable the concrete compressive strength to be higher. Various authors have studied the importance of molar ratio of Na_2SiO_3/NaOH and suggested that to achieve maximum compressive strength the binder content to be constant. The reported constant binder content value is 2.5 [4]. Rangan [5] proposed a mix design methodology for geopolymer concrete with fly ash and [6] suggested modifications in Indian Standard code for suitability of GPC. Black [7] carried out research on fly ash-based geopolymer concrete by considering different mix proportions and developed a mix design process by varying the water to geopolymer solids ratio with two different molarities of NaOH, i.e. 8M and 12M. The research concluded that the flash set was a significant problem for GPC mixes.

In the present study, a mix design procedure was developed for both normal- and standard-grade geopolymer concrete by varying the ingredients. The ingredients varied for all the mixes are quantity of fly ash, quantity of water, grading of fine aggregate, fine aggregate-to-total aggregate ratio by maintaining sodium silicate-to-sodium hydroxide ratio as 1 and sodium hydroxide molarity. Based on the past work done on GPC, the present research work is planned by considering the parameters, viz. type of binder, binder content, alkaline/binder ratio. The ratio of sodium silicate to sodium hydroxide is kept at 2.5 with molarity of NaOH as 8M. This investigation aims to study the influence of the above-considered parameters on strength and durability of geopolymer concrete.

2 Research Significance

From the literature survey, to the best of authors' knowledge, there is no proper mix design for fly ash and GGBS-based geopolymer concrete till date, and it shows that the study needs to focus on mix design aspects for geopolymer concrete. This will help the structural engineers in design aspects to implement the same for the field application. The present investigation aims a proper mix design methodology for fly ash and GGBS-based GPC.

3 Materials

3.1 Fly Ash and GGBS

Materials used in this research are GGBS obtained from Andhra Cements, Vishakhapatnam, India, and fly ash from Ramagundam Thermal Power Plant, India, with a specific gravity of 2.90 and 2.17, respectively. The chemical compositions of GGBS and fly ash were presented in Table 1.

Table 1 Chemical composition of both fly ash and GGBS (% by mass)

Chemical composition	Fly ash	GGBS
SiO_2	60.10	34.02
Al_2O_3	26.50	20.00
Fe_2O_3	4.20	0.81
SO_3	0.33	0.93
CaO	4.00	32.65
MgO	1.21	7.86
Na_2O	0.20	NIL
LOI	0.85	NIL

3.1.1 SEM and XRD for Fly Ash and GGBS

Scanning electron microscopy (SEM) is performed to study the microstructure of fly ash and GGBS. The scanned images of fly ash and GGBS are shown in Figs. 1 and 2. Scanning electron microscopy image gives an approximate idea about the shape, angularity, size and surface texture of fly ash and GGBS. The GGBS particles appear

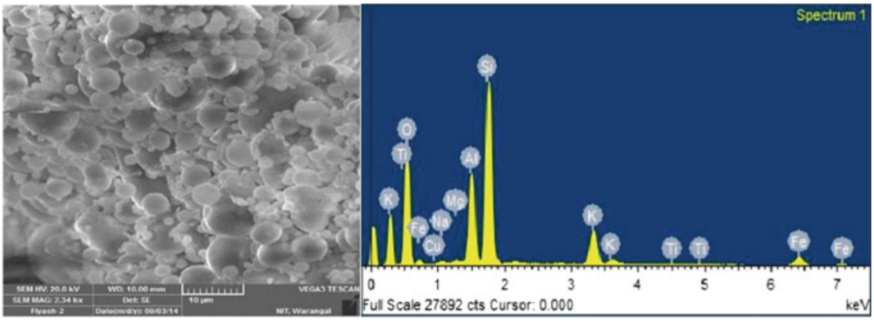

Fig. 1 Scanning electron microscope of fly ash and EDXA of fly ash

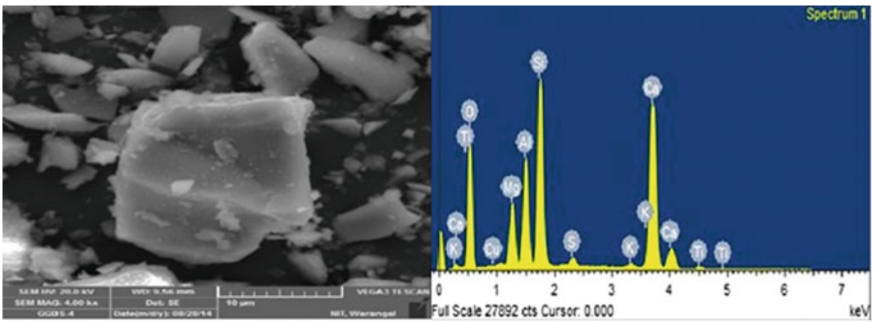

Fig. 2 Scanning electron microscope of GGBS and EDXA of GGBS

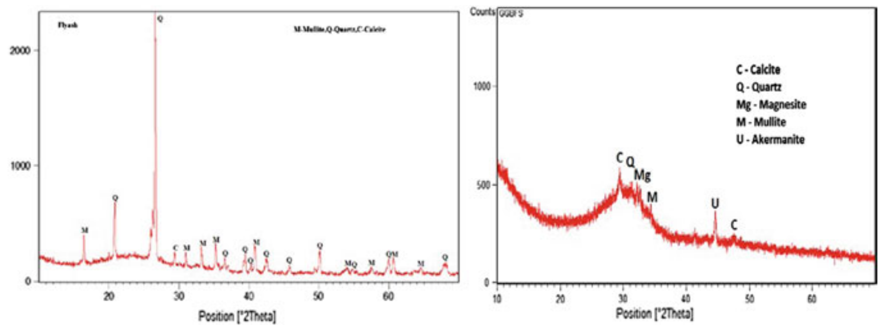

Fig. 3 XRD analysis for fly ash and GGBS

to have straight, flaky-elongated shape with sharp-edged angularity, rough surface texture and large variation in size (1–10 μm). The fly ash particles appear to have spherical shape with smooth surface in a broad range of sizes (with the lower limit being approximately 1/10 the maximum fly ash particle size, i.e. 1–10 μm in size). The energy-dispersive X-ray spectroscopy of fly ash and GGBS is also shown in Figs. 1 and 2. From the energy-dispersive X-ray spectroscopy, it is seen that GGBS is enriched with more silica percent than other elements. Fly ash particles contain more percent of silica and alumina (Fig. 3).

3.2 Alkaline Liquid

The alkaline solution is the combination of sodium hydroxide and sodium silicate solutions. Sodium hydroxide is used in the present study because it is less expensive than potassium hydroxide and widely available. Sodium hydroxide of 98% purity available in pellets form is used in the investigation. These sodium hydroxide pellets were dissolved in potable water and prepared the solution of required molarity. Sodium hydroxide solution of required molarity and sodium silicate in liquid form and the chemical composition of the sodium silicate is Na_2O—7.5–8.5%, SiO_2—26.5% and remaining is H2O content are mixed and stored at room temperature for 24 h before its use (Fig. 4).

3.3 Fine Aggregate

A locally available river sand is used as a fine aggregate, and it conforms to Zone-2 according to IS: 383 [8]. The specific gravity and bulk density are 2.62 and 2.59, respectively.

Fig. 4 Sodium hydroxide and sodium silicate solution

3.4 Coarse Aggregate

A locally available crushed rock maximum size of 20 mm is used as a coarse aggregate, and it is according to IS: 383 [8].

3.5 Water

Potable water was used for entire research work to prepare NaOH solution.

3.6 Preparation of Concrete

The fly ash and GGBS are mixed well until once it reaches homogeneity, and thereafter, fine and coarse aggregate is added, and these are allowed to mix for 2 min in Hobart electric mixer. For instance, the prepared alkaline activator is added to the prepared mix which is a combination of fly ash, GGBS, fine aggregate, and it is mixed well for another 3 or 4 min in Hobart electric mixer. The prepared fresh mixes are cohesive and resistant to segregation. Afterward, GPC is poured into the molds of size 100 mm × 100 mm × 100 mm by three layers consecutively with compaction and vibration to avoid air bubbles in concrete. After 24 h of casting, the specimens were demolded, and these were cured under ambient temperature until the age of testing.

3.7 Experimental Program

An experimental program consisting of five mixes, in each mix fly ash—GGBS proportion varied between 75FA:25GGBS, 50FA:50GGBS, 25FA:75GGBS and 0FA:100 GGBS for the binder. For the corresponding mixes, alkaline liquid-to-binder ratios were selected as 0.45, 0.5, 0.55 and 0.6, respectively. Geopolymer concrete density was noted, and it varied from 2200 to 2400 kg/m^3. Once the density of concrete is known, then the total amount of binder and alkaline solution can be calculated easily. The ratio of sodium silicate to sodium hydroxide solution is kept constant as 2.5 for the total experimental program.

4 Results and Discussions

The density of the fly ash and GGBS based geopolymer concrete specimens are shown in Fig. 5. With increase in density, there is an increase in the alkaline/binder ratio, and the maximum density was observed for the mix of 0% FA+100% GGBS. Maximum density was observed at alkaline/binder ratio 0.6 for all the combinations. Geopolymer concrete is a new concrete, and the density of the geopolymer was quite similar to that of the conventional concrete. The density of the geopolymer concrete depends on the binder content, alkaline/binder ratio and method of compaction. The density range observed for geopolymer concrete was 2300–2500 kg/m^3.

The UPV test is a measure to presence of voids and the consistency of concrete. The 7 days UPV for different combinations of the fly ash and GGBS mix was found to be 3.26–4.5 km/s for outdoor-cured specimens for different combinations, whereas

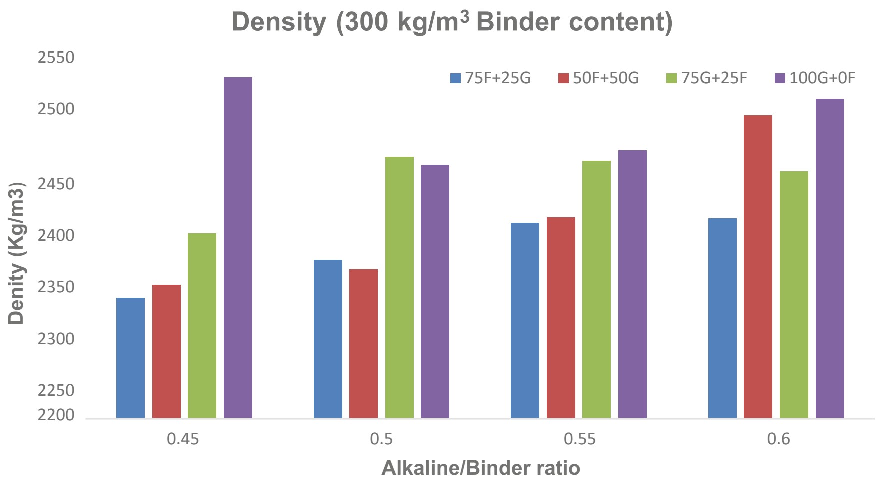

Fig. 5 Density for fly ash and GGBS-based geopolymer concrete (300 binder content)

for higher GGBS content mixes, there is a little rise in the values compared to that of lower GGBS content. **Whitehurst** classified fly ash-based geopolymer concrete as excellent, good, doubtful, poor and very poor for UPV values of 4.5 km/s and above, 3.5–4.5, 3.0–3.5, 2.0–3.0 km/s and below 2.0 km/s, respectively. Generally, high-pulse velocity reading in concrete is indicative of concrete of good quality. The presence of voids has been recognized to have an influence on the UPV transmission. The measured 28-day UPV values for all geopolymer concrete specimens are presented in Fig. 6. In geopolymer concrete, for the attainment of strength, polymerization process plays an important role. The quality of the concrete mainly depends on the internal microstructure formed.

Figure 7 shows the compressive strength of different alkaline to binder ratios with binder content 300 kg/m^3. In the present study, effect of fly ash and GGBS concrete under outdoor curing was studied. The compressive strength of GPC cured under outdoor curing (0% FA+100% GGBS) combination shows the higher strength than the mixes prepared with the other combinations of GGBS. In order to eliminate the oven curing, the specimens were casted with the fly ash and GGBS combination. For many practical applications, it is very important that the concrete should be cast and cured under normal temperatures. The maximum compressive strength of 45 MPa is attained at 100% GGBS even under outdoor curing. This concludes that combination of fly ash and GGBS can produce satisfactory results even with 8M NaOH. Hence, the obtained results proved that oven curing can be eliminated for producing GPC, where there is difficulty in providing oven curing. At 7 days age of curing, 100% GGBS achieved the maximum compressive strength. In the case of 75% FA-25%, GGBS proportion indicates the lesser compressive strength. The

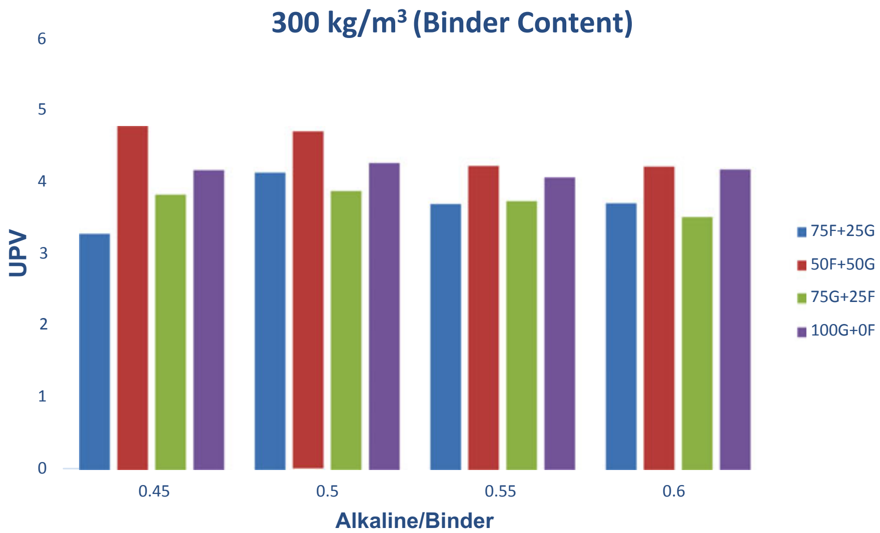

Fig. 6 UPV for fly ash and GGBS-based geopolymer concrete (300 binder content)

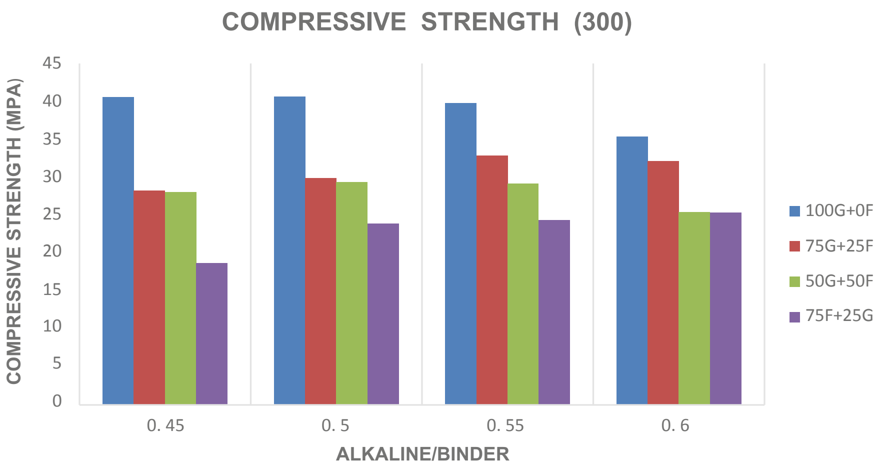

Fig. 7 Compressive strength for fly ash and GGBS-based geopolymer concrete (300 binder content)

increase in compressive strength is mainly due to high amount of calcium present in GGBS. The improvement of strength of fly ash and GGBS-based GPC is due to increased calcium content present in GGBS which significantly accelerates the polymerization process to improve strength.

5 Conclusions

- The percentage increase of GGBS in binder content shows the increase in compressive strength of geopolymer mortar.
- The combination of fly ash and GGBS is a possible solution for producing GPC even under outdoor curing condition.
- The geopolymer concrete dry density varied from 2400 to 2500 kg/m^3 for (100% GGBS+0% fly ash) binder proportion, and for remaining proportions, it varied from 2300 to 2400 kg/m^3 which is likely to be conventional concrete.
- For higher density samples show the higher in the compressive strength when the age of 7 days for all mixes.
- The significant increase in compressive strength was observed at alkaline/binder ratio of 0.55 for a binder content of 300 kg/m^3.
- UPV performance is good for GPC at the age of 7 days, and it shows the similar trend to that of conventional concrete noticed, i.e. 3.5–4.5 km/s. This range shows the good sign of concrete quality and homogeneity.

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