Quantitative assessment of fly ash based geopolymeric mortar using granulated blast furnace slag as fine aggregate

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Abstract

Implementing the utilization of industrial by-products in lieu of natural resources represents a dual-pronged approach towards fostering sustainability. The construction industry stands as a significant domain wherein vast quantities of natural resources are excavated incessantly to satiate the ever-growing demands associated with what is often referred to as 'development'. In this article, we have presented a unique solution to decrease the natural resource over exploitation. We have used granulated blast furnace slag (GBFS) as fine aggregate from Iron and steel Industries along with fly ash which is a by-product of thermal power industries to create high strength geopolymer mortar. Our approach minimizes the contribution of conventional cements and contribute to the sustainability in the construction industry. The main challenge behind the idea is optimization of GBFS concentration. Other parameter that needs optimality are, sodium hydroxide to sodium silicate ratio, geopolymer binder to fine aggregate ratio, molarity etc. In this study we have only focussed on GBFS optimal concentration. We have taken four different mixtures based on different concentrations of GBFS ranging from 0 to 100% (0 indicate 0% GBFS and 100 river sand). We note that, the compressive strength of 25GBFS enhance by 12.5% from 0GBFS batch. Granulated blast furnace slag sand exhibits potential as a viable alternative to river sand for partial substitution. Additionally, the utilization of fly ash geopolymeric mortar, incorporating GBFS sand, presents an emerging and environmentally friendly option for sustainable construction materials. Such innovative solutions can be effectively employed in the production of precast building components, contributing to a more eco-conscious manufacturing process.

Keywords: *Granulated Blast Furnace slag, fly ash, geopolymeric mortar, compressive strength*

1. Introduction

River sand is the most crucial element in the making of mortar and concrete across the globe. Its appeal comes from easy availability, omni presence, good physical, mechanical and durability properties. In addition, sand helps to sustain a constant volume which may distort in setting, hardening and while resisting applied forces, resulting in better overall sustainability. Meanwhile, excessive mining of river sand for using as fine aggregate is majorly responsible in depletion of river bed, which reduces water holding capacity and slippage of riverbanks [1]. Essentially, sand in river bed is what preserves the environment equilibrium [2]. According to the report from United Nations Environment Programme [3], there will be huge surge in aggregate utilization from 22 billion tonnes in 1970 to 60 billion tonnes by 2030. However, not more than 5% of the world's sand are good enough to produce quality construction product [4]. The scarcity of river sand in the procurement process has prompted researchers to explore alternative solutions for its substitution. As a result, the concept of manufacturing sand (m-sand) has emerged as a potential alternative.

At present, the world is facing the challenge of accumulating landfills filled with waste materials and by-products generated by various industries. Among these by-products is Granulated Blast Furnace Slag (GBFS) originating from iron industries. GBFS is formed when the molten slag is rapidly cooled through high-pressure water jets during the manufacturing of pig iron. As per the report from Indian Minerals Yearbook 2021 [5], depending on the composition of Iron ore, for ore feed containing 60-65% Iron, blast furnace slag production ranges from 300-450 kg per tonne of pig or crude iron produced. Currently, steel plants from India generates 24 million tonnes of blast furnace slag which projected to be 45-50 million tonnes by 2030.

On the other hand, suitability of selecting fine aggregate largely depends on the binding matrix. Cement matrix ruling the domain in such context, but cement production generates 7% of world's carbon dioxide (CO_2) [6], quantitatively around 1 tonne of CO_2 emits per tonne of cement production [7]. Viewing the sustainability and eco-friendly prospects, geopolymer matrix is novel method coined by French scientist prof. Joseph Davidovits [8], he suggested any pozzolanic source materials (like fly ash, rice husk ash, metakaolin etc.) mixes with alkaline activator forms alumino-silico framework of covalently bonded, non-crystalline (amorphous) 3D network [9]. Several studies suggested the better physical, mechanical, and durable properties of fly ash based geopolymeric mortar [10-13]. Thus, in lieu of opting cement matrix this study concern over more sustainable and eco-friendly approach of geopolymeric binder.

In this study, we have taken five combinations of fly ash and GBFS sand based geopolymeric mortar, where GBFS sand substitute the river sand between (0-100) %, namely 0GBFS (0% GBFS and 100% sand), 25GBFS (25% GBFS and 75% sand), 50GBFS (50% GBFS and 50% sand) and 100GBFS (100% GBFS sand), we have investigated on different parameters such as density, water absorption and compressive strength to explore the suitability of GBFS sand as river sand substitution in fly ash based geopolymeric medium.

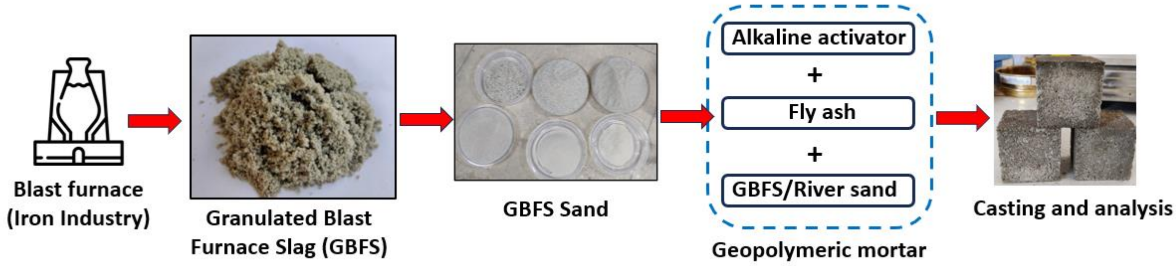


Fig. 1 Process flow diagram of fly ash/GBFS sand based geopolymeric mortar.

2. Materials and methods

2.1 Raw Materials

Fly ash from NTPC-SAIL Power Company Ltd. (NSPCL), Bhilai (C.G.), which is class-F fly ash confirming to IS 3812: 2013 (Part-I) [14] and GBFS from Bhilai Steel Plant (BSP), Bhilai (C.G.) and locally available river sand collected and both graded confirming to zone-II of IS 383:2016 [15]. Chemical composition of fly ash and GBFS tabulated in Table 1. Physical properties of river sand and GBFS sand showed in Table 2. Raw materials proportion tabulated in Table 3.

Table 1. Chemical composition of FA and GBFS (% wt.).

Chemical composition	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**TiO_2**	**CaO**	**K_2O**	**MgO**	**Na_2O**	**SO_3**
Fly Ash (FA)	54.20	29.80	4.65	1.77	1.11	1.24	0.62	0.14	0.30
(GBFS)	30.30	12.30	1.01	0.56	38.70	0.50	8.13	0.19	1.18

Table 2. Physical properties of fine aggregate.

Fine aggregate	**Apparent density (kg/m^3)**	**Specific gravity**	**Fineness modulus**	**Water absorption (%)**
River Sand (RS)	2650	2.60	2.76	0.8
GBFS	1290	2.10	2.65	7.5

2.2 Specimen preparation

Laboratory grade Sodium Hydroxide (NaOH) of 10M concentration and ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide kept 1 along with ratio of fly ash to fine aggregate is 1:4 and ratio of alkaline activator solution to binder is (0.45-0.55). In a mixer, fly ash was mixed with fine aggregate for 5 minutes and then poured pre-prepared alkaline activator solution for another 5 minutes. The geopolymer mix was then transferred to oiled 70.6 x 70.6 x 70.6 mm^3 cubes, filled in two layers with each layer had 25 rodding and vibrated on vibrating table for 1-2 minutes for proper compaction. All the specimens transferred to hot air oven curing at a temperature of 80°C for 24 hrs and left for ambient curing until testing age. Mix proportion is listed in Table 3.

2.3 Testing technique

2.3.1 Water absorption

Three cubes of 28 days maturation from each mix were oven dried at temperature of 100-105°C (temperature set below 110 °C to avoid disturbance in the microstructure of mortar) for 4 hours and is weight determined as initial dried weight. The samples were then immersed in water for 24 hours and its saturated surface dry weight was recorded as the final weight. Water absorption of specimens reported as the percentage increase in weight. Water absorption calculated using eq. (1)

$$WA\ (\%) = \frac{Wf - Wi}{Wi} x\ 100 \qquad (1)$$

Where, Wf = Final weight, Wi = Initial weight

2.3.2 Mortar density

Mortar of all the specimen with different substitution percentage of GBFS weighted after 28 days of casting, average of three samples weight recorded and mortar density evaluated using eq. (2)

$$D\ (g/cm^3) = \frac{W}{V} \qquad (2)$$

where, W = Average sample weight, V= Volume of cube

2.3.3 Compressive strength

Compressive strength of fly ash/GBFS sand based geopolymeric mortar recorded using compression testing machine confirming to IS 516:1959 [16]with considering rate of loading of 2.9 kN/s, where mean of one specimen (three samples) tested simultaneously to provide a reading. Likewise, similar fashion is opted for all different composition of fly ash-GBFS sand based geopolymeric mortar.

Table 3. Mix ingredients of fly ash/GBFS sand based geopolymeric mortar (kg/m^3).

Mix ID	Fly Ash	NaOH (10M)	Na_2SiO_3	Fine Aggregate	
				(RS)	(GBFS)
0GBFS	375	44.65	44.65	1490	0
25GBFS	375	44.65	44.65	1120	370
50GBFS	375	44.65	44.65	745	745
100GBFS	375	44.65	44.65	0	1490

3. Results and discussion

3.1 Fine aggregate analysis

River sand and GBFS sand were evaluated using IS 2386:1963 (Part-III) [17] and tabulated in Table 2.

3.2 Water absorption analysis

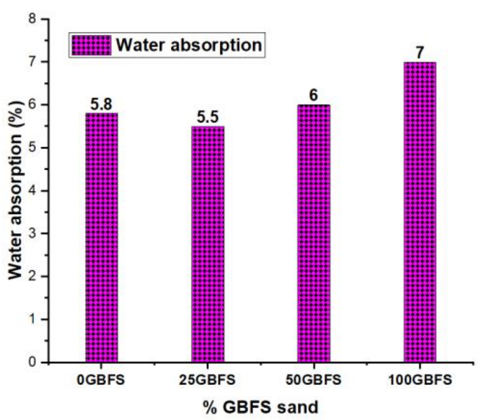
Percentage variation in water absorption lies between 5.8 % to 7%, where 25GBFS showed minimum water absorption with a decrease of 5.17% from 0GBFS, 50GBFS showed increase of 3.45% and 100GBFS results in maximum water absorption with 20.69% increment from 0GBFS. Results plotted and showed in fig. 2(a).

3.3 Mortar density analysis

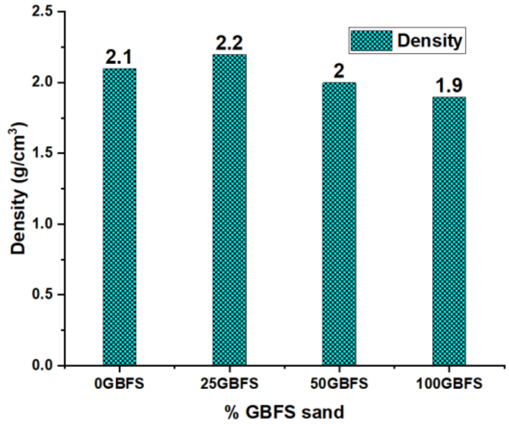
Fig. 2(b) demonstrates the variability of mortar density after 28 days of casting. GBFS mortar density varies in between (1.9 – 2.2) g/cm^3, 100GBFS showed minimum density and 25GBFS results in highest density of 1.9 and 2.2 g/cm^3 respectively. It is inferred that fineness and specific gravity plays major role in the density of the product, so on increasing percentage GBFS sand, density of mortar decreases notably. Comparing to 0GBFS, 25GBFS showed 4.75% increment and 100GBFS results in 9.5% decrement.

Table 4. Compressive strength of fly ash/GBFS sand based geopolymeric mortar.

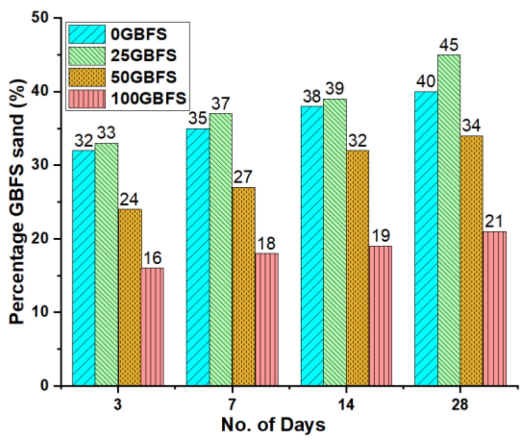
Mix ID	**Compressive strength (MPa)**			
	3 Days	**7 Days**	**14 Days**	**28 Days**
0GBFS (100 % River sand)	32	35	38	40
25GBFS (75 % River sand)	33	37	39	45
50GBFS (50 % River sand)	24	27	32	34
100GBFS (0 % River sand)	16	18	19	21



(a)



(b)



(c) **(d)**

Fig. 2 (a) Water absorption (b) Mortar density (c) Compressive strength (d) Failure modes of mortar.

3.4 Compressive strength analysis

The compressive strength of all specimens listed out in Table 4. In geopolymer technology, alumino-silicate source material dissolve to aluminate and silicate, set to equilibrium then formation of gelation (releases H_2O), reorganisation (again releases H_2O) and finally polycondensation and hardening happens [18]. All in all, with time hardening takes place, which can be clearly noticed from fig. 2(c) compressive strength of all mix increases from 3 days to 28 days. Every single mix follows inverted U-shape pattern starting from 3days up to 28 days, and maximum strength reported at 25GBFS mix for all the combinations. Whereas, maximum strength of 45MPa achieved on 28 days in 25GBFS and minimum strength of 21MPa reported in 100GBFS, which is 12.5% highest increment and 47.5% highest decrement respectively from 0GBFS.

Conclusion

The investigation examined the potential use of Granulated Blast Furnace Slag (GBFS) as a substitute for river sand in fly ash based geopolymeric mortar. The study found that incorporating GBFS in the geopolymeric mortar showed promising results, particularly when used as a partial replacement for river sand. The best outcomes were observed when 25% GBFS was used in conjunction with river sand. Furthermore, the compressive strength results indicated that the geopolymeric mortar with 25GBFS exhibited a comparable strength to 43 grade OPC cement, with a 28-day strength of 45MPa. Similarly, the geopolymeric mortar with 50GBFS demonstrated a strength equivalent to 33 grade OPC cement. Additionally, the investigation assessed water absorption, and it was observed that the geopolymeric mortar with 25GBFS exhibited the lowest water absorption among all the mixes. This finding suggests that the combination of 25GBFS offers enhanced durability properties.

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Conflict of Interest: The authors declare no conflict of interest.

Authors contribution: PKG* has performed the study, AW and GKA have done the literature survey, PKG* and RGB prepared the manuscript, MM, RKC and PKG reviewed and edited the manuscript. All authors have agreed to publish the manuscript.

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