Mix Design of Fly Ash and GGBS based Geopolymer Concrete activated with Water Glass

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ABSTRACT

Geopolymer Concrete (GPC) has emerged as an alternative to cement concrete due to its reduced carbon footprint and excellent mechanical properties. However, not much emphasis is made on the development of mix designs using industrial waste. The current study focuses on the mix-design considerations for GPC using fly ash and Ground Granulated Blast Furnace Slag (GGBS). The mix design of GPC involves in selecting materials to produce the desired strength. In this investigation, Water Glass (WG) is used as an activator for the activation of the polymerization reaction. The mix design of GPC is the optimization of a group of various parameters, such as the activator to binder ratio, aggregate to binder ratio, coarse aggregate to fine aggregate ratio, activator concentration, and amount of binder content. The activator to binder ratio affects workability and strength, while the activator concentration influences the polymerization reaction and final strength development. The selection of suitable aggregates plays a vital role in achieving a dense and durable GPC matrix. The mix design for GPC requires a holistic approach that considers the selection of appropriate binders, activators, and aggregates. Proper optimization of these factors can result in excellent strength and durability of the GPC and a reduced carbon footprint. Further research is needed to explore alternative binders, evaluate long-term performance, and establish standardized mix design guidelines for the widespread adoption of GPC in construction.

Keywords-water glass; geopolymer concrete; mix design; fly ash; GGBS

I. INTRODUCTION

Due to the rapid growth of the construction industry, the cement usage is increasing day by day. Urbanization and population growth increase cement footprint [1]. Cement is one of the chief ingredients used for the production of concrete. The use of cement in concrete can be eliminated by producing Geopolymer Concrete (GPC). By substituting cement with geopolymer materials in the construction industry, a dual benefit is achieved, reducing pollution and utilizing industrial waste [2, 3]. The consistency of geopolymers falls within the specified ranges for Ordinary Portland Cement (OPC) [4]. Mix proportions of GPC mainly depend on the alkaline solution to binder ratio and alkaline activator concentration [2]. Mix design by considering target strength and performance was developed in [5]. A suitable design approach was used with regard to the performance requirements of GPC and actual production circumstances in [6]. Fly ash content is a direct indicator of workability and strength [7-10]. Mix proportions for GPC developed utilizing a new data-driven mix design tool that is built on an artificial neutral network to forecast fresh and hardened properties of Geopolymer concrete were studied in [11]. Alkaline activator to binder ratio and alkaline activator concentration influence the compressive strength of GPC [12]. Increasing slag and sodium silicate to sodium hydroxide ratio up to 3, the GPC's mechanical characteristics increase while setting time decrease [13]. Mix design of GPC depends on the alkali/binder ratio, binder content, sodium silicate/sodium hydroxide ratio, molarity, and water/solids ratio [4]. Workability and strength of fly ash-based GPC depend on alkaline/binder ratio, super plasticizer-to-binder ratio and water-to-binder [12]. Modifying water glass for Ground

Granulated Blast Furnace Slag (GGBS)-based GPC leads to extended setting times [11]. By incorporating GGBS along with low calcium fly ash as binders, the GPC achieved comparable strength and setting time to that of OPC [11]. The type and dosage of the activator used are crucial factors in the geopolymer production process. Geopolymer produces high compressive strength due to its denser matrix arrangement [2]. Using low modulus Water Glass (WG) results in a thicker diffusion layer and an increased presence of OH^- and Na^+ ions in the water glass. This activation of a greater proportion of Si-Al reaction in the raw material leads to improved strength of GPC [6]. GPC composites of different strength grades demonstrate remarkable resistance against sulfate attack when compared to OPC composites. Partially replacing fly ash in geopolymer mortar significantly enhances its resistance against sulphuric acid attack [8, 14, 15]. The decrease in consistency value corresponds to a higher slag content in the mixture [14]. The main limitation of GPC is the curing process, which necessitates heat curing or steam curing [16]. GPC is a suitable alternative to traditional cement, aiming to effectively diminish the carbon footprint [17-19]. To enhance workability and setting time in Alkali-Activated Slag Concrete (AASC), one approach is to substitute a portion of GGBS with a binder abundant in SiO_2 and CaO. This alteration implies that AASC blends likely to possess superior strength in comparison to OPC mixes and also reduces reliance of natural resources [10, 15]. The increase in compressive strength of GPC results in a corresponding enhancement of its shear strength [17-19].

II. EXPERIMENTAL PROGRAM

Combinations of low calcium fly ash and GGBS were taken as binders. The specific gravity of GGBS and fly ash was 2.87 and 2.19, respectively. Their chemical compositions after XRF analysis are shown in Table I.

TABLE I. CHEMICAL COMPOSITION OF GGBS AND FLYASH (% MASS)

	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	SO_3	LOI
Flay ash	60.12	26.35	4.21	1.26	4.1	0.23	0.35	3.25
GGBS	34.29	20.15	32.4	7.39	0.8	Nil	0.91	3.85

To activate the binder, WG is used as activator. The chemical composition of WG is 24.95%-SiO_2, 12.79%-Na_2O, and 62.2%-H_2O. WG is an impure form of sodium silicate and its grade is indicated by the SiO_2/Na_2O ratio. An activator with a SiO_2/Na_2O ratio of 1.99 was used, its pH value of 12 and a density of 1.6 gm/cc. The fine aggregates utilized in this application were Godavari river sand, possessing a specific gravity of 2.6 and a fineness modulus of 2.73. Crushed granite chips were employed as coarse aggregates, featuring a specific gravity of 2.7, and having a nominal maximum size of 10 mm.

A. Specimen Preparation

The dry materials were carefully placed in a 100 kg capacity pan mixer. Optimum dosages of WG solution were added in the mixer, and continuous mixing was carried out for 5-10 min. Once the mixing process was completed, slump test was conducted to verify workability. The ready-mixed concrete was immediately poured into standard cubic molds measuring 100 mm × 100 mm × 100 mm and compacted with a compacting rod. The molds were left undisturbed for a period of 24-72 hr depending on the composition of the binder used in the mix.

B. Specimen Curing

The specimens were carefully removed from the molds and curing was conducted at ambient temperature. The curing duration for GPC is affected by several factors, including the properties of the WG solution and the proportion of fly ash and GGBS in the mix.

C. Specimen Testing

The specimens were subjected to compression testing using a 3000 kN tester, applying load at the standard rate recommended by IS 516. The intensity values were reported after a curing period of 28 days.

III. MIX PROPORTIONS

The investigation aims to assess the influence of the WG solution on both the workability and strength characteristics of GPC when subjected to ambient curing conditions. After considering the existing mix designs from the literature were taken as a reference, and a new formulation was designed.

A. Factors that Influence the Mix Proportion of GPC

The factors considered in this investigation are: binder content, fly ash, and GGBS proportions, and WG to binder ratio. The investigation specifically examines the following effects on the strength of GPC.

B. The Influence of the WG to Binder Ratio (WG/B) on the Strength of GPC

The WG/B ratios considered for the laboratory testing and analysis are: 0.4, 0.45, 0.5, 0.55, 0.6, and 0.65. Additionally, the considered fly ash to GGBS ratios (F:G) were 40:60, 50:50, and 60:40. When WG/B increased, it resulted in higher early strength development, due to the higher concentration of the activator, which accelerates the geopolymerization reactions and enables the quick formation of the geopolymeric gel. Consequently, the concrete attained strength at a faster rate. The results indicated that increasing the WG/B up to 0.5 resulted in improved GPC strength and workability. However, further increases in the ratio led to increased workability only for a WG/B of 0.6, while strength gradually decreased regardless of the F:G value. When the WG/B reached 0.65, the mixture became excessively fluid, negatively affecting workability and causing issues like segregation and bleeding. Figures 1-3 exhibit the variation of the compressive strength of GPC for different WG/B ratios.

C. The Impact of the Aggregate to Binder Ratio (AG/B) on Strength

By fixing the unit weight of GPC at 2400 kg/m^3, for binder content of 340 kg/m^3 and WG/B ratio equal to 0.5, the AG/B was calculated as 5.55. For different binder contents, the AG/B values are shown in Table II. Increasing the AG/B leads to a decrease in the strength of GPC. Figures 4-6 show the strength of GPC for different AG/B values.

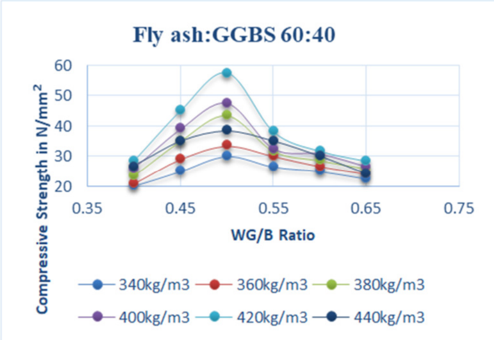

Fig. 1. Compressive strength of GPC for different WG/B and F:G = 60:40.

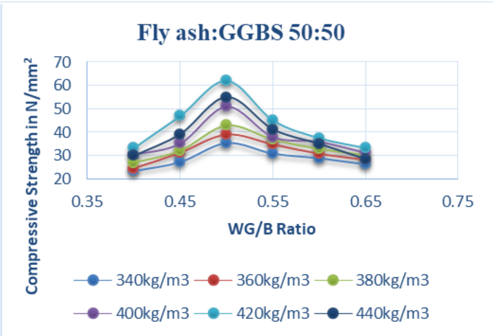

Fig. 2. Compressive strength of GPC for different WG/B and F:G = 50:50.

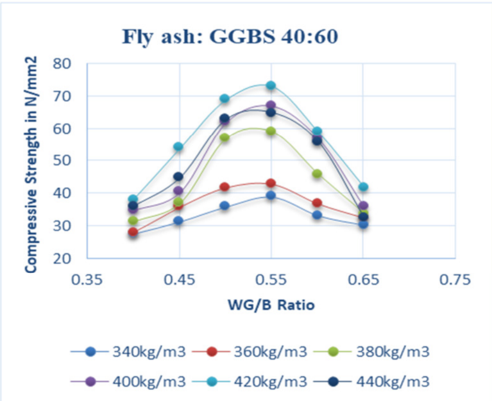

Fig. 3. Compressive strength of GPC for different WG/B F:G = 40:60.

D. Amount of Binder Content on Strength

The considered minimum and maximum binder content were 340 kg/m^3 and 440 kg/m^3 respectively, as per IS10262, and were based on nominal maximum size of coarse aggregates of 12.5mm. The strength of GPC was found to be notably impacted by the quantity of binder content present in the mixture. By increasing the binder content, the strength of GPC improved up to 420 kg/m^3 and was after slightly reduced, due to the formation of a more extensive geopolymeric gel and enhanced bonding between particles. As a result, the GPC exhibits enhanced compressive strength. Excessive binder content results in reduced workability. Figures 7-8 show the variation of the compressive strength of GPC for different binder content values.

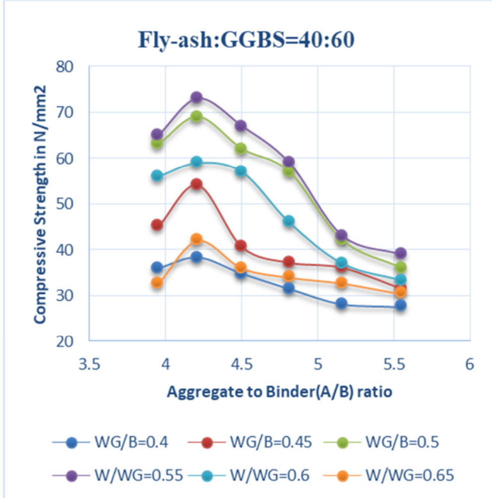

Fig. 4. Compressive strength of GPC for different AG/B to binder ratio and F:G = 40:60.

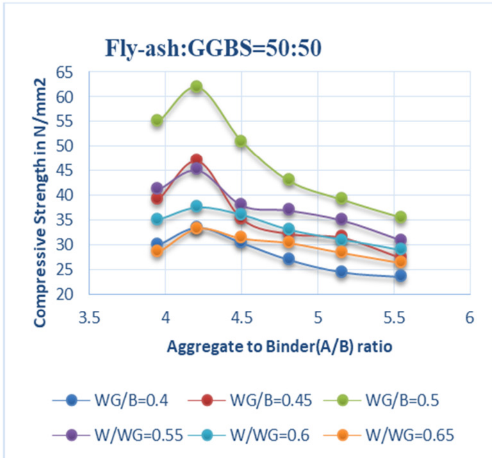

Fig. 5. Compressive strength of GPC for different AG/B to binder ratio and F:G = 50:50.

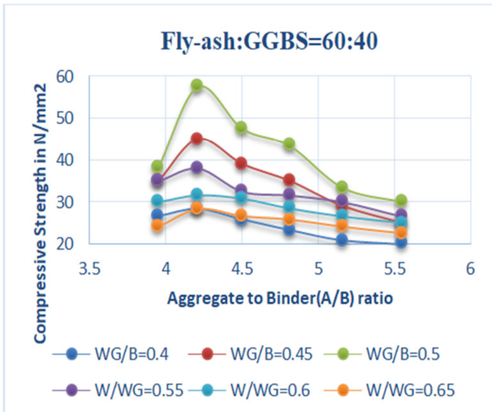

Fig. 6. Compressive strength of GPC for different AG/B to binder ratio and for F:G = 60:40.

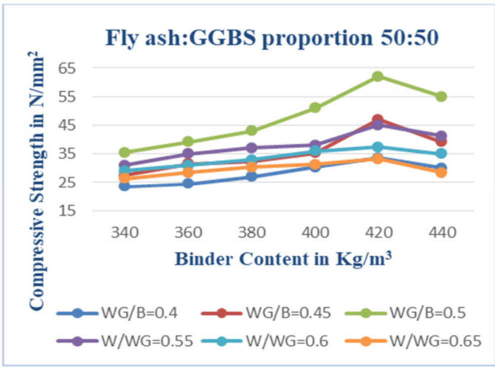

Fig. 7. Compressive strength of GPC for different binder content and for F:G = 50:50.

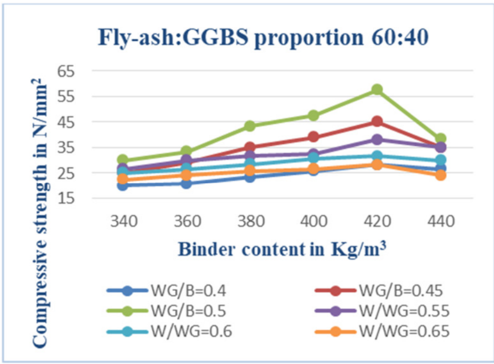

Fig. 8. Compressive strength of GPC for different binder content and for F:G = 60:40.

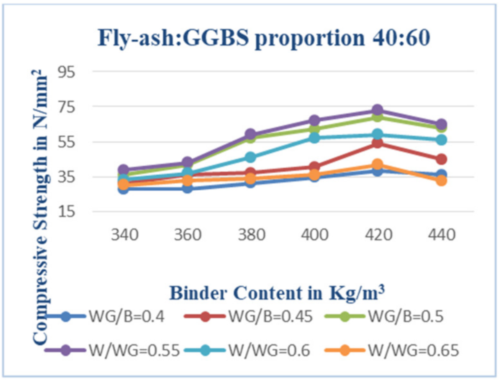

Fig. 9. Compressive strength of GPC for different binder content and for F:G = 40:60.

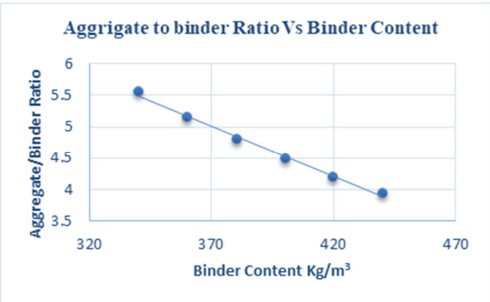

Fig. 10. Variation of AG/B of GPC for different binder content values.

IV. MIX DESIGN METHOD OF GPC

Figures 1-9 and Table II are used as references for the proposed mix design of GPC. In order to reduce the number of trials to attain the desired strength of GPC and streamline the mix design process, the following procedure is proposed.

A. Proposed Mix Design Methodology Steps

1) Step 1: Calculation of the Target Mean Strength

As the target mean strength, is determined by the guidelines outlined in IS 10262. The calculation for the target mean strength (F_t) is:

$$F_t = F_{ck} + 1.65\ S \quad (1)$$

where F_t is the target mean strength of the GPC after 28 days, F_{ck} is the compressive strength of GPC, and S is the standard deviation.

2) Step 2: Estimation of WG/B

Figures 1-3 depict the variations in compressive strength of GPC under different combinations of GGBS and fly ash contents. For F:G equal to 60:40 and 50:50, the compressive strength of the concrete exhibited an ascending trend until the WG/B reached 0.5. Subsequently, the strength started to decrease, and this decline continued until the WG/B reached 0.65. However, when F:G = 60:40, the compressive strength increased until WG/B = 0.55. Notably, when the WG/B was maintained at 0.5, the strength consistently increased regardless of the binder content, encompassing both fly ash and GGBS.

3) Step 3: Estimation of AG/B

The AG/B was selected from Figures 4-6 and was based on the target strength of the GPC.

4) Step 4: Selection of the Binder Content for the Required AG/B

Figure 10 illustrates the relationship between the AG/B and binder content (Kg/m^3). Based on this information the appropriate binder content was selected.

5) Step 5: Estimation of Coarse and Fine Aggregates

The coarse aggregate to total aggregate content ratio is shown in Table II. These values are taken as per IS10262-2019.

6) Step 6: Estimation of WG content

The quantity of WG required can be determined based on the WG/B. The mass of WG content per unit volume of GPC (in kg/m³) is selected based on the target strength requirements. Subsequently, the quantity of WG is determined.

V. CONCLUSIONS

The experimental work yielded the following findings:

- Increasing the proportion of GGBS in the mixture resulted in higher compressive strength of GPC, indicating that GGBS positively influenced the overall strength of the material. When GGBS proportions exceeded 50%, the workability of GPC reduced for the WG/B less than 0.55.
- The WG/B increase after 0.5 results in higher early strength development, due to the higher concentration of the

activator, which accelerates the polymerization reactions and facilitates the rapid formation of the polymeric gel. Consequently, the concrete gains strength at a faster rate. When the WG/B increased to 0.6, the GPC became excessively fluid, negatively affecting workability and causing issues like segregation and bleeding.

- Increasing the binder content leads to higher strength in GPC, because a higher amount of binder results in a more extensive geopolymeric gel formation and better bonding between particles.
- Increasing the AG/B leads to a decrease in the strength of GPC, because a higher proportion of aggregates reduces the amount of binder available to form the geopolymeric gel, resulting in weaker bonding between the particles.

TABLE II. COMPRESSIVE STRENGTH AND SLUMP PROPERTIES OF GPC FOR VARIOUS FLY ASH TO GGBS AND WG/B

CA/TA	**IS10262**	**Cl 5.5.1**	**0.52**		**0.51**		**0.5**		**0.49**		**0.48**		**0.47**	
WG/B			**0.4**		**0.45**		**0.5**		**0.55**		**0.6**		**0.65**	
F: G	**Binder (kg/m^3)**	**TA/B**	**CS**	**S**	**CS**	**S**	**CS**	**S**	**CS**	**S**	**CS**	**S**	**CS**	**S**
50:50	**340**	**5.55**	23.5	25	27.4	32	35.5	47	31	59	29	73	26.4	77
	360	**5.16**	24.5	37	31.5	41	39.2	51	35	62	31	75	28.4	83
	380	**4.81**	27	42	32.3	50	43	75	37	93	33	105	30.4	120
	400	**4.5**	30.4	50	35.3	67	51	95	38	105	36	115	31.3	127
	420	**4.21**	33.5	63	47	73	62	127	45.1	135	37.5	155	33.3	163
	440	**3.95**	30	67	39.2	77	55	135	41.2	155	35	167	28.5	180
60:40	**340**	**5.55**	20	30	25	35	30	65	26.5	72	25	87	22.5	95
	360	**5.16**	20.8	50	29	53	33.35	77	30	89	26.6	93	24.1	125
	380	**4.81**	23.3	55	35	59	43.4	85	31.6	95	28.5	115	25.8	132
	400	**4.5**	25.8	62	39	73	47.5	97	32.5	117	30.8	127	26.6	135
	420	**4.21**	28.3	71	45	79	57.5	115	38	126	31.6	135	28.3	150
	440	**3.95**	26.6	77	35	85	38.3	125	35.0	132	30	145	24.1	165
40:60	**340**	**5.55**	27.7	20	31.5	28	36	34	39	43	33.3	49	30.4	55
	360	**5.16**	28.1	23	36.1	32	42	43	43	47	37	57	32.7	63
	380	**4.81**	31.5	32	37.2	37	57	49	59	53	46	61	34	72
	400	**4.5**	34.8	41	40.6	43	62	51	67	59	57	67	36	75
	420	**4.21**	38.35	48	54.1	51	69	55	73	62	59	69	42	79
	440	**3.95**	36	51	45.1	55	63	65	65	73	56	81	32.7	93

S=Slump in mm; CS=Compressive Strength in N/mm^2; TA/B=Total Aggregate to Binder ratio; F:G=Flyash:GGBS

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