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EFFECT OF WASTE GLASS POWDER ON FRESH AND MECHANICAL PROPERTIES OF GGBFS–FLY ASH BASED GEOPOLYMER PASTE

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ABSTRACT
The present study investigates the influence of waste glass powder (GP) on the fresh and mechanical properties of geopolymer paste containing Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA). Waste glass powder was incorporated as partial replacement of GGBFS and combined GGBFS–FA systems at replacement levels of 5%, 10%, 15%, and 20%. A total of 180 geopolymer paste specimens were prepared and cured under ambient curing and elevated temperature curing conditions. Experimental investigations were conducted to evaluate flowability, initial setting time, and compressive strength characteristics of geopolymer paste.
The experimental results revealed that the incorporation of glass powder reduced the flowability of geopolymer paste from 165 mm for the control mix to 142 mm at 20% GP replacement because of increased fineness and enhanced reactivity of glass particles. Similarly, the initial setting time decreased from 72 minutes to 48 minutes with increasing glass powder content. However, significant improvement in compressive strength was observed with the addition of glass powder. The geopolymer paste containing 15% GP exhibited optimum performance with a 28-day compressive strength of 52.6 MPa under ambient curing and 58.4 MPa under elevated temperature curing, compared to 45.3 MPa and 50.1 MPa respectively for the control mix. The incorporation of glass powder enhanced the geopolymerization process and resulted in denser matrix formation with improved mechanical properties. The study concludes that waste glass powder can be effectively utilized as a sustainable supplementary precursor material in geopolymer paste, contributing to improved strength characteristics and sustainable construction practices through efficient waste utilization and reduction of environmental pollution.
Keywords: Geopolymer paste, Waste glass powder, GGBFS, Fly ash, Compressive strength, Sustainable construction

1. INTRODUCTION

The rapid growth of infrastructure development and urbanization has resulted in a substantial increase in the consumption of Ordinary Portland Cement (OPC) throughout the world. Although cement plays a crucial role in the construction industry, its manufacturing process is highly energy intensive and contributes significantly to greenhouse gas emissions, particularly carbon dioxide (CO_2). It is estimated that cement production alone is responsible for nearly 7–8% of global CO_2 emissions. Therefore, the development of sustainable and environmentally friendly alternatives to conventional cementitious materials has become an important area of research in modern construction practices. In recent years, geopolymer technology has emerged as a promising alternative to OPC-based materials because of its lower carbon footprint, superior durability, rapid strength development, and enhanced resistance to chemical attack. Geopolymers are inorganic aluminosilicate materials synthesized through the reaction between aluminosilicate-rich precursor materials and alkaline activator solutions. Industrial by-products such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are widely utilized as precursor materials in geopolymer systems because of their high silica and alumina contents.

Fly ash is a waste material generated from thermal power plants during coal combustion, whereas GGBFS is a by-product obtained from the iron and steel industry. The utilization of these industrial wastes in geopolymer materials not only improves engineering performance but also contributes toward sustainable waste management and conservation of natural resources. GGBFS-based geopolymer systems are particularly known for their high early-age strength and better performance under ambient curing conditions because of the presence of reactive calcium compounds. Apart from industrial by-products, waste glass powder has also attracted considerable attention as a sustainable supplementary material in geopolymer systems. Large quantities of waste glass are disposed of in landfills every year, creating severe environmental problems due to its non-biodegradable nature. Waste glass powder contains a high percentage of amorphous silica, which makes it highly reactive under alkaline conditions. The incorporation of glass powder in geopolymer paste can improve geopolymerization reactions, enhance matrix densification, and contribute to better mechanical properties.

Previous studies have reported that the incorporation of waste glass powder in geopolymer materials improves compressive strength, durability, and microstructural characteristics. However, limited research has been conducted on geopolymer paste containing simultaneous utilization of Fly Ash, GGBFS, and waste glass powder under different curing conditions. In addition, the combined influence of these materials on fresh and mechanical properties requires further investigation. The present study aims to investigate the effect of waste glass powder on the flowability, setting time, and compressive strength of geopolymer paste containing GGBFS and combined GGBFS–Fly Ash systems. Different percentages of glass powder were used as partial replacement materials, and the geopolymer specimens were cured under ambient and elevated temperature curing conditions. The findings of this study are expected to contribute toward the development of sustainable geopolymer materials suitable for future construction applications with reduced environmental impact.

2. LITERATURE REVIEW

Geopolymer materials have emerged as a promising sustainable alternative to Ordinary Portland Cement (OPC) because of their lower environmental impact, improved durability, and utilization of industrial by-products. Geopolymers are synthesized through the reaction between aluminosilicate-rich materials and alkaline activator solutions, resulting in the formation of strong three-dimensional polymeric structures. Various industrial and agricultural wastes such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Rice Husk Ash (RHA), silica fume, and waste glass powder have been widely investigated as precursor materials in geopolymer systems.

Several researchers have studied the effect of Fly Ash and GGBFS on the mechanical properties of geopolymer materials. Hardjito and Rangan reported that the compressive strength of fly ash-based geopolymer concrete is highly influenced by curing temperature, alkaline activator concentration, and curing duration. Their study demonstrated that elevated temperature curing significantly accelerates geopolymerization reactions and improves early-age strength development.

Nath and Sarker investigated the influence of GGBFS incorporation in geopolymer systems and observed that the presence of GGBFS improved early-age compressive strength because of its high calcium content and enhanced reactivity. The study also reported reduction in setting time and formation of denser geopolymer matrices with increasing GGBFS content.

Reddy et al. proposed a mix design methodology for geopolymer concrete using Fly Ash and GGBFS under ambient curing conditions. Their investigation showed that geopolymer concrete can achieve compressive strengths ranging from 32 MPa to 66 MPa even without heat curing. The researchers also concluded that geopolymer systems exhibit better compressive strength compared to conventional concrete for similar liquid-to-binder ratios.

The utilization of waste glass powder in geopolymer systems has gained considerable attention in recent years because of its high silica content and sustainable waste management potential. J. Temuujin demonstrated that the addition of waste glass powder significantly improves the compressive strength of geopolymer paste because of enhanced pozzolanic reactivity and formation of compact microstructure.

Xi Jiang et al. investigated fly ash-based geopolymer paste containing waste glass powder under ambient and elevated temperature conditions. Their study reported that incorporation of waste glass powder improved workability and mechanical properties of geopolymer materials. The researchers observed increased compressive strength with higher glass powder content because of improved geopolymer gel formation.

Tawatchai Tho-In et al. examined geopolymer pastes prepared using high-calcium fly ash and ground waste glass. The study concluded that finely ground waste glass can effectively participate in geopolymerization reactions and contribute to strength enhancement. Dense microstructures and reduced porosity were observed with optimum glass powder replacement levels.

Wrood H. Sachet and Wissam D. Salman reviewed the influence of slag addition and alkaline activator ratios on geopolymer mixtures. Their findings indicated that slag incorporation significantly improved compressive and tensile strength while reducing flowability and setting time because of increased reactivity and rapid geopolymerization.

Chowdhury et al. studied the mechanical and rheological properties of geopolymer concrete containing GGBFS. Their investigation revealed that the inclusion of GGBFS increased compressive strength by nearly 110% compared to conventional geopolymer systems. The study also reported improvements in flexural strength and durability properties.

Although previous studies have demonstrated the beneficial effects of Fly Ash, GGBFS, and waste glass powder individually, limited research is available on geopolymer paste containing simultaneous incorporation of these materials under different curing conditions. Furthermore, detailed investigations focusing on the fresh and mechanical properties of geopolymer paste with varying percentages of waste glass powder are comparatively limited.

Therefore, the present study aims to investigate the effect of waste glass powder on the flowability, setting time, and compressive strength of geopolymer paste containing GGBFS and combined GGBFS–Fly Ash systems under ambient and elevated temperature curing conditions.

3. MATERIALS USED

The materials used for the preparation of geopolymer paste in the present investigation include Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), waste Glass Powder (GP), Sodium Hydroxide (NaOH), and Sodium Silicate (Na_2SiO_3). The physical and chemical properties of these materials significantly influence the fresh and mechanical properties of geopolymer paste.

3.1 Fly Ash (FA)

Class F Fly Ash obtained from a thermal power plant was used as a geopolymer precursor material. Fly Ash mainly consists of silica and alumina, which are essential for geopolymerization reactions. The utilization of Fly Ash in geopolymer systems contributes toward sustainable waste management and reduction of environmental pollution.

Chemical Properties of Fly Ash

Property	**Value**
$SiO_2 + Al_2O_3 + Fe_2O_3$	**91.23%**
SiO_2	**61.66%**
MgO	**0.72%**
SO_3	**0.54%**
Loss on Ignition	**0.69%**

Physical Properties of Fly Ash

Property	Value
Specific Gravity	2.16
Fineness	328 m^2/kg
Particle Size	35.03 µm

3.2 Ground Granulated Blast Furnace Slag (GGBFS)

Ground Granulated Blast Furnace Slag (GGBFS) obtained from the steel industry was used as the primary binder material. GGBFS possesses high calcium content and enhanced reactivity, which improves setting characteristics and strength development of geopolymer paste.

Chemical Properties of GGBFS

Property	Value
CaO	**37.63%**
SiO_2	**34.81%**
Al_2O_3	**17.92%**
MgO	**7.80%**
Fe_2O_3	**0.66%**

Physical Properties of GGBFS

Property	Value
Specific Gravity	2.88–2.91
Fineness	365–390 m^2/kg
Particle Size	28.73 µm

3.3 Glass Powder (GP)

Waste Glass Powder used in the present study was produced by grinding waste glass into fine powder form. Because of its high silica content and amorphous nature, glass powder actively participates in geopolymerization reactions and improves matrix densification.

Chemical Properties of Glass Powder

Property	Value
SiO_2	71.10%
CaO	9.20%
Al_2O_3	0.95%
MgO	4.40%
Na_2O	12.60%

Physical Properties of Glass Powder

Property	Value
Specific Gravity	2.58
Unit Weight	2421 kg/m^3
Particle Size	22.42 µm

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3.4 Alkaline Activators

A combination of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) solutions was used as the alkaline activator for geopolymerization. Analytical grade sodium hydroxide pellets were used for preparation of 10M NaOH solution, while commercially available sodium silicate solution was utilized in the study. The ratio of Sodium Silicate to Sodium Hydroxide solution was maintained at 2:1 for all geopolymer mixes.

Properties of Alkaline Activators

Property	Value
NaOH Concentration	10 M
Na_2SiO_3 / NaOH Ratio	2:1
Form of NaOH	Pellets
Type of Na_2SiO_3	Commercial Liquid Solution
Na_2O	12.60%

4. EXPERIMENTAL PROGRAM

The experimental program was carried out to evaluate the effect of waste Glass Powder on the fresh and mechanical properties of geopolymer paste containing GGBFS and Fly Ash. Different geopolymer paste mixes were prepared using varying percentages of glass powder under ambient and elevated temperature curing conditions.

4.1 Mix Proportions

In the present investigation, glass powder was used as a partial replacement material for GGBFS and combined GGBFS–Fly Ash systems at replacement levels of 5%, 10%, 15%, and 20%.

Mix Combinations

Mix ID	GGBFS (%)	Fly Ash (%)	Glass Powder (%)
M1	100	0	0
M2	95	0	5
M3	90	0	10
M4	85	0	15
M5	80	0	20
M6	50	50	0
M7	47.5	47.5	5
M8	45	45	10
M9	42.5	42.5	15
M10	40	40	20

The ratio of Sodium Silicate to Sodium Hydroxide solution was maintained at 2:1 for all geopolymer mixes. A 10M Sodium Hydroxide solution was used throughout the investigation.

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4.2 Preparation of Geopolymer Paste

The dry materials, including GGBFS, Fly Ash, and Glass Powder, were thoroughly mixed in dry condition to obtain uniform distribution of particles. The alkaline activator solution consisting of Sodium Hydroxide and Sodium Silicate was prepared separately and mixed prior to casting. The alkaline activator solution was gradually added to the dry binder materials and mixed thoroughly until a homogeneous geopolymer paste was obtained.

4.3 Casting of Specimens

The prepared geopolymer paste was poured into cube moulds of size 70.6 mm × 70.6 mm × 70.6 mm in three layers. Proper compaction was carried out to remove entrapped air and achieve uniformity within the specimens. After casting, the top surface of the specimens was properly finished and levelled.

4.4 Curing Conditions

The geopolymer specimens were cured under two different curing conditions:

Ambient Curing: The specimens were kept at room temperature for the required curing duration.

Elevated Temperature Curing: The specimens were cured at 60°C for 24 hours in a hot air oven to accelerate geopolymerization reactions and early-age strength development.

4.5 Testing Methods

Various laboratory tests were conducted to evaluate the fresh and mechanical properties of geopolymer paste.

4.5.1 *Flow Table Test*

Flow table test was conducted to determine the workability and flow characteristics of geopolymer paste mixes containing different percentages of glass powder.

4.5.2 *Setting Time Test*

Initial setting time tests were conducted to evaluate the influence of glass powder incorporation on the setting characteristics of geopolymer paste.

4.5.3 *Compressive Strength Test*

Compressive strength tests were carried out on cube specimens at different curing ages using a Compression Testing Machine (CTM). The compressive strength values were calculated based on the maximum load carried by the specimens before failure.

5. RESULTS AND DISCUSSION

The experimental investigation was carried out to evaluate the influence of waste Glass Powder (GP) on the fresh and mechanical properties of geopolymer paste containing Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA). The effect of varying glass powder content on flowability, setting time, and compressive strength was studied under ambient and elevated temperature curing conditions.

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5.1 Flowability Test Results

The flowability of geopolymer paste was determined using the flow table test. The results indicated that the incorporation of glass powder reduced the flowability of geopolymer paste because of the increased fineness and higher surface area of glass particles.

Flow Table Test Results

Mix ID	Flow Value (mm)
M1	165
M2	160
M3	154
M4	148
M5	142
M6	170
M7	164
M8	158
M9	151
M10	145

The control mix containing 100% GGBFS exhibited a flow value of 165 mm, whereas the geopolymer mix containing 20% glass powder showed a reduced flow value of 142 mm. Similarly, the GGBFS–Fly Ash based geopolymer mixes also showed gradual reduction in flowability with increasing glass powder content.

The reduction in flowability may be attributed to the finer particle size and increased reactivity of glass powder, which accelerated the geopolymerization process and increased water demand within the paste matrix.

5.2 Setting Time Test Results

Initial setting time tests were conducted to study the influence of glass powder on the setting characteristics of geopolymer paste.

Initial Setting Time Results

Mix ID	Initial Setting Time (minutes)
M1	72
M2	68
M3	61
M4	54
M5	48
M6	84
M7	77
M8	70

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M9	63
M10	57

The results showed that the setting time of geopolymer paste decreased with increasing glass powder content. The control mix containing 100% GGBFS exhibited an initial setting time of 72 minutes, whereas the mix containing 20% glass powder recorded a setting time of 48 minutes.

The reduction in setting time can be attributed to the enhanced geopolymerization reactions caused by the high silica content and amorphous structure of waste glass powder. The incorporation of GGBFS also contributed to rapid setting because of the presence of reactive calcium compounds.

5.3 Compressive Strength Results

Compressive strength tests were conducted on geopolymer cube specimens cured under ambient and elevated temperature curing conditions. The results indicated that incorporation of waste glass powder improved the compressive strength of geopolymer paste up to an optimum replacement level.

Compressive Strength Results under Ambient Curing

Mix ID	7-Day Strength (MPa)	28-Day Strength (MPa)
M1	34.5	45.3
M2	37.2	48.6
M3	39.8	51.4
M4	41.5	52.6
M5	38.9	49.2
M6	30.8	42.4
M7	33.6	45.2
M8	36.9	48.8
M9	38.4	50.5
M10	35.7	47.1

Compressive Strength Results under Elevated Temperature Curing

Mix ID	7-Day Strength (MPa)	28-Day Strength (MPa)
M1	40.8	50.1
M2	44.2	53.5
M3	47.1	56.2
M4	49.3	58.4
M5	45.6	54.7
M6	36.2	46.3
M7	39.1	49.8
M8	42.5	53.1
M9	44.8	55.6

M10	41.6	51.9

The results indicate that compressive strength increased with the incorporation of glass powder up to 15% replacement level. The highest compressive strength was observed for mix M4 and M9 under both ambient and elevated temperature curing conditions. The improvement in strength may be attributed to the high silica content and pozzolanic reactivity of waste glass powder, which enhanced geopolymer gel formation and improved matrix densification. The finer glass particles also improved particle packing within the geopolymer matrix, resulting in reduced porosity and enhanced strength characteristics.

However, a slight reduction in compressive strength was observed at 20% replacement level due to excessive glass powder content, which may have disturbed the optimum binder composition and geopolymerization process. The elevated temperature curing condition exhibited higher compressive strength compared to ambient curing because of accelerated geopolymerization reactions and rapid development of geopolymer gel structure.

6. CONCLUSIONS

Based on the experimental results, the following conclusions are drawn:

1. Incorporation of glass powder reduced the flowability and setting time of geopolymer paste because of its finer particle size and higher reactivity.
2. Compressive strength increased with increasing glass powder content up to 15% replacement level under both ambient and elevated temperature curing conditions.
3. The maximum 28-day compressive strength of 58.4 MPa was achieved for geopolymer paste containing 15% glass powder under elevated temperature curing.
4. Elevated temperature curing resulted in higher compressive strength compared to ambient curing because of accelerated geopolymerization reactions.
5. The incorporation of waste glass powder improved matrix densification and enhanced geopolymer gel formation.
6. Waste glass powder can be effectively utilized as a sustainable supplementary precursor material in geopolymer systems for sustainable construction applications.

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