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MICROSTRUCTURAL ANALYSIS AND SUSTAINABILITY ASSESSMENT OF GLASS POWDER BASED GEOPOLYMER PASTE

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ABSTRACT

The present study investigates the microstructural characteristics of geopolymer paste containing Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and waste Glass Powder (GP). Glass powder was incorporated at replacement levels of 5%, 10%, 15%, and 20% to evaluate its influence on geopolymer gel formation and matrix densification. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses were conducted under ambient and elevated temperature curing conditions.

SEM analysis revealed that incorporation of glass powder improved the compactness and homogeneity of geopolymer paste by reducing porosity and microcracks. The geopolymer mix containing 15% glass powder exhibited the densest matrix formation. EDS analysis confirmed increased silicon and calcium-rich geopolymer gel formation with increasing glass powder content. The Si/Al ratio increased from 2.14 for the control mix to 2.87 for the mix containing 15% glass powder, indicating enhanced geopolymerization.

The study demonstrates that waste glass powder can be effectively utilized as a sustainable supplementary precursor material for improving the microstructural performance of geopolymer paste while contributing toward sustainable construction and waste management practices.

Keywords: Geopolymer paste, Glass powder, SEM, EDS, Sustainability, GGBFS

1. INTRODUCTION

The construction industry is one of the major contributors to carbon dioxide emissions due to the extensive use of Ordinary Portland Cement (OPC). The increasing environmental concerns associated with cement production have encouraged researchers to develop sustainable alternative binder materials for construction applications.

Geopolymer technology has emerged as a promising alternative because it utilizes industrial by-products such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) as precursor materials. These materials are rich in silica and alumina and can produce strong geopolymer binders when activated using alkaline solutions. Geopolymer materials exhibit excellent mechanical strength, durability, and chemical resistance while significantly reducing environmental impact compared to conventional cementitious systems.

In recent years, waste Glass Powder (GP) has gained considerable attention as a supplementary geopolymer material because of its high amorphous silica content and pozzolanic reactivity. Utilization of waste glass powder not only improves geopolymer properties but also helps in reducing landfill disposal of non-biodegradable glass waste.

Microstructural analysis plays an important role in understanding geopolymerization behaviour and matrix development in geopolymer materials. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) are commonly used techniques to evaluate morphology, porosity, matrix densification, and elemental composition of geopolymer systems.

The present study investigates the microstructural characteristics and sustainability potential of geopolymer paste containing Fly Ash, GGBFS, and waste Glass Powder. SEM and EDS analyses were performed to study geopolymer gel formation and matrix densification under different replacement levels of glass powder.

2. LITERATURE REVIEW

Geopolymer materials have attracted considerable attention as sustainable alternatives to Ordinary Portland Cement (OPC) because of their lower carbon emissions and effective utilization of industrial by-products. Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are widely used as geopolymer precursor materials because of their high silica and alumina contents.

Hardjito and Rangan reported that geopolymer materials exhibit superior mechanical and durability properties compared to conventional cementitious systems. Their study highlighted the significant influence of curing temperature and alkaline activator concentration on geopolymerization reactions and strength development.

Nath and Sarker observed that incorporation of GGBFS in geopolymer systems improves early-age strength and matrix densification because of the formation of calcium-rich geopolymer gels. Elevated calcium content in GGBFS contributes to rapid geopolymerization and enhanced microstructural performance.

In recent years, waste Glass Powder (GP) has emerged as a promising supplementary geopolymer material because of its high amorphous silica content and pozzolanic reactivity. Temuujin et al. reported that incorporation of glass powder significantly improved compressive strength and compactness of geopolymer paste.

Xi Jiang et al. investigated fly ash-based geopolymer paste containing waste glass powder and observed improved geopolymer gel formation and reduced porosity with increasing glass powder content. Similarly, Zhang et al. performed SEM and EDS analysis on geopolymer systems containing glass powder and reported denser matrix formation and enhanced geopolymerization products.

Salmabanu Luhar and Ismail Luhar reviewed the utilization of waste glass in geopolymer composites and concluded that waste glass can effectively improve mechanical and microstructural properties while promoting sustainable waste management practices.

Although several studies have investigated geopolymer systems containing Fly Ash, GGBFS, and waste glass powder individually, limited research is available on the combined utilization of these materials with detailed SEM and EDS based microstructural analysis. Therefore, the present study focuses on evaluating the microstructural characteristics and sustainability potential of geopolymer paste containing Fly Ash, GGBFS, and waste Glass Powder.

3. MATERIALS AND METHODS

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 an aluminosilicate precursor material. Fly Ash mainly consists of silica and alumina, which are essential for geopolymerization reactions.

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 obtained from the steel industry was used as the primary geopolymer binder material. GGBFS possesses high calcium content and enhanced reactivity, which improves geopolymerization and strength development.

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 was produced by grinding waste glass into fine powder form. Glass powder contains a high percentage of amorphous silica, which actively participates in geopolymerization reactions.

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/m³
Particle Size	22.42 µm

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. A 10M Sodium Hydroxide solution was prepared and the ratio of Sodium Silicate to Sodium Hydroxide was maintained at 2:1.

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 investigation was conducted to evaluate the microstructural characteristics of geopolymer paste containing Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and waste Glass Powder (GP). Different geopolymer mixes were prepared by partially replacing GGBFS and combined GGBFS–Fly Ash systems with waste glass powder.

4.1 Mix Proportions

Glass Powder was incorporated at replacement levels of 5%, 10%, 15%, and 20% in geopolymer paste mixes.

Mix Combinations

Mix ID	GGBFS (%)	Fly Ash (%)	Glass Powder (%)

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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

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

4.2 Preparation of Geopolymer Paste

The dry materials including Fly Ash, GGBFS, and Glass Powder were thoroughly mixed to obtain uniform distribution. The alkaline activator solution consisting of Sodium Hydroxide and Sodium Silicate was prepared separately and gradually added to the dry binder materials.

Mixing continued until a homogeneous geopolymer paste was obtained. The prepared paste was poured into cube moulds of size 70.6 mm × 70.6 mm × 70.6 mm and properly compacted to eliminate entrapped air.

4.3 Curing Conditions

The geopolymer specimens were cured under two different curing conditions:

- Ambient curing at room temperature
- Elevated temperature curing at 60°C for 24 hours

After curing, the specimens were prepared for microstructural analysis.

4.4 SEM Analysis

Scanning Electron Microscopy (SEM) analysis was carried out to study the morphology, matrix densification, porosity, and geopolymer gel formation of geopolymer paste specimens. SEM images were obtained for selected geopolymer mixes under different replacement levels of Glass Powder.

4.5 EDS Analysis

Energy Dispersive Spectroscopy (EDS) analysis was performed to determine the elemental composition of geopolymer paste specimens. The analysis was used to identify the presence of silicon, aluminium, calcium, and other geopolymeric reaction products responsible for geopolymer gel formation.

5. RESULTS & DISCUSSION

The present investigation was carried out to evaluate the influence of waste Glass Powder (GP) on the microstructural characteristics of geopolymer paste containing Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS). Scanning Electron Microscopy (SEM) and Energy

Dispersive Spectroscopy (EDS) analyses were conducted to study geopolymer gel formation, matrix densification, and elemental composition of geopolymer paste.

5.1 SEM Analysis

SEM analysis was performed to evaluate the morphology and compactness of geopolymer paste containing different percentages of Glass Powder. The SEM images revealed significant changes in the microstructure with incorporation of waste glass powder.

The control mix (M1) containing 100% GGBFS exhibited comparatively higher porosity and unreacted particles within the geopolymer matrix. However, the incorporation of Glass Powder improved the compactness and homogeneity of the geopolymer paste. The geopolymer mixes containing 10% and 15% Glass Powder showed denser matrix formation with reduced microcracks and fewer voids. The fine particles of glass powder improved particle packing and enhanced geopolymerization reactions, resulting in formation of a more compact geopolymer gel structure.

Among all mixes, the geopolymer paste containing 15% Glass Powder (M4 and M9) exhibited the densest and most homogeneous microstructure. The improved matrix densification may be attributed to the high amorphous silica content of Glass Powder, which actively participated in geopolymer gel formation.

However, a slight increase in unreacted particles and microvoids was observed in geopolymer mixes containing 20% Glass Powder. Excessive replacement of geopolymer precursor materials may have affected the optimum geopolymerization process and matrix development.

The SEM analysis confirmed that incorporation of waste Glass Powder significantly improved the microstructural characteristics of geopolymer paste by reducing porosity and enhancing geopolymer gel formation.

5.2 EDS Analysis

EDS analysis was conducted to evaluate the elemental composition and geopolymeric reaction products present in geopolymer paste specimens.

The EDS spectra confirmed the presence of major elements such as silicon (Si), aluminium (Al), calcium (Ca), oxygen (O), and sodium (Na), which are responsible for geopolymer gel formation. The incorporation of Glass Powder increased the silica content within the geopolymer matrix and enhanced geopolymerization reactions.

Elemental Composition of Selected Geopolymer Mixes

Mix ID	Si/Al Ratio	Major Elements Observed
M1	2.14	Si, Al, Ca, O
M3	2.46	Si, Al, Ca, Na, O
M4	2.87	Si, Al, Ca, Na, O
M9	2.81	Si, Al, Ca, Na, O

The geopolymer mixes containing Glass Powder exhibited higher Si/Al ratios compared to the control mix, indicating enhanced geopolymer gel formation. The increased silica content contributed to the formation of denser aluminosilicate networks within the geopolymer matrix.

The presence of calcium-rich phases confirmed the formation of C-A-S-H gel in GGBFS-based geopolymer systems. The combined formation of geopolymer gel and calcium aluminosilicate hydrate gel contributed to improved matrix densification and compactness.

The geopolymer paste containing 15% Glass Powder exhibited the most stable geopolymer matrix with improved elemental distribution and reduced porosity. The EDS results were consistent with the SEM observations and confirmed the beneficial influence of Glass Powder on geopolymerization behaviour.

Overall, the microstructural investigation demonstrated that waste Glass Powder can be effectively utilized as a sustainable supplementary precursor material for improving the geopolymer gel structure and matrix densification of geopolymer paste.

6. CONCLUSIONS

The present study investigated the microstructural characteristics of geopolymer paste containing Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), and waste Glass Powder (GP) using SEM and EDS analysis. Based on the experimental investigation, the following conclusions can be drawn:

1. Incorporation of waste Glass Powder improved the compactness and homogeneity of geopolymer paste by reducing porosity and microcracks.
2. SEM analysis revealed that geopolymer mixes containing 10–15% Glass Powder exhibited denser matrix formation and enhanced geopolymer gel development.
3. EDS analysis confirmed the presence of silicon, aluminium, calcium, and sodium-rich geopolymeric reaction products within the geopolymer matrix.
4. The Si/Al ratio increased with incorporation of Glass Powder, indicating improved geopolymerization behaviour and gel formation.
5. Geopolymer paste containing 15% Glass Powder exhibited the most stable and compact microstructure among all mixes.
6. Waste Glass Powder can be effectively utilized as a sustainable supplementary precursor material for improving the microstructural performance and sustainability of geopolymer systems.

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