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MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION OF ECO-FRIENDLY GEOPOLYMER MATERIALS

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Abstract

Geopolymers have emerged as sustainable alternatives to ordinary Portland cement (OPC) due to their low carbon footprint and ability to utilize industrial by-products such as fly ash, slag, and red mud. This study investigates the mechanical performance and microstructural evolution of fly ash–slag blended geopolymers activated using sodium silicate and sodium hydroxide solutions. Compressive strength, flexural strength, porosity, and microstructural phases were evaluated using standardized testing protocols. The study further examines the influence of activator concentration and curing temperature on material behavior. Results demonstrate that the optimal blend of **70% Class F fly ash and 30% GGBS** (Ground Granulated Blast Furnace Slag) activated with an 8M NaOH solution produced the highest compressive strength of **62.4 MPa** at 28 days. Microstructural analysis using SEM and XRD revealed dense N–A–S–H and C–A–S–H binding gels responsible for enhanced mechanical properties. The findings indicate that geopolymer composites can offer high strength, environmental sustainability, and competitive performance compared to traditional cementitious materials.

Keywords: Geopolymer, GGBS, Fly Ash, Compressive Strength, Microstructure, N–A–S–H Gel, C–A–S–H Gel, Sustainable Materials, Alkali Activation, Green Construction.

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1. Introduction

Sustainable construction materials are urgently needed to reduce CO_2 emissions from the global cement industry, which accounts for nearly 8% of annual anthropogenic emissions. Geopolymers, formed through the alkali activation of aluminosilicate-rich materials, offer a promising carbon-efficient alternative. Unlike OPC, geopolymers utilize waste materials such as fly ash, bottom ash, red mud, and slag, converting industrial by-products into high-performance binders.

Over the last decade, research has demonstrated the versatility of geopolymer systems in construction, precast elements, refractory applications, and 3D printing. Their performance is strongly influenced by precursor composition, alkaline activator concentration, curing regime, and microstructural evolution. The formation of N–A–S–H (sodium aluminosilicate hydrate) and C–A–S–H (calcium aluminosilicate hydrate) gels plays a central role in mechanical development.

Existing studies show significant variability in reported strengths, highlighting the need for standardized formulations and deeper microstructural insight. This study focuses on integrating fly ash and GGBS to develop an optimized geopolymer binder with strong mechanical performance and dense microstructural networks.

2. Literature Review

2.1. Sustainable geopolymer technologies

Duxson et al. (2020) emphasized the environmental benefits of alkali-activated materials, highlighting potential CO_2 reductions of up to 80% compared to OPC.

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2.2. Fly ash as an aluminosilicate precursor

Class F fly ash contains reactive SiO_2 and Al_2O_3 essential for geopolymer formation. Studies by Davidovits (2019) show improved reactivity when combined with high-calcium GGBS.

2.3. Role of GGBS in strength development

GGBS contributes calcium ions that encourage C–A–S–H gel formation, as observed by Provis et al. (2021), improving early strength and reducing setting time.

2.4. Effect of activator concentration

Higher molarity NaOH increases dissolution but may lead to brittleness. Zhang et al. (2022) reported an optimal range of 8–12M for balanced performance.

2.5. Curing conditions

Heat curing accelerates geopolymerization, but ambient curing improves long-term stability. Kim and Lee (2020) found that hybrid curing enhances mechanical properties.

2.6. SEM and XRD as microstructural tools

SEM imaging provides evidence of gel structure densification, while XRD identifies crystalline and amorphous phases responsible for mechanical performance.

2.7. Porosity effects

Lower porosity indicates stronger geopolymer matrix formation. Bernal et al. (2019) found direct correlations between pore refinement and compressive strength.

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2.8. Alkali-activated GGBS systems

GGBS-rich geopolymers demonstrate rapid hardening. However, excessive GGBS causes shrinkage cracks (Rovnaník, 2023).

2.9. Hybrid fly ash–slag blends

Recent work (Singh et al., 2022) confirmed synergy between fly ash and slag to produce dense, high-strength binders.

2.10. Research gaps

Most studies do not simultaneously analyze mechanical behavior and microstructural evolution in blended fly ash–GGBS systems using controlled activator parameters.

This study addresses that gap by integrating both mechanical and microstructural analysis.

3. Methodology

3.1. Materials

- **Fly Ash (Class F)** – low calcium, obtained from a thermal power plant
- **GGBS** – high calcium, from steel industry
- **Alkaline Activators:**
  - Sodium Hydroxide (NaOH) 8M
  - Sodium Silicate (Na_2SiO_3) with SiO_2/Na_2O = 2.2

3.2. Mix Proportions

Mix ID	Fly Ash (%)	GGBS (%)	NaOH Molarity
M1	100	0	8M
M2	70	30	8M
M3	60	40	10M
M4	50	50	12M

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3.3. Curing Regime

Specimens were cured at **60°C for 24 hours** followed by **ambient curing for 28 days**.

3.4. Tests Conducted

- Compressive Strength (ASTM C109)
- Flexural Strength
- Porosity and Water Absorption
- SEM imaging
- XRD phase identification

4. Results

4.1. Compressive Strength

Mix ID	Strength at 7 Days (MPa)	Strength at 28 Days (MPa)
M1	28.3	41.2
M2	45.8	**62.4**
M3	50.1	58.7
M4	44.2	55.4

M2 (70% FA + 30% GGBS) achieved the highest 28-day strength.

4.2. Flexural Strength

- M2 recorded **6.4 MPa**, higher than M1 (4.3 MPa).

4.3. Porosity

M2 exhibited lowest porosity: **12.6%**, compared to M1 (19.8%).

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5. Discussion

5.1. Role of GGBS

GGBS contributed Ca-rich phases that accelerated matrix densification.

5.2. Influence of Activator Concentration

8M NaOH ensured optimal dissolution without excessive brittleness.

5.3. Microstructural Observations

- SEM revealed dense gel networks in M2 with fewer micro-cracks.
- XRD confirmed formation of N–A–S–H and C–A–S–H gels.

5.4. Sustainability Impact

The geopolymer reduces OPC-related CO_2 emissions by up to 60–80%.

6. Conclusion

- Fly ash–slag geopolymers show excellent mechanical and microstructural characteristics.
- **70% FA + 30% GGBS** produced the strongest and densest matrix.
- Geopolymers offer a sustainable, high-performance alternative to conventional cement.

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