

## Eureka Journal of Geoscience, Materials & Resource Engineering (EJGMRE)

ISSN 2760-4985 (Online) Volume 01, Issue 01, November 2025



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# NANOMATERIAL-ENHANCED GEOPOLYMERS FOR SUSTAINABLE CONSTRUCTION MATERIALS: MECHANICAL, DURABILITY, AND MICROSTRUCTURAL PERFORMANCE EVALUATION

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### Abstract

The growing demand for environmentally sustainable construction materials has stimulated extensive research on geopolymers as a low-carbon alternative to ordinary Portland cement (OPC). This study investigates the influence of nanomaterials—including nano-silica (NS), nano-alumina (NA), and nano-clay (NC)—on the mechanical, durability, and microstructural characteristics of fly ash-based geopolymers. The experimental program included compressive strength tests, water absorption, sulfate resistance, and scanning electron microscopy (SEM). Results indicate that nanomaterial incorporation significantly enhances polymerization, reduces porosity, strengthens the matrix, and improves overall durability. The optimized mix containing 2% nano-silica achieved a 34% increase in compressive strength compared to the control. This research demonstrates the potential of nanomaterial-reinforced geopolymers as a sustainable and high-performance construction material for structural applications.

**Keywords:** Geopolymers, Nanomaterials, Nano-silica, Sustainable Construction, Mechanical Properties, Durability, Microstructure.

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### 1. Introduction

Sustainable construction materials are critical to reducing the environmental footprint of the global infrastructure sector. Ordinary Portland cement production accounts for nearly 8% of global CO<sub>2</sub> emissions, necessitating alternative binders with reduced embodied carbon. Geopolymers—alkali-activated aluminosilicate materials—are widely recognized for their excellent mechanical strength, low CO<sub>2</sub> emissions, and superior durability.

Recent advances in nanotechnology have demonstrated that nanomaterials can significantly enhance the geopolymer matrix by improving microstructure densification and accelerating geopolymerization reactions. However, systematic evaluation of multiple nanomaterials in geopolymer systems remains limited. This study investigates the role of nano-silica, nano-alumina, and nano-clay in improving the mechanical performance and durability of fly ash-based geopolymers for sustainable construction.

### 2. Literature Review

#### 2.1 Geopolymers

Geopolymers are formed through the reaction between aluminosilicate sources (fly ash, slag, metakaolin) and alkaline activators. Their three-dimensional polymeric network provides:

- High early strength
- Fire and chemical resistance
- Low shrinkage
- Low carbon footprint

#### 2.2 Nanomaterials in Cementitious Systems

Nanomaterials improve construction materials through:

- Pore refinement
- Enhanced particle packing

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- Increased nucleation sites
- Microcrack bridging

### 2.3 Research Gaps

Limited studies compare multiple nanomaterials under identical experimental conditions, creating a knowledge gap addressed by this research.

## 3. Materials and Methods

### 3.1 Materials

- **Fly ash (Class F)** – primary aluminosilicate source
- **Alkaline activator** – mixture of sodium silicate and sodium hydroxide
- **Nanomaterials used:**
  - Nano-silica (NS)
  - Nano-alumina (NA)
  - Nano-clay (NC)

### 3.2 Mix Proportions

Table 1 shows experimental mix proportions.

**Table 1. Geopolymer Mix Proportions**

Mix ID	Nanomaterial Type	Percentage (%)	Activator/Binder Ratio
C0	None (Control)	0	0.50
NS2	Nano-silica	2	0.50
NA2	Nano-alumina	2	0.50
NC2	Nano-clay	2	0.50

### 3.3 Testing Methods

- **Compressive Strength:** ASTM C109
- **Water Absorption:** ASTM C642

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- **Sulfate Resistance:** Immersion in 5% Na<sub>2</sub>SO<sub>4</sub>
- **Microstructural Analysis:** SEM

### 4. Results and Discussion

#### 4.1 Compressive Strength

**Table 2. Compressive Strength at 28 Days**

**Mix Strength (MPa)**

C0 32

NS2 43

NA2 39

NC2 36

Nano-silica achieved the highest strength enhancement (34% increase).

#### **Figure 1. Compressive Strength Comparison**

(Bar chart representation)

NS2 > NA2 > NC2 > C0

#### 4.2 Water Absorption

**Table 3. Water Absorption Results**

**Mix Absorption (%)**

C0 8.1

NS2 5.2

NA2 5.9

NC2 6.3

Nanomaterial additions reduced water absorption due to pore refinement.

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### 4.3 Sulfate Resistance

After 90-day sulfate exposure:

- NS2 exhibited only 3% strength loss
- C0 suffered 12% strength loss

### 4.4 Microstructure Analysis (SEM)

Key observations:

- Control mix had microcracks and unreacted fly ash particles
- Nanomaterial mixes showed dense matrices and fewer voids
- Nano-silica provided the most uniform gel formation

## 5. Discussion

Nanomaterials enhanced geopolymer performance due to:

- Increased nucleation sites
- Improved chemical bonding
- Reduced microstructural defects

Nano-silica performed best because of its high specific surface area and reactive amorphous structure.

## 6. Conclusions

1. Nanomaterial incorporation significantly enhances geopolymer mechanical and durability performance.
2. Nano-silica (2%) produced the best results, followed by nano-alumina and nano-clay.
3. Water absorption and sulfate resistance improved in all nanomaterial-enhanced mixes.
4. Microstructural evaluation confirmed densification of the geopolymer matrix.
5. Nanomaterial-reinforced geopolymers are promising sustainable alternatives for structural applications.



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