

Performance of Geopolymer Concrete with Nano Materials as Additives

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Abstract

This study examines the mechanical performance and microstructural characteristics of geopolymer concrete incorporating nano-materials such as nano-silica and nano-alumina. The research focuses on developing a sustainable alternative to conventional cement-based concrete by utilizing industrial and agricultural by-products including fly ash, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA).

Geopolymer mixes were prepared by partially replacing fly ash with RHA in varying proportions ranging from 0% to 15%. Alkaline activators consisting of sodium hydroxide and sodium silicate solutions were used to initiate the geopolymerization process. Experimental investigations were carried out to evaluate fresh properties such as workability and hardened properties including compressive strength and split tensile strength at curing periods of 7 and 28 days.

The results indicate that the incorporation of RHA improves strength up to an optimum replacement level of 10%, beyond which strength decreases due to reduced workability and increased water demand. The addition of nano-materials enhances the microstructure by refining pore distribution and accelerating gel formation, thereby improving durability and strength.

Overall, the study demonstrates that geopolymer concrete with nano-materials is an environmentally friendly and high-performance alternative to traditional concrete.

Keywords-Geopolymer concrete; Nano-silica; Rice husk ash; Fly ash; GGBS; Sustainable construction

1. Introduction

The construction industry plays a vital role in the development of modern infrastructure, but it also contributes significantly to environmental degradation. One of the major concerns is the extensive use of Ordinary Portland Cement (OPC), which is the primary binding material in conventional concrete. The production of cement requires high energy consumption and results in substantial carbon dioxide (CO₂) emissions, accounting for nearly 5–8% of global emissions. This has led to an urgent need for sustainable and eco-friendly alternatives in construction materials.

In recent years, geopolymer concrete (GPC) has emerged as a promising alternative to traditional cement-based concrete. Unlike OPC concrete, geopolymer concrete is produced by activating aluminosilicate-rich materials such as fly ash, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA) using alkaline solutions like sodium hydroxide and sodium silicate. This process, known as geopolymerization, forms a strong and durable binder without the use of cement. As a result, geopolymer concrete significantly reduces carbon emissions and promotes the utilization of industrial and agricultural waste materials.

Geopolymer concrete offers several advantages over conventional concrete. It exhibits high compressive strength, low shrinkage, excellent resistance to chemical attacks, and superior durability. Additionally, it performs well under high temperatures and harsh environmental conditions due to its inorganic composition. The inclusion of materials such as GGBS also enhances early strength development, making it suitable for structural applications. Furthermore, the use of waste materials like fly ash and rice husk ash helps in reducing landfill disposal and conserving natural resources.

To further improve the performance of geopolymer concrete, recent research has focused on incorporating nanomaterials such as nano-silica and nano-alumina. These nano-scale additives enhance the microstructure of the concrete by refining pore structure and accelerating the formation of binding gels like N-A-S-H and C-A-S-H. This results in improved mechanical strength, durability, and overall performance of the material. The addition of nanomaterials also contributes to better bonding within the matrix, leading to a denser and more compact structure.

Despite its advantages, geopolymers concrete has certain limitations, including complex mix design procedures, handling challenges associated with alkaline solutions, and the lack of standardized guidelines. However, ongoing research is continuously addressing these challenges, making geopolymers technology more practical and adaptable for real-world applications.

In this context, the present study focuses on evaluating the performance of geopolymers concrete with nanomaterials as additives. The objective is to develop a sustainable and high-performance concrete by optimizing the use of industrial by-products and nano-additives. This approach not only reduces environmental impact but also enhances the structural properties of concrete, making it a viable solution for future construction practices.

2. Literature Review

Shaik Numan Mahdi et al. (2021) investigated the use of rice husk ash (RHA) in geopolymers concrete. Their study revealed that replacing 10% of fly ash with RHA resulted in optimum compressive strength of around 42 MPa at 28 days. The improvement was attributed to the high silica content of RHA, which enhances the Si/Al ratio and promotes better bonding in the geopolymers matrix.

Shaswat Kumar Das et al. (2022) emphasized the potential of RHA as a sustainable material in alkali-activated systems. They noted that RHA contains 85–90% amorphous silica and can significantly improve strength and durability when properly processed. However, its performance depends on particle size, fineness, and burning conditions.

Ramhit Sahu et al. (2022) compared geopolymers concrete with conventional concrete and found that GPC achieves comparable compressive strength, although slightly lower in some cases due to water release during polymerization. Despite this, GPC offers advantages such as waste utilization and environmental sustainability.

Rattapon Somna et al. (2022) studied geopolymers blocks made with fly ash and RHA. Their findings showed that increasing RHA content improves compressive strength due to higher silica content and better matrix formation. Additionally, finer RHA particles further enhance strength and reduce environmental impact.

Thiru Kumaran et al. (2023) examined the combined effect of RHA and nano-alumina in geopolymers concrete. The study concluded that the addition of nano-alumina improves strength and reduces water absorption by filling microvoids. The best performance was observed at 12M NaOH concentration with 2% nano-alumina.

Mohammed Ali M. Rihan et al. (2024) investigated geopolymers concrete incorporating sugarcane bagasse ash (SCBA). Their results indicated that increasing SCBA content reduces workability and strength, but still achieves acceptable performance. Elevated curing temperatures significantly improved strength due to enhanced geopolymers merization.

Hussein M. Hamada et al. (2025) studied the combined effect of RHA and nano-silica. They found that RHA reduces workability but improves strength and durability. The addition of nano-silica further enhances compressive, tensile, and flexural strength by densifying the microstructure.

Nanduri Sai Surya Sudheer et al. (2025) reported that the combination of nano-silica and nano-aluminium significantly improves the mechanical properties of geopolymers concrete. The mix with 3% nano additives showed superior compressive and tensile strength at both early and later ages.

3. Materials and Methods

Materials

Fly Ash (FA)

Fly ash is the primary source of silica (SiO_2) and alumina (Al_2O_3) in geopolymers concrete. In this study, Class F fly ash was used, which is obtained as a by-product from thermal power plants. It has a specific gravity of about 2.38 and good fineness characteristics. Fly ash improves workability due to its spherical particles and contributes to long-term strength through geopolymers merization.



Figure. 3.1: Fly Ash.

Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a calcium-rich supplementary cementitious material obtained from the iron manufacturing industry. It has a specific gravity of about 2.85 and appears off-white in colour. GGBS accelerates the setting process and enhances early strength by forming calcium-based gels such as C-S-H and C-A-S-H. It also improves durability and reduces water demand due to its dense structure.

Rice Husk Ash (RHA)

Rice husk ash is an agricultural waste product rich in amorphous silica (about 85–90%). It is used as a partial replacement for fly ash (0–15%). RHA enhances the microstructure by filling pores and increasing density, which improves strength and resistance to chemicals. However, higher percentages may reduce workability due to increased water demand.



Figure. 3.2: RHA from brick manufacturers.

Fine Aggregate

Fine aggregate used in this study is crushed stone sand passing through a 4.75 mm sieve. It has a specific gravity of 2.46 and water absorption of 1.8%. Fine aggregate fills the voids between coarse aggregates and contributes to workability and strength of concrete.

Coarse Aggregate

Coarse aggregates of size 20 mm (passing) and 4.75 mm (retained) were used. They have a specific gravity of 2.58 and low water absorption of 0.25%. Coarse aggregates provide strength, stiffness, and structural stability to the concrete.

Alkaline Activators

Alkaline activators are essential for initiating the geopolymerization process. A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used.

- **Sodium Hydroxide (NaOH):** Used in pellet form and dissolved in water to prepare the required molarity (typically 12M). It helps dissolve silica and alumina from source materials.
- **Sodium Silicate (Na_2SiO_3):** A viscous liquid that provides additional silica and accelerates the formation of geopolymer gel, improving strength and durability.

These activators together form a strong binding matrix in geopolymer concrete.



Figure. 3.3: NaOH pallets and Na_2SiO_3 solution.

3.1 Mix Design

Table 3.1: Mix proportion

Binder (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)
485	544.2	1291
1	1.12	2.66

Table 3.2: Details of Mix Proportions of Concrete for 1 cube

Nomenclature	Rice husk ash %	Fly ash g	GBS g	RH A g	Fine aggregate g	Coarse aggregate g	Na_2SiO_3 ml	NaOH ml	Water ml
MRHA ₀	0%	954	409	0	1830	4352	279	120	390
MRHA ₅	5%	886	409	68	1830	4352	279	120	390
MRHA ₁₀	10%	818	409	136	1830	4352	279	120	390
MRHA ₁₅	15%	749	409	204	1830	4352	279	120	390

3.2 Methodology

3.2.1 Specimen Preparation

Preparation of Alkaline Solution

Sodium hydroxide (NaOH) pellets are dissolved in water to prepare the required molarity. For 12 M NaOH, 480 grams of NaOH pellets are dissolved in 1 litre of water. Sodium silicate solution was mixed with NaOH solution in a predetermined ratio of 2.5:1. This solution was prepared 24 hours of before casting to allow stabilization and cooling.

Casting and curing of concrete specimens

1. Preparing of mould

Clean and prepare the mold Ensure that mold is free from dust, oil, and other contaminants. Apply a thin layer of mold release agent to prevent the mortar from sticking to the mold Concrete specimens were prepared using cube moulds of $150 \times 150 \times 150$ mm and cylindrical moulds measuring 150 mm in diameter and 300 mm in height for both mix design methods. Moulds (cubes, cylinders) are cleaned and oiled before use.

2. Mixing of the Materials

Required quantity of materials are taken as per the mix design. Dry materials (fly ash, GGBS, RHA, fine aggregate, coarse aggregate) are first mixed by hand mixing for 2–3 minutes. The prepared alkaline solution is then added gradually to the dry mix. Mixing continues for about 3–5 minutes until a homogeneous and workable mix is obtained.

3. Pouring the concrete into mould and compacting

Concrete is placed in moulds in three layers, each layer compacted using: Tamping rod, or Table vibrator. Surface is finished smoothly.

Curing the Concrete

- Demould after the initial set, carefully remove the mould from the mortar.
- After casting, the samples were kept under ambient laboratory conditions for curing, and their properties were evaluated after 7 and 28 days.



Figure. 3.4: Casting and curing of concrete specimens.

3.2.2 Test on Fresh Concrete

The slump test is carried out to evaluate the workability and consistency of geopolymer concrete. A standard slump cone is placed on a flat, non-absorbent surface and filled with freshly prepared GPC in three equal layers. Each layer is compacted properly using a tamping rod to remove air voids. After filling, the top surface is levelled, and the cone is carefully lifted in a vertical direction. The concrete then subsides, and the decrease in height is measured as the slump value. This value indicates how easily the geopolymer concrete can be mixed, handled, and placed. A higher slump represents better flowability, while a lower slump indicates a stiffer mix.

3.2.3 Tests on Hardened Concrete

After curing, geopolymer concrete is tested to evaluate its strength and durability. The main tests include compressive strength and split tensile strength.

Compressive Strength Test

This test measures the load-carrying capacity of concrete. Cube specimens of size $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$ are used. After curing for 7 and 28 days, the specimens are cleaned and placed in a Compression Testing Machine (CTM).

Load is applied gradually until failure. The maximum load is recorded and compressive strength is calculated as:
 Compressive Strength = Load at Failure / Cross-sectional Area

Split Tensile Strength Test

Concrete is weak in tension, so this test evaluates its tensile strength. Cylindrical specimens of 150 mm diameter and 300 mm height are used. After curing, the cylinder is placed horizontally in the CTM. Load is applied along its length, creating tensile stress across the diameter. The specimen cracks vertically, indicating its tensile strength.



Figure. 3.5: Compressive strength test on cube specimens.



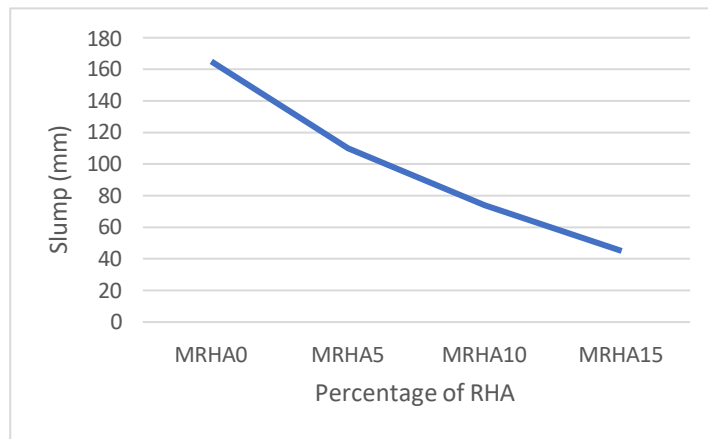
Figure. 3.6: Split tensile test on cylinder specimen.

4. Result and Discussion

4.1 Test Results of Fresh Concrete Slump Test Results

Table 4.1: Slump values of RHA % variation

Sl. No.	Nomenclature	RHA (%)	Slump (mm)
1	MRHA ₀	0	165
2	MRHA ₅	5	110
3	MRHA ₁₀	10	74
4	MRHA ₁₅	15	45


Chart 4.1: Comparison of Slump for different RHA %

4.2 Test Results of Hardened Concrete

4.2.1 Compressive Strength Test Results:

Table 4.2: 7 days compressive strength test results

Sl.No.	Nomenclature	RHA (%)	Load at failure (kN)			Average Load at Failure (kN)	Compressive strength (MPa)
1	MRHA ₀	0	392.5	395	398	395.16	17.56
2	MRHA ₅	5	405	412.5	410	409.16	18.18
3	MRHA ₁₀	10	420	415	418	417.66	18.56
4	MRHA ₁₅	15	327.5	322.5	326	325.33	14.45

Table 4.3: 28 days compressive strength test results

Sl.No.	Nomenclature	RHA (%)	Load at failure (kN)			Average Load at Failure (kN)	Compressive strength (MPa)
1	MRHA ₀	0	643	648	651	647.33	28.77
2	MRHA ₅	5	668	675	679	674	29.95
3	MRHA ₁₀	10	682	680	687	683	30.35
4	MRHA ₁₅	15	615	621	627	621	27.6

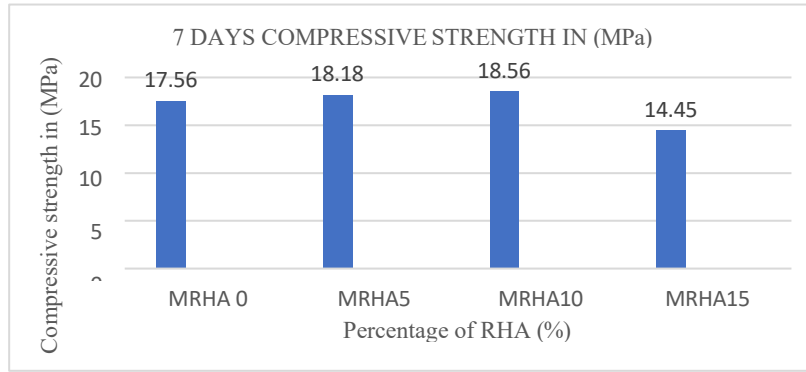


Chart 4.2: Comparison of compression strength for 7 days.

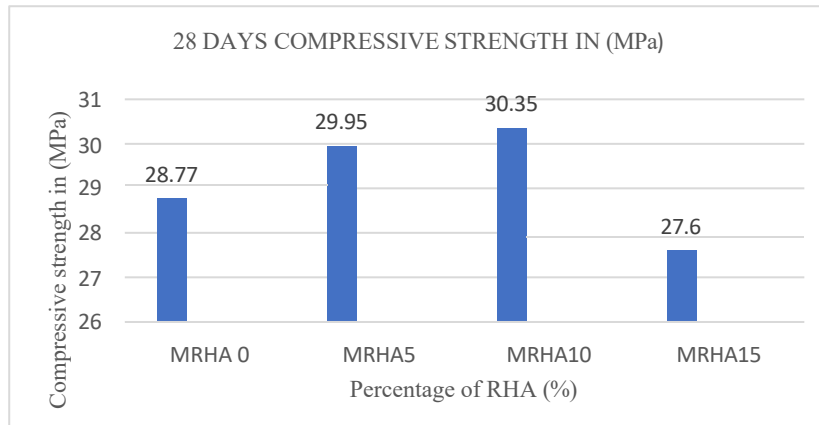


Chart 4.3: Comparison of compressive strength for 28 days.

Table 4.2 and Chart 4.2 show the 7-day compressive strength of concrete with varying RHA content. Strength increases from

17.56 MPa (0% RHA) to a peak of 18.56 MPa (10% RHA). At 15% RHA, the strength decreases significantly to 14.45 MPa. This indicates that the optimum RHA content for early strength is around 10%.

The 28-day compressive strength increases from 28.77 MPa (0% RHA) to a peak of 30.35 MPa (10% RHA). Beyond this, strength decreases to 27.6 MPa at 15% RHA. This indicates an optimum RHA replacement level of about 10%. The bar chart clearly shows the variation in strength with RHA content.



Figure. 4.1: Crack patterns observed in cube specimens

4.2.2 Split tensile Strength Test Results

Table 4.4: 7 days split tensile strength test results

Sl. No.	Nomenclature	RHA (%)	Load at failure (kN)		Average Load at Failure (kN)	Split tensile strength (MPa)
1	MRHA ₀	0	255.5	262.5	259	1.46
2	MRHA ₅	5	270	277.5	273.75	1.54
3	MRHA ₁₀	10	298.5	292.5	295.5	1.67
4	MRHA ₁₅	15	267.5	271	269.25	1.52

Table 4.5: 28 days split tensile strength test results

Sl. No	Nomenclature	RHA (%)	Load at failure (kN)		Average Load at Failure (kN)	Split tensile strength (MPa)
1	MRHA ₀	0	415	422.5	418.75	2.36
2	MRHA ₅	5	435	441	438	2.47
3	MRHA ₁₀	10	449	453	451	2.55
4	MRHA ₁₅	15	438	441	439.5	2.48

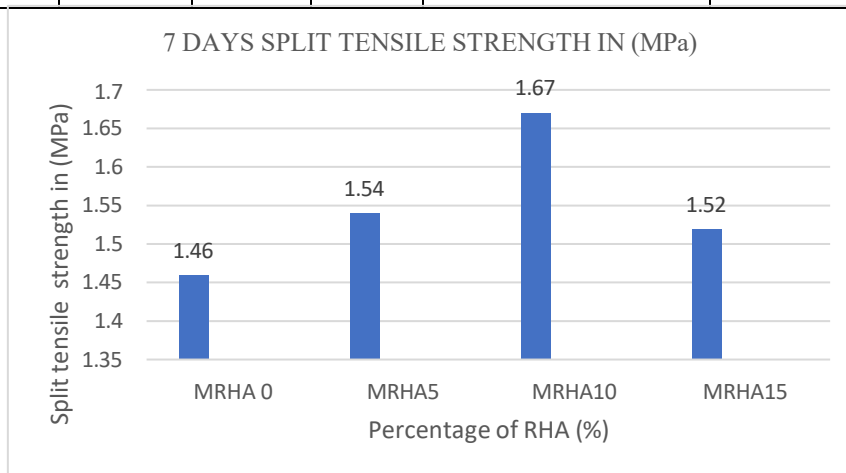


Chart 4.4: Comparison of split tensile strength for 7 days

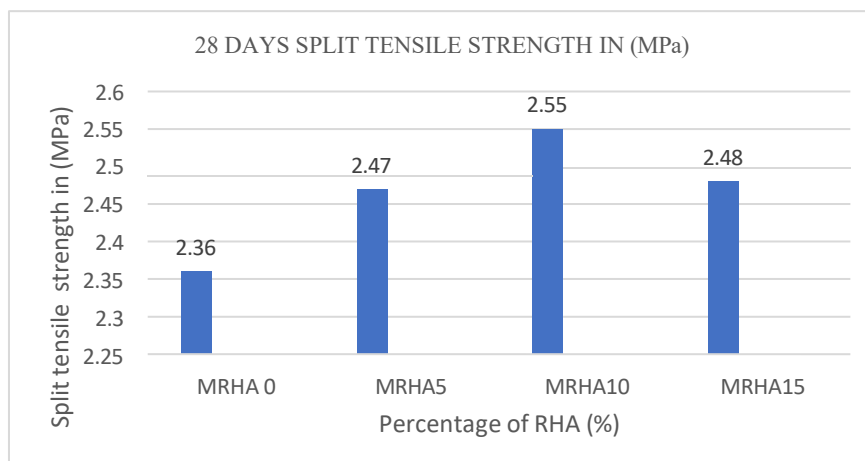


Chart 4.5: Comparison of split tensile strength for 28 days

Table 4.5 and Chart 4.5 show the 28-day split tensile strength of concrete with varying RHA content. Strength increases from 2.36 MPa (0% RHA) to a peak of 2.55 MPa at 10% replacement. At 15% RHA, the strength decreases to 2.48 MPa. This indicates an optimum RHA content of about 10% for maximum strength.

Table 6.4 and Chart 6.4 show the 7-day split tensile strength of concrete with different RHA contents. Strength increases from

1.46 MPa at 0% RHA to a maximum of 1.67 MPa at 10%. At 15% RHA, the strength decreases to 1.52 MPa. This indicates an optimum RHA content of about 10% for improved early strength.



Figure. 4.2: Crack patterns observed in cylinder specimens

5. Conclusion and Scope for Future Work

5.1 CONCLUSIONS

This study evaluates the performance of geopolymer concrete (GPC) using Rice Husk Ash (RHA) as a partial replacement for fly ash, along with GGBS and alkaline activators. The experimental work examined both fresh and hardened properties as per IS code guidelines. Workability was measured using the slump test. Standard specimens- cubes ($150 \times 150 \times 150$ mm) and cylinders (150×300 mm)—were prepared and cured under ambient conditions for 7 and 28 days. After curing, compressive strength and split tensile strength were tested to assess mechanical performance.

Important conclusions drawn from the present study are as follows:

1. The mechanical properties of geopolymer concrete improve with the inclusion of RHA up to an optimum level of 10%. Beyond this percentage, both compressive and split tensile strengths decrease significantly.
2. At 10% RHA replacement, the maximum strengths were achieved Compressive strength = 30.35 MPa (28 days) and Split tensile strength = 2.55 MPa (28 days)
3. The early-age (7-day) and later-age (28-day) strengths show similar trends, confirming the consistency of performance.

The strength improvement is due to the high amorphous silica content of RHA, which enhances geopolymerization and forms a denser alumino-silicate gel structure, improving load-bearing capacity and tensile resistance.

5.2 Scope for Future Work

- Structural Applications: Study reinforced GPC elements such as beams, columns, and slabs for real-world use.
- Environmental Impact: Analyze CO₂ emission reduction and energy efficiency compared to OPC concrete.
- Workability Enhancement: Investigate the use of superplasticizers to improve flow at higher RHA content.
- Durability Studies: Examine resistance to acid, sulphate, and chloride exposure for long-term performance.

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