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Research Article

Influence of Rice Husk Ash and Nano Clay on the Performance of Sustainable Self-compacting Geopolymer Concrete

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ABSTRACT

The present research aims to investigate the performance of self-compacting geopolymer concrete (SCGC) with sustainable binder materials such as Rice Husk Ash (RHA) and Nano Clay (NC). The main precursors used were fly ash (FA) and ground granulated blast furnace slag (GGBFS), and RHA was substituted for FA in proportions ranging from 0 to 30% to enhance the performance of the geopolymer matrix. The selected RHA mixture was further modified by changing the amounts of NC to obtain the desired results. Fresh, mechanical, durability, and microstructural properties of developed mixtures were assessed. The results indicated M-3 (55% FA+ 30% GGBFS + 15% RHA) as an optimum ratio for RHA and the addition of 2% NC (NC-2) further improved the mechanical performance of SCGC. The results indicated that the use of RHA to enhance the performance of these materials was effective up to a certain replacement rate, after which it gradually decreased. The inclusion of NC enhanced the performance by contributing to pore refinement and creating a more compact matrix. The chosen NC composition exhibited enhanced mechanical strength, reduced water absorption, reduced chloride ion ingress and sulfate exposure, and improved internal quality. SEM observations showed a rather dense and firmly bound geopolymer matrix. The selected NC-2 mix had a 28-day compressive strength of 50.92 MPa and water absorption of 3.20%. The chloride ion penetration and the sulfate strength deterioration at 90 days were 720 C and 5.84%, respectively. The findings demonstrate the potential of combining RHA and NC to produce sustainable and durable SCGC.

Keywords: Rice husk ash; Nanoclay; Geopolymerization; Aluminosilicate binder; Nano-modification.

1. INTRODUCTION

Construction is widely known to be one of the most resource-intensive industries, which utilizes a tremendous number of raw materials and is a major source of carbon dioxide (CO_2) emissions (Demissew, 2022; Brefo *et al.*2025). Many of these emissions are from the manufacture of cement, where energy-intensive activities like the formation of clinker at high temperatures are involved. Given the growing need for infrastructure in the world, the environmental impact of traditional cement-based materials is becoming a serious concern. (Bumanis *et al.* 2022; Chen *et al.* 2024). Therefore, it is essential that sustainable and environmentally friendly alternatives are developed that can minimise the carbon footprint of construction activities without compromising their performance. In this regard, geopolymer concrete (GC) has surfaced as a viable substitute, since it can use industrial waste materials as the main constituents of the binder and hence it can reduce greenhouse gas emissions substantially (Parvathikumar *et al.* 2025; Jessa and Ajidahun, 2024; Pacheco-Torgal, 2026; Zhang, 2026).

GC is obtained by synthesizing concrete by alkali activation of aluminosilicate-rich materials and forms a three-dimensional polymer network that gives excellent mechanical strength and durability properties (Shivasakthivadivelan *et al.* 2025). GGBFS and FA are widely accessible as industrial by-products and commonly used as precursor materials (Varma *et al.* 2023). Such utilization of these materials not only helps to reduce waste disposal problems but also makes an important contribution to sustainable resource use by turning industrial wastes into useful construction materials (Blesson and Rao, 2023; Li et al., 2023). Many research works have shown that GC is chemically resistant, less permeable and has higher durability in comparison to OPC based concrete. These properties render GC as a promising material for sustainable infrastructure construction. (Alahmari *et al.* 2023; Bharti *et al.* 2020; Prakash *et al.* 2024; Thadathil and Girdhar, 2024).

SCGC is an innovative form of concrete that has garnered considerable focus due to its exceptional fresh-state characteristics. (Amala and Umarani, 2024). Under its own weight, SCGC can flow to fill complex formwork, and can pass through areas with a high reinforcement content without mechanical vibration. This self-compacting property promotes efficiency in construction, reduces labor and noise pollution, and ensures uniform compaction, which improves the quality of the concrete structure (Mol *et al.* 2021; Naresh *et al.* 2024). However, it is still a challenge to obtain an optimum balance between workability and mechanical performance, especially when using supplementary materials as part of the geopolymer matrix (Nuruddin *et al.* 2011; Ramineni *et al.* 2018).

Agricultural waste ash is a potentially valuable material, which, with its high silica content, has become a sustainable supplementary binder material in recent years. (Manoj *et al.* 2025). In the past, agricultural residues were typically burned in the open or landfilled, resulting in environmental degradation and loss of valuable resources. RHA is one of the effective agricultural wastes high in silica, which can be utilized as a supplemental reactive material in GC. Converting these residues to reactive ash is an environmentally friendly solution for waste management and for reducing the need for conventional raw materials. The RHA can play an active role in the geopolymerisation process, improve particle packing, and provide an increase in a denser and finer binder matrix. (Jittin *et al.* 2020; Ogwang *et al.* 2021; Chiranjeevi *et al.* 2023; Onsongo *et al.* 2025; Amran *et al.* 2021).

Nanotechnology offers a simple yet effective approach to improve the properties of cementitious and geopolymeric materials by the optimization of their internal morphology. (Kavitha *et al.* 2024). Nanomaterials, owing to their exceedingly small particle size and extensive specific surface area, significantly influence the microstructure and reaction mechanisms within the binder matrix. They serve as nucleation sites, enhance reaction rates, and have a beneficial effect on the pore structure, which in turn results in better mechanical and durability properties. Among various nanomaterials, NC has attracted considerable interest due to its layered silicate structure, high surface area, chemical stability, and cost-effectiveness. (Rashad, 2019; Xie and Fang, 2019; Xu *et al.* 2021).

The mechanism of action of NC is as a micro-filler that fills the voids in the geopolymer structure and develops a dense and homogeneous structure (Jindal and Sharma, 2020). It was reported that the use of NC in GC resulted in an increase in the mechanical properties, and a decrease in permeability and resistance to aggressive environment (Middendorf *et al.* 2026; Tamilarasan *et al.* 2025). However, the effectiveness of NC is highly dependent on its dosage and dispersion. A high dosage of NC can cause particle agglomeration, loss of workability, and poor dispersion, ultimately resulting in inferior concrete. Hence, the optimum dosage of NC is very important to obtain the optimum mechanical properties and workability of the SCGC (Rezaie *et al.* 2025; Wu *et al.* 2023).

This current study is intended to explore the performance of SCGC made with RHA and NC. RHA is used as a sustainable supplementary binder material, and NC is added to refine the pores and to better pack particles. The effects of these substances 33are evaluated through various rheological, mechanical, and durability characteristics. In addition, the microstructural characteristics are assessed to understand the intrinsic composition of the matrix. 999The test findings would contribute to the production of high-performance, environmentally friendly SCGC.

1.1 Research Significance

Due to the growing need for sustainable construction materials, GC has emerged as an environmentally friendly substitute for Portland cement. Agricultural waste ash can be added to minimize the environmental impact and utilize renewable resources, but its properties will impact the concrete performance. The addition of NC improves the packing and geopolymerization, which leads to better microstructure. (Wu *et al.* 2023). But very limited investigations have been conducted on their synergistic effect on SCGC. Thus, this research aims to create an optimized mixture that combines the two materials for enhanced workability, strength, and durability. The results are intended to find a way to sustainable construction, decrease carbon emission and develop high-performance GC as construction material.

2. MATERIALS AND RESEARCH METHODOLOGY

2.1 Fly Ash (FA)

In the current study, Class F FA was adopted as the main aluminosilicate source for manufacturing SCGC. It is collected from a local thermal power station and meets the requirements of ASTM C618. Due to the presence of alumina and silica in significant proportions, it can be used as a good source material for geopolymerization, leading to the formation of a stable aluminosilicate gel network.

2.2 GGBFS

GGBFS was used as a secondary precursor to help increase the reactivity of the geopolymer binder and increase early-age strength under ambient curing environments. The GGBFS was purchased from a commercial supplier that met the specifications of ASTM C989. Calcium, which is present in GGBFS, facilitates the formation of calcium-rich aluminosilicate hydrate gels, which results in better strength development and densification of the matrix.

2.3 Rice Husk Ash

A sustainable supplementary precursor, RHA, was utilised to partially replace the FA in the geopolymer binder. The rice husk was calcined at 700 °C for 2 h, cooled, and processed in a lab-sized rotary ball mill to obtain a fine RHA powder with a particle size of less than 75 µm. RHA, with their amorphous nature and high silica content, actively involve in geopolymerization process and also it is promoting sustainable utilization of agricultural waste.

2.4 Nano Clay

NC was added as nano-modifying material to enhance the GC microstructure and performance. NC as a nucleation site during geopolymerization and refinement of pore structure through filler effect because of its large specific surface area and layered silicate structure. NC used in this study was in nano range and supplied by a certified commercial manufacturer. The physical and chemical composition of the materials used in this research are presented in Tables 1 & 2. Fig.1. depicts the binder materials used in this investigation.

2.5 Fine Aggregate

The fine aggregate utilised was locally available river sand which meets the (IS 383 - 1970) Zone II grading. Before mixing, the sand was clean, with no organic impurities, and in a saturated surface dry condition. The quality of the fine aggregate is crucial for the desired flowability, stability and segregation resistance of SCGC.

2.6 Coarse Aggregate

The coarse aggregate utilised in the entire investigation was crushed granite of nominal 12.5 mm size. To enhance the passability and eliminate blockage when self-compacting concrete (SCC) was flowing, a smaller size of aggregate was chosen. The aggregates were washed, oven-dried, and kept in the lab before being used.

2.7 Alkaline Activator Solution (AAS)

The AAS used was sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The AAS was prepared by dissolving analytical-grade NaOH pellets in distilled water to the desired molarity at least 24 hours prior to mixing to allow the temperature to stabilize.

2.8 Superplasticizer (SP)

Polycarboxylate ether (PCE) was added to ensure the desired segregation resistance, filling, and passing ability of SCGC. The dosage of SP was varied in the trial mixes to meet the fresh property requirements without affecting the geopolymerization process.

2.9 Water

Potable water free from harmful substances was used in the preparation of the sodium hydroxide solution and for washing all the laboratory equipments. The water met the requirements for producing concrete, and it was free from impurities that could affect the geopolymerization reaction.

Table 1. Material characteristics

Property	FA	GGBFS	RHA	NC
Colour	Light-Greyish	Off White	Dark-Greyish	Cream White
Bulk Density (kg/m^3)	980	1250	560	680
Blaine Fineness (m^2/kg)	380	430	450	375
Specific Gravity	2.20	2.90	2.12	2.60

Table 2. Chemical constituents of the materials

Oxide	FA	GGBFS	RHA	NC
SiO_2	55.80	34.90	89.20	61.80
Al_2O_3	27.60	13.20	0.85	18.50
Fe_2O_3	6.80	0.60	0.45	3.20
CaO	3.90	40.80	1.25	0.90
MgO	1.20	7.90	0.70	2.10

2.10 Research Methodology

2.10.1 Mix Constituents

The SCGC mix proportions were optimized using a systematic two-phased optimization process. There was no specific mix design procedure available for SCGC; therefore, the mixture proportions were determined using the principles of (IS 10262-2019) and (EFNARC -2005) for SCC and the relevant literature pertaining to GC. (Alahmari *et al.* 2023; Bharti *et al.*, 2020). The total binder content for all SCGC mixtures was kept at 500 kg/m^3. Initially, FA was used at 350 kg/m^3 and GGBFS at 150 kg/m^3 per m^3 of binder. In the first phase of the study, the RHA content was varied to partially substitute the FA, while keeping the content of GGBFS unchanged. The RHA replacement level ranged from 0 to 30% of the FA content to find the optimum replacement level.

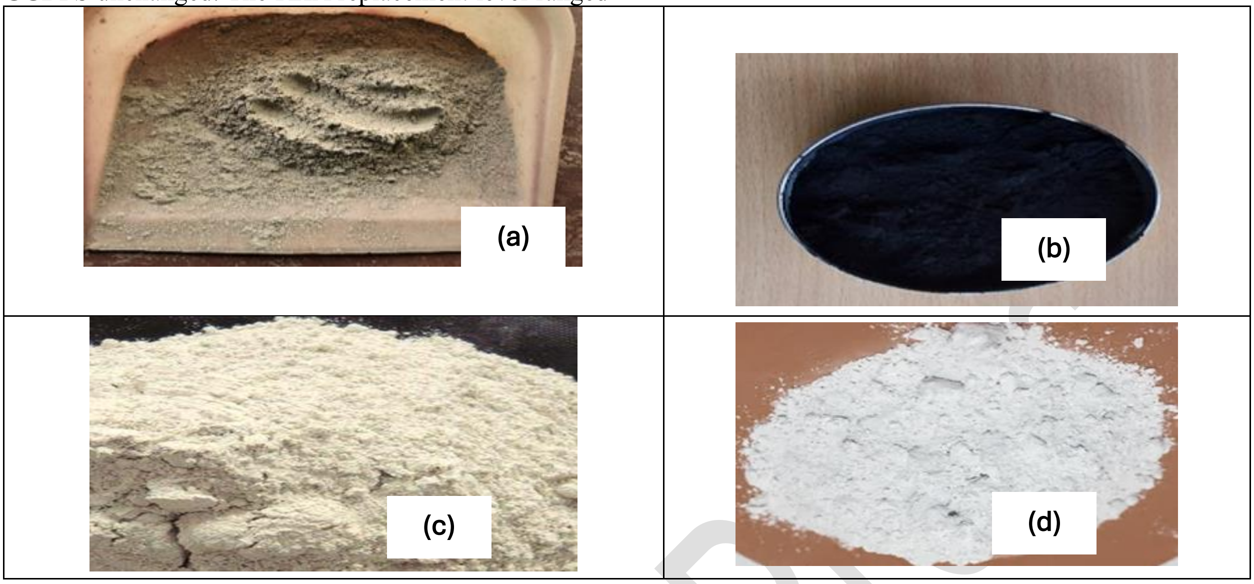

Fig. 1: Materials used (a) FA; (b) RHA; (c) GGBFS and (d) NC

The AAS comprised 12 Molar NaOH and Na_2SiO_3 in a ratio of Na_2SiO_3/NaOH of 2.5, which was maintained on a mass basis. For all mixtures, the AAS-to-binder ratio was kept constant at 0.45, and the effective water-to-binder ratio was kept constant at 0.31. No additional free water was added during mixing. To impart the desired self-compacting properties, a PCE-based SP was used at 1.2% of the total binder content.

In the second phase, NC was added to the optimum RHA mixture by substituting 0–4% of the total binder with the same binder quantity. The relative proportions of the activating solution to the binder, the formulation of the activating solution, the accessible water content, and the dosage of admixtures remained constant throughout the whole experimental program. This ensured that the properties of the SCGC observed are predominantly due to the addition of RHA and NC. The mixture ratios utilized for Phase I and Phase II are summarized in Tables 3 and 4, correspondingly.

Table 3. Mix proportions for phase I

Mix ID	FA	GGBFS	RHA	NC	Total Binder
	(kg/m³)				
M0	350	150	0	0	500
M1	325	150	25	0	500
M2	300	150	50	0	500
M3	275	150	75	0	500
M4	250	150	100	0	500
M5	225	150	125	0	500
M6	200	150	150	0	500

Table 4. Mix proportions for phase II

Mix ID	FA	GGBFS	RHA	NC	Total Binder
	(kg/m³)				
NC0	275.00	150.00	75.00	0.00	500
NC1	272.25	148.50	74.25	5.00	500
NC2	269.50	147.00	73.50	10.00	500
NC3	266.75	145.50	72.75	15.00	500
NC4	264.00	144.00	72.00	20.00	500

2.10.2 Specimen Preparation, Curing and Testing Methods

The solution containing the NaOH was prepared for 24 hours before to mixing. The dry ingredients were combined for approximately 3 minutes, after which the AAS and SP were added progressively. The mixture lasted about 5 minutes before a consistent and unified SCGC was produced. The fresh concrete was thereafter employed for property assessments and specimen casting.

Immediately following the mixing, the fresh characteristics of the SCGC were assessed in accordance with the EFNARC (2005) standards. The L-box, T_{500}, slump flow, and V-funnel tests were conducted to assess the flowability, viscosity, filling ability, passing ability, and blocking resistance of the concrete. Subsequently, the concrete was transferred into the moulds without external vibration, allowing it to flow and compact under its own weight.

A 15cm cube specimen was cast for compressive strength testing in accordance with IS 516

(Part 1 – 2021). Cylindrical specimens with a 15 cm diameter and a 30 cm height were prepared for split tensile strength (STS) testing in accordance with (IS 5816:1999). Prism specimens with a 10 × 10 × 50 cm dimension were cast for flexural strength (FS) testing in accordance with IS 516 (Part 1 - 2021). The specimens were then demoulded and cured under ambient laboratory conditions at 27 ± 2 °C until the required testing ages. The ultrasonic pulse (UPV) test was conducted in accordance with IS 13311 (Part 1 -1992) to assess the internal quality, uniformity, and compactness of the SCGC specimens. The mean value was reported for three specimens tested for each blend.

The durability behaviour of the SCGC was evaluated in terms of water absorption (WA) in accordance with ASTM C642. The specimens were dried to constant mass, immersed in water for 28 days, then weighed to determine the percentage of water absorbed.

The RCPT was carried out at 30 and 90 days using 10 cm dia x 5 cm thick samples with an applied voltage of 60 V for 6 h according to (ASTM C1202). As there is no specific defined method available for sulfate resistance evaluation of SCGC, the sulphate exposure process was selected with reference to (ASTM C1012).

These tests were carried out to assess the resistance of the concrete to moisture ingress, chloride penetration, and sulphate attack. Scanning electron microscopy (SEM) was performed only on the optimum mix to examine the morphology and compactness of the geopolymer matrix. The SEM observations were correlated with the mechanical and durability performance of the optimum concrete.

3. ANALYSIS AND INTERPRETATION OF RESULTS

3.1 Fresh Properties of SCGC

Fresh properties of the prepared SCGC mixes were assessed to study the impact of RHA and NC on workability and self-compacting properties of the developed mixtures. The fresh-state properties of SCGC are detailed in Table 5. As the amount of RHA increased, the workability of the SCGC decreased. The slump flow was reduced from 722mm to 672mm as RHA was increased from 0% to 30%, as illustrated in Fig.2. The T_{500} flow time was increased from 3.2s to 4.2 s as the RHA increased from 0% to 30%. Similarly, the flow time in the V-funnel was raised to 11.50 s, from 8.50 s, and the ratio for L-box was lowered to 0.86 (from 0.92 This reduced workability may be attributed to the probable absorption of AAS by the porous particles of RHA. (Adeniyi *et al.* 2020). However, it was found that all RHA mixtures met the recommended limits for SCC; hence, the mixtures still had enough filling and passing properties. (Putri *et al.* 2024).

The same trend was noticed during the optimization phase of the NC. The fresh properties of the reference mixture (NC-0) were found to be similar to those of the control mixture: a slump flow of 720 mm, T_{500} flow time of 3.2 s, V-funnel time of 8.50 s and L-box ratio of 0.92. As the amount of NC slowly increased, slump flow decreased from 720 mm to 650 mm by incorporating 0- 4% NC content. Similarly, the T_{500} flow time rose from 3.2 s to 4.5 s and the V-funnel flow time rose from 8.50 s to 12.20 s.

The L-box ratio also decreased slowly from 0.92 to 0.86, which meant that the passing ability was a little lowered. This behaviour was primarily attributed to the very fine particle size and high surface area of the NC, which was responsible for increasing the cohesiveness of the fresh mixture. The workability reduced with the increase in the content of NC, while the cohesiveness increased with the NC content, which in turn resulted in lesser segregation tendency and a more stable concrete mixture in the fresh state. The results show that the fresh behaviour of SCGC was affected by both RHA and NC, which increased the viscosity and decreased the flowability of the mixture. All the mixtures were, however, within acceptable limits as stated by the EFNARC guidelines for SCC (Tian *et al.* 2024). The results demonstrate that the selected binder combinations are acceptable fresh characteristics based on the measured workability parameters.

Table 5. Fresh properties of SCGC

Mix	T_{500} (s)	V-Funnel (s)	L-Box Ratio	Slump Flow (mm)
M-0	3.2	8.50	0.92	722
M-1	3.3	8.78	0.91	712
M-2	3.4	9.20	0.90	702
M-3	3.6	9.80	0.89	693
M-4	3.8	10.50	0.88	681
M-5	4.0	11.00	0.87	677
M-6	4.2	11.50	0.86	672
NC-0	3.2	8.50	0.92	720
NC-1	3.5	9.00	0.91	700
NC-2	3.8	9.80	0.90	688
NC-3	4.2	11.50	0.88	663
NC-4	4.5	12.20	0.86	650

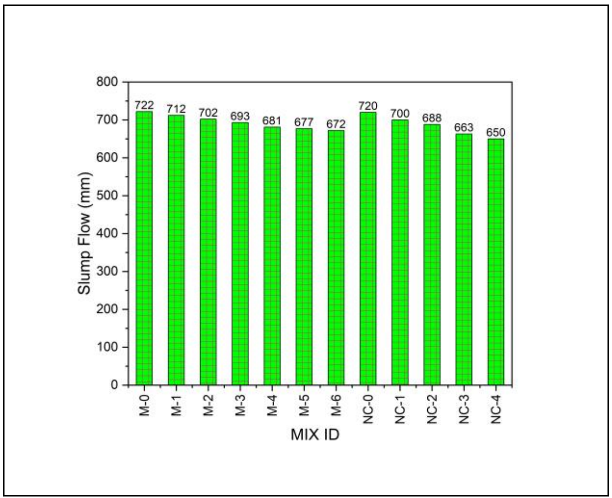

Fig. 2: Variation in slump flow

3.2 Mechanical Performance of SCGC

The mechanical properties of the SCGC were assessed at various curing ages to investigate the effect of the composition of the binder on strength development. The performance comparisons were made against the reference mixture to analyze the changes in performance by adding RHA and NC. These findings are outlined and discussed in subsequent subsections

3.2.1 Compressive Strength (CS)

The mean CS results for all the mixtures are given in Table 6. The CS observed for the control mixture M-0 was 24.83 MPa, 33.60 MPa, and 41.53MPa at 3, 7, and 28 days, respectively. In Phase I, the addition of RHA enhanced the strength of the mixes up to Mix M-3. For M-3, the highest CS of 46.90 MPa was achieved at 28 days as compared to the control mixture. The fine particles and high silica content of RHA enhanced the geopolymerization process and the formation of a more compact concrete matrix, which contributed to this improvement. (Hamada *et al.* 2025).

The CS was then reduced as the RHA content was raised further. The further addition of NC also enhanced the compressive strength. The highest strength was achieved in NC-2, with strengths of 29.03 MPa, 39.82 MPa, and 50.92 MPa at 3, 7, and 28 days, respectively.

The CS of NC-2 after 28 days was about 8.5% higher than that of NC-0. The nano-filler effect of NC was responsible for this improvement, as it created a finer pore structure and a better bond between the geopolymer matrix (Wang *et al.* 2022). The CS of NC-3 and NC-4 showed a slight decrease. This might be attributed to the tendency of the NC particles to agglomerate at higher doses, which prevented better dispersion in the binder matrix (Zhao *et al.* 2020). All the mixtures of NC, however, resulted in higher CS at 28 days than the reference mixture. The overall results show that the addition of 15% RHA and 2% NC resulted in the highest CS.

Table 6. Illustrative mean CS data

Mix	3 D	7 D	28 D
		(MPa)	
M-0	24.83	33.60	41.53
M-1	25.50	34.55	42.80
M-2	26.31	35.80	44.64
M-3	27.40	37.22	46.90
M-4	26.64	36.40	45.36
M-5	25.36	34.94	43.24
M-6	23.90	32.80	40.70
NC-0	27.42	37.25	46.91
NC-1	28.20	38.58	48.80
NC-2	29.03	39.82	50.92
NC-3	28.40	39.05	47.63
NC-4	27.20	37.62	45.40

3.2.2 Split Tensile Strength (STS)

Fig.3 shows the mean STS of all the mixtures. The STS for the control mixture (M-0) at 28 days was measured at 3.88 MPa. Incorporation of RHA in the mix up to Mix M-3 resulted in an increase in the STS during Phase I. The highest value of 4.42 MPa was recorded after 28 days for M-3, which is approximately 13.9% higher than with the control mixture. The smaller particle sizes and elevated silica concentration of RHA led to a better geopolymerisation reaction and a denser binder matrix with improved bonding between the binder and aggregate (Verma *et al.* 2024). The STS decreased with increasing RHA content above the optimal level. This decrease could be ascribed to over-replacement of FA, which decreased the amount of reactive aluminosilicate material to produce geopolymer gel. The STS was further improved in Phase II by incorporating the NC. The reference mixture NC-0 showed an STS of 4.43 MPa after 28 days, while NC-2 with 2% NC yielded the maximum value of 4.86 MPa. This indicates an improvement of about 9.7% over NC-0.

The nano-filler effect of NC mainly caused the improvement, which refined the pore structure, reduced micro voids, and strengthened the bond between the geopolymer matrix (Jindal and Sharma, 2020). A slight decrease was noted for NC-3 and NC-4, but these values were still higher than the reference mixture. This behaviour could be attributed to the fact that with the increase in dosage, the NC particles aggregated, and hence the distribution of the particles in the concrete matrix was not uniform. The overall trend of the STS results was similar to that of CS results. In Phase I, 15% RHA, and in Phase II, 2% NC, were found to be the optimum content for the best performance. The overall findings suggest that the use of RHA and NC has positively enhanced the tensile properties of SCGC.

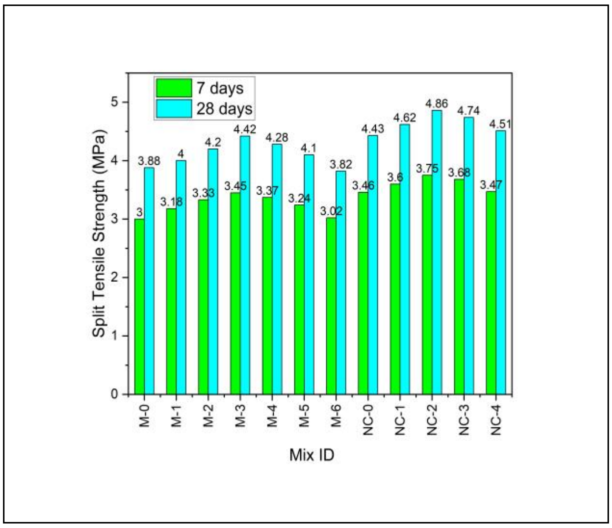

Fig. 3: Variation of STS with curing age

3.2.3 Flexural Strength (FS)

The FS of the control mix (M-0) was 4.25 MPa and 5.20MPa at 7 and 28 days, respectively. The FS was gradually increased with the addition of RHA from M-1 to M-3, as depicted in Fig.4. Of these mixtures, M-3 had the greatest FS of 5.95MPa after 28 days, approximately 14.4% greater than the control mixture. This enhancement can be attributed to the finer particles and silica content of RHA, which improved the geopolymer matrix and the bond between the binder and aggregates. (Hamada *et al.* 2025). The FS of the RHA gradually decreased with the increasing content of RHA up to M-3. The 28-day FS of M-4, M-5, and M-6 were 5.76 MPa, 5.48 MPa, and 5.08 MPa, respectively.

This decrease could be attributed to the lesser amount of reactive binder available to generate geopolymer gel at higher replacement rates. Further incorporation of NC resulted in even better FS. The results showed that the FS of the reference mix (NC-0) was 5.96 MPa after 28 days, while the highest FS was obtained for NC-2, which was 6.48 MPa after 28 days. The FS of the NC-2 was found to be around 8.7% higher than that of the NC-0 sample.

A slight decrease in FS was noted for NC-3 and NC-4, having a 28-day FS of 6.32 MPa and 6.02 MPa, respectively. This could be explained by the tendency of the NC particles to aggregate at higher concentrations and thus lead to less dispersion of the particles in the concrete matrix. (Arman *et al.*2026). Among the RHA mixes, the best performance was achieved for M-3 and among the NC mixes, the best performance was achieved for NC-2. The results showed that the RHA and NC mixtures were able to enhance the flexural properties of SCGC.

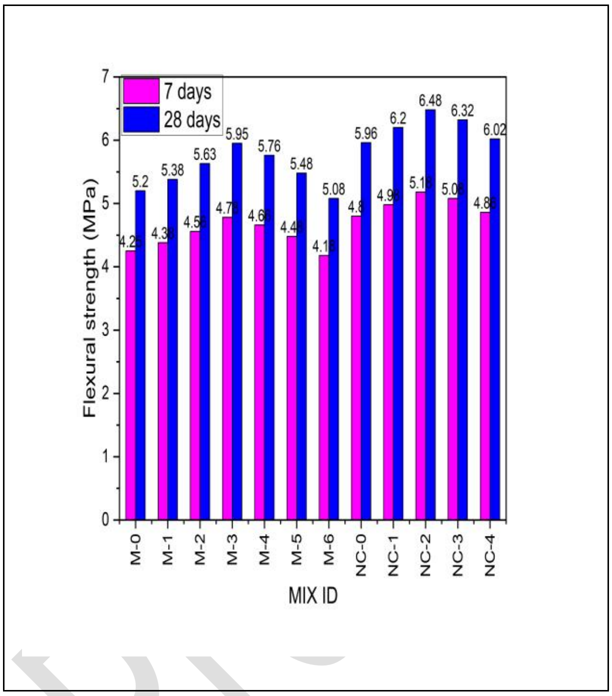

Fig. 4: Variation of FS with curing age

3.2.4 UPV Test

The UPV values for the SCGC mixes varied from 3.96 to 4.60 km/s, which indicates that all GC mixes had good to excellent internal quality, as illustrated in Fig.5. The reference mix (M-0) obtained a UPV value of 3.96 km/s, which is indicative of good quality concrete. The addition of RHA content in the mixture resulted in gradual improvement of UPV values until reaching the highest value of 4.42 km/s for M-3, which showed the creation of a denser and homogeneous geopolymer matrix. This improvement is due to the increased geopolymerization process and filler effect provided by the finely divided RHA, which decreased the internal pores and microcracks. (Sujitha *et al.* 2025).

In the case of NC-modified mixtures, UPV increased from 4.36 km/s for NC-0 to NC-2, which was considered excellent-quality concrete. NC was added, which refined the pore structure, sped up the formation of geopolymer gel, and enhanced the bonding between the binder and aggregates, thus making the internal structure denser. The UPV values of NC-3 (4.56 km/s) and NC-4 (4.33 km/s) were slightly decreased from the value of NC-2, but both values were in excellent and good quality ranges. The observed UPV trend was similar to the CS, STS, and FS results, which indicates that the mixtures with the best mechanical performances showed better internal integrity and lower porosities. The overall results of UPV showed that by adding suitable amount of RHA and NC, the quality and uniformity of the SCGC got enhanced.

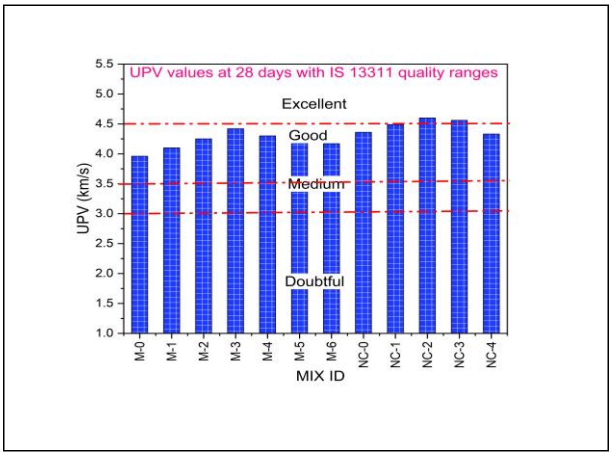

Fig. 5: Variation of UPV test

3.3 Durability properties

The durability performance of the SCGC was assessed to understand its resistance to different environmental exposure conditions. The results were used to evaluate the impact of RHA and NC on the long-term performance of the developed mixtures.

3.3.1 Water Absorption (WA)

The WA of the SCGC mixtures at 28 days is exhibited in Fig.6. The WA values vary between 3.20% to 4.69%. The lower the WA, the denser the concrete matrix, and the more durable the concrete. The highest moisture absorption capacity was in the reference mix (M-0), at 4.69%. The absorption rate gradually decreased with the increase in the RHA content to 4.43% (M-1), 4.16% (M-2), and 3.82% (M-3). This phenomenon is primarily due to the finer particles of RHA that filled the small voids and enhanced the bonding within the geopolymer matrix. Consequently, the concrete permeability was lowered. After M-3, the WA increased slightly to 3.96% (M-4), 4.19% (M-5), and 4.37% (M-6). This could be due to the fact that the higher RHA content resulted in a less compact matrix and more unreacted particles, which resulted in a small increase in porosity. Further improvement in the durability of the NC mixes was observed.

The absorption rate reduced from 3.73% (NC-0) to 3.47% (NC-1) and reached the lowest value of 3.20% (NC-2). NC was used as a micro-filler, which was able to improve the pore structure and make the concrete denser with less WA. Slight increases were found for NC-3 (3.28%) and NC-4 (3.45%), which can be attributed to the lesser dispersion of NC at high contents. The absorption rate decreased with the increase in strength of the mixes due to their dense interparticle structure. By comparison, M-3 recorded the best efficiency among the RHA mixes, while NC-2 achieved minimal WA among all the mixes. These findings suggest that the optimum addition of RHA and NC is an effective way to enhance the durability of SSCC by reducing the water permeability of the concrete.

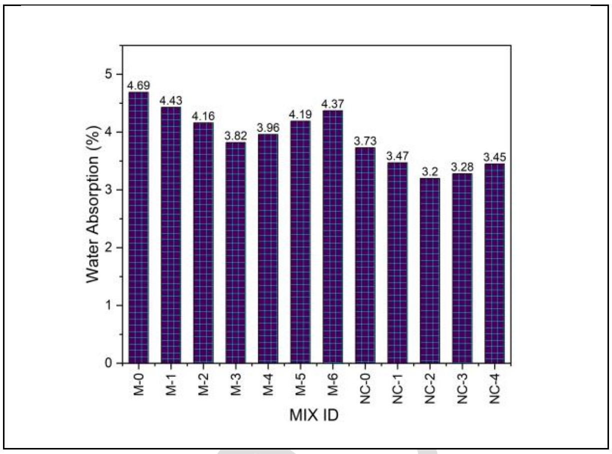

Fig. 6: Variation of WA test

3.3.2 Rapid Chloride Penetration Test

Table 7 shows the RCPT values of the materials at 30 and 90 days. The charge through the concrete specimens diminished with increasing curing age, which shows that the resistance to chloride ion penetration increases as the age of the concrete increases. The lower the coulombs, the lower the penetrability of the concrete and the higher the durability. The reference mix (M-0) had the highest charge passed, i.e., 1860 coulombs at 30 days and 1626 coulombs at 90 days, which signify relatively higher chloride absorbency.

The charge gradually diminished with the increase of RHA content. The RHA mixes exhibited a higher chloride penetrability resistance than the other RHA mixes, as can be seen in the results of 1446 coulombs for the M-4 mix at 30 days and 1218 at 90 days. A slight increase in charge passed was, however, noted for M-5 and M-6, indicating that the higher the RHA content, the less compact the geopolymer matrix. The resulting concrete was even more resistant to chloride by incorporating NC. The electrical conductivity and pore solution chemistry of the GC may also influence the RCPT results. The charge reduced from 1398 coulombs (NC-0) to 1212 coulombs (NC-1), and the lowest value was 945 coulombs and 720 coulombs at 30 days and 90 days, respectively, for NC-3. The denser microstructure and the reduction of the movement of chloride ions through the concrete were attributed to this improvement due to the pore-filling effect of the NC. The classification of all the RHA mixes according to ASTM C1202 is low chloride ion penetrability. All the NC mixes were classified as very low, indicating that they have excellent resistance to chloride ingress. The RCPT results followed a trend similar to the compressive strength, UPV, and WA results. The strength and WA of these mixes also had a similar relationship with charge passed, as the higher the strength, the lower the WA, and hence the denser and less permeable the geopolymer matrix. NC-3 had the highest resistance to chloride ion infiltration of all the mixtures, while the mix with no other additives (M-0) had the lowest.

Table 7. RCPT results

Mix ID	30 Days (Coulombs)	90 Days (Coulombs)	Penetrability Rating (90 Days)
M-0	1860	1626	Low
M-1	1750	1513	Low
M-2	1644	1408	Low
M-3	1475	1225	Low
M-4	1446	1218	Low
M-5	1636	1362	Low
M-6	1724	1455	Low
NC-0	1398	1128	Low
NC-1	1212	968	Very Low
NC-2	986	743	Very Low
NC-3	945	720	Very Low
NC-4	1088	925	Very Low

3.3.3 Sulphate Attack

The results of residual CS after 30- and 90-days exposure in sulphate solution for all the SCGC mixes are exhibited in Fig.7. The CS of all the mixes decreased after being subjected to sulphate. This resulted in an increase in the percentage of strength loss from 30 days to 90 days. The strength loss at 30 days and 90 days was the highest at 6.85% and 11.62%, respectively, for the reference mix (M-0). With the addition of RHA, the strength deterioration gradually decreased. The M-3 mix of RHA showed the lowest deterioration rate at 4.58% at 30 days and 7.86% at 90 days. This shows the incorporation of RHA resulted in an increase in the resistance of the concrete to sulphate attack by forming a dense matrix. The strength reduction increased from M-4 to M-6 with values of 4.92%, 5.68%, and 6.34%, respectively. This could be attributed to the increase in RHA content, which caused some decrease in the compactness of the concrete and resulted in more penetration of sulphates. The strength loss of NC mixes was less than that of RHA mixes. The deterioration decreased from 4.32% (NC-0) to 3.84% (NC-1) and reached the lowest value of 3.26% at 30 days and 5.84% at 90 days for NC-2.

This enhanced performance is said to be due to the pore-filling properties of the NC, which minimised the entry of the sulphate ions and increased the durability of the concrete. Both the NC-3 and NC-4 mixes experienced slight deterioration in strength, while both of these mixes did better than the reference mix and RHA mixes. It is also noted that all mixes experienced higher strength loss after 90 days when compared to 30 days, suggesting that the longer the exposure to sulphates, the higher the strength loss. The M-3 mix showed the most satisfactory sulphate resistance for RHA mixes, and the NC-2 showed the lowest deterioration of strength of all the RHA mixes.

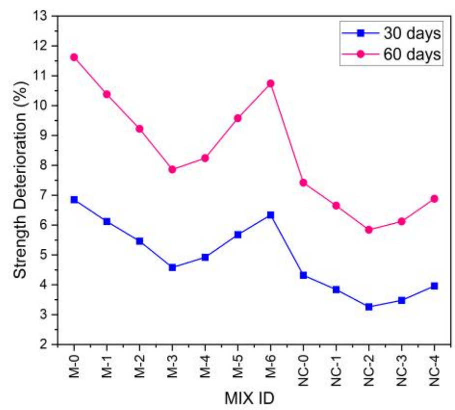

Fig. 7: Change in strength after sulphate exposure

3.4 Microstructural Observations

The microstructural characteristics of the optimum mixture have been analyzed using SEM. SEM imaging was performed at an accelerating voltage of 20.00 kV, and images are exhibited with a scale bar of 20 μm.

The SEM image of the M-3 mix reveals a relatively dense and compact structure with good particle bonding, as illustrated in Fig.8. The dense matrix shows that the interaction between geopolymer reaction products and the binder particles is good, leading to a decrease in the internal voids. The incorporation of RHA is believed to be helpful in refining the matrix due to its very fine particle size and silica-rich properties. This allows for better packing and further development of a more continuous geopolymer matrix. It is noticed that there are also some particles that are not fully reacted or reacted incompletely, which is a common phenomenon in geopolymer systems. There are also a few localized microcracks that can be seen; these can be related to the drying or shrinking of the sample, or they can be preparation-induced cracks.

These cracks, however, are limited and not seen to be the main features of the microstructure. Good internal cohesion is suggested by the strong bonding between the particles and matrix. The mechanical and durability characteristics of the M-3 mix are in good agreement with the dense structure obtained from the laboratory tests. A small matrix having fewer interconnecting pores may limit the flow of water and aggressive ions in and out of the concrete mass. This observation agrees with the results of higher strength, higher UPV, lower WA, and higher resistance to chemical attack obtained for M-3. Hence, the microstructural support obtained from SEM of the M-3 mixture reflects the enhanced performance of the mixture among the RHA-modified mixes.

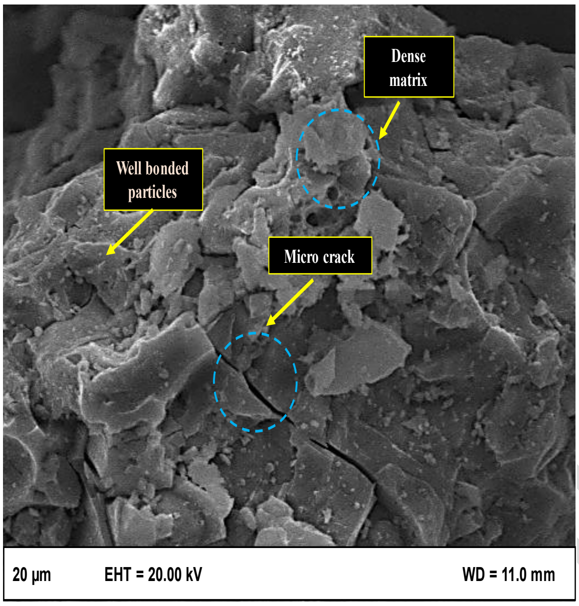

Fig. 8: SEM micrograph of M-3 mix

The SEM image of this NC-2 mix reveals a dense and relatively compact structure with good continuity of the geopolymer matrix, as exhibited in Fig.9. The incorporation of NC seems to have resulted in refinement of the internal structure by filling the fine voids between the reaction products. This led to a densely packed matrix and fewer pores were identified, suggesting a higher compactness of the matrix. The microstructure shows a few small pores and some micro-cracks. These features, however, are few and far between and are embedded in a complex matrix. The fine NC particles can offer a filling effect and extra reactive surfaces to promote to a more refined geopolymer structure. Concrete with fewer pores may also impede the flow of water and aggressive ions in the concrete. The improved mechanical and durability performance of NC-2 is reflected by its microstructural characteristics. The high strength and UPV can be attributed to the dense matrix, whereas the low pore structure is consistent with the low WA and high chloride and sulphate exposure resistance. The NC-2 microstructure shows the further refinement of the geopolymer matrix, which is a beneficial effect of NC on the performance of SCGC, in comparison to the RHA-modified mix.

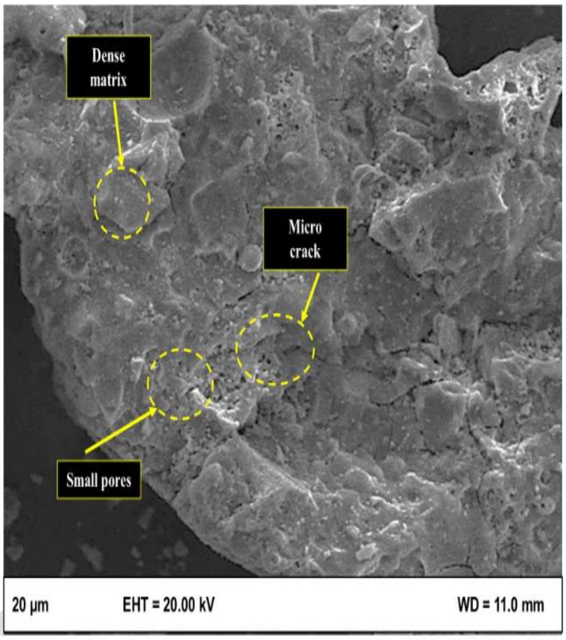

Fig. 9: SEM micrograph of NC-2 mix

4. CONCLUSIONS

From the experimental investigation on SCGC with incorporation of rice husk ash (RHA) and nano clay, the following conclusions are drawn:

- The self-compacting properties of all the developed mixtures were within the recommended EFNARC acceptance limits. The flowability of the concrete however was decreased gradually as the RHA and NC contents increased.
- The incorporation of RHA improved the mechanical properties up to M-3. Above this percentage, a progressive decline in strength was noticed, suggesting that an increase in RHA replacement was not as beneficial.
- The compressive strength of the M-3 mix at 28 days was 46.90 MPa, while the reference mix was 41.53 MPa. Similar improvements were observed in the tensile and flexural behaviour. Further, NC was added to the selected RHA-based mixture, which further improved its strength.
- The trend of the split tensile strength and flexural strength was similar. The highest values of 4.86 MPa and 6.48 MPa, respectively, were obtained for NC-2 at 28 days.

- The UPV results are from 3.96 to 4.60 km/s which is good to excellent concrete quality according to (IS 13311- Part 1-1992).
- The addition of RHA and NC led to a reduction in WA. The lowest value of 3.20% was obtained for NC-2, which shows decreased water uptake.
- The results obtained from the RCPT indicated a definite trend of decrease in chloride ion penetration with age. After 90 days, the NC-modified mixtures exhibited very low chloride penetrability, with NC-3 displaying the lowest charge passed of 720 coulombs.
- The results of the sulphate exposure showed that the developed mixtures had less strength loss than the reference concrete. NC-2 had the least loss of strength at 30 days (3.26%) and 90 days (5.84%).
- The SEM observation of M-3 showed a relatively dense matrix with good particle bonding and NC-2 showed further refinement of the structure with less visible pores.
- Such observations are in line with the improvements in mechanical and durability properties. The RHA modified mixtures, M-3 gave a favorable balance of the fresh, mechanical and durability properties.
- The incorporation of NC was then done which further enhanced the performance of concrete. Based on the experimental findings, NC-2 achieved the good performance especially in terms of mechanical characteristics, moisture absorption, sulphate resistance, UPV and microstructural characteristics. The results clearly show the potential of RHA and NC for the production of durable and sustainable SCGC.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Adeniyi, F. I., Ogundiran, M. B., Hemalatha, T. and Hanumantrai, B. B., Characterization of raw and thermally treated Nigerian kaolinite-containing clays using instrumental techniques, *SN Appl. Sci*., 2, 821 (2020). https://doi.org/10.1007/s42452-020-2610-x

Alahmari, T. S., Abdalla, T. A. and Rihan, M. A. M., Review of Recent Developments Regarding the Durability Performance of Eco-Friendly Geopolymer Concrete, *Build.*, 13(12), 3033 (2023). https://doi.org/10.3390/buildings13123033

Amala, M. and Umarani, C., Experimental investigation on mechanical and microstructural properties of self-compacting geopolymer concrete with different mineral admixtures, *Mater. Res. Exp.*, 11(9), 095305 (2024). https://doi.org/10.1088/2053-1591/ad75e9

Amran, M., Fediuk, R., Murali, G., Vatin, N., Karelina, M., Ozbakkaloglu, T., Krishna, R. S., Sahoo, A., Das, S. and Mishra, J., Rice Husk Ash-Based Concrete Composites: A Critical Review of Their Properties and Applications, *Cryst.*, 11(2), 168 (2021). https://doi.org/10.3390/cryst11020168

Arman, A., Taghvaei, M., Zirakian, T., Amirkardoust, A., Sistaninezhad, R., Sedaghat Shayegan, D. and Taghvaei, S., Effect of Nano-Clay Dosage on the Compressive Strength Development of Concrete, *SSRN,* (2026). https://doi.org/10.2139/ssrn.7005082

ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution, ASTM International.

ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International.

ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International.

ASTM C989, Standard Specification for Slag Cement for Use in Concrete and Mortars, ASTM International.

Bharti, R., Shobharam, S., Gautam, M. and Prabhakar, V., Review: An overview of geopolymer concrete, *Int. J. Tech. Res. Sci.,* 5(10), 13–19 (2020). https://doi.org/10.30780/ijtrs.v05.i10.003

Blesson, S. and Rao, A. U., Agro-industrial-based wastes as supplementary cementitious or alkali-activated binder material: a comprehensive review, *Innov. Infrastruct. Sol.,* 8(4), 125 (2023). https://doi.org/10.1007/s41062-023-01096-8

Brefo, J. A., Osei, A. K. and Opoku, J., Sustainable low-carbon cement technologies for reducing U.S. construction carbon emissions, *Eng. Sci. Technol. J.*, 6(6), 240–255 (2025). https://doi.org/10.51594/estj.v6i6.1954

Bumanis, G., Korjakins, A. and Bajare, D., Environmental Benefit of Alternative Binders in Construction Industry: Life Cycle Assessment, *Environ.,* 9(1), 6 (2022). https://doi.org/10.3390/environments9010006

Chen, L., Yang, M., Chen, Z., Xie, Z., Huang, L., Osman, A. I., Farghali, M., Sandanayake, M., Liu, E., Ahn, Y. H., Al-Muhtaseb, A. H., Rooney, D. W. and Yap, P. S., Conversion of waste into sustainable construction materials: A review of recent developments and prospects, *Mater. Today Sustain*., 27, 100930 (2024). https://doi.org/10.1016/j.mtsust.2024.100930

Chiranjeevi, K., Vijayalakshmi, M. M. and Praveenkumar, T. R., Investigation of fly ash and rice husk ash-based geopolymer concrete using nano particles, *Appl. Nanosci.,* 13(1), 839–846 (2023). https://doi.org/10.1007/s13204-021-01916-2

Demissew, G. A., Production of Sustainable Concrete by Using Challenging Environmentally Friendly Materials Instead of Cement, *IntechOpen*, (2022). https://doi.org/10.5772/intechopen.99239

EFNARC, The European Guidelines for Self-Compacting Concrete: Specification, Production and Use, EFNARC (2005).

Hamada, H. M., Al-Attar, A., Beddu, S., Askar, M. K., Yousif, S. T. and Majdi, A., Impact of rice husk ash on geopolymer concrete: A literature review and future directions, *Case Stud. Constr. Mater*., 22, e04476 (2025). https://doi.org/10.1016/j.cscm.2025.e04476

IS 10262:2019, Concrete Mix Proportioning – Guidelines, Bureau of Indian Standards.

IS 13311 (Part 1):1992, Non-Destructive Testing of Concrete – Ultrasonic Pulse Velocity, Bureau of Indian Standards.

IS 383, Coarse and Fine Aggregate for Concrete – Specification, Bureau of Indian Standards, (1970).

IS 516 (Part 1/Sec 1):2021, Hardened Concrete – Methods of Tests, Bureau of Indian Standards.

IS 5816:1999, Splitting Tensile Strength of Concrete – Method of Test, Bureau of Indian Standards.

Jessa, E. and Ajidahun, A., Sustainable practices in cement and concrete production: Reducing CO_2 emissions and enhancing carbon sequestration, *World J. Adv. Res. Rev.,* 22(2), 2301–2310 (2024). https://doi.org/10.30574/wjarr.2024.22.2.1412

Jindal, B. and Sharma, R., The effect of nanomaterials on properties of geopolymers derived from industrial by-products: A state-of-the-art review, *Constr. Build. Mater.,* 252, 119028 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119028

Jittin, V., Bahurudeen, A. and Ajinkya, S. D., Utilisation of rice husk ash for cleaner production of different construction products, *J. Clean. Prod.,* 263, 121578 (2020). https://doi.org/10.1016/j.jclepro.2020.121578

Kavitha, E., Revathi, S., Reena, L. and Vinodhini, C., Influence of nano-SiO_2 and nano-TiO_2 on self-compacting concrete: A study of rheology and strength improvement, *J. Environ. Nanotechnol*., 13(4), 161–168 (2024). https://doi.org/10.13074/jent.2024.12.2441074

Li, L., Xie, J., Zhang, B., Feng, Y. and Yang, J., A state-of-the-art review on the setting behaviours of ground granulated blast furnace slag- and metakaolin-based alkali-activated materials, *Constr. Build. Mater*., 368, 130389 (2023). https://doi.org/10.1016/j.conbuildmat.2023.130389

Manoj, P. C., Selvam, B., Vinodhini, C., Nirmal, L. M., Elavarasan, R. and Kavitha, E., Influence of Rice Husk Ash on the durability of geopolymer concrete under different molarities, *Procedia Struct. Integr*., 70, 207–214 (2025). https://doi.org/10.1016/j.prostr.2025.07.045

Middendorf, B., Kosenko, D. and Singh, N. B., Nanomaterials in geopolymer concrete: revolutionizing sustainable cement solutions, *Res. Chem.,* 19, 102897 (2026). https://doi.org/10.1016/j.rechem.2025.102897

Mol, J. S. J. and Eswaramoorthi, P. D., A study on self-compacting geopolymer concrete, *Int. J. Eng. Appl. Sci. Technol.,* 5(10), (2021). https://doi.org/10.33564/ijeast.2021.v05i10.048

Naresh, T., Mallik, M., Rao, S. V., Madduru, S. R. C. and Nandipati, S., Influence of Activator Solution and Binder Composition on the Characteristics of Self-Compacting Geopolymer Concrete, *Civ. Eng. Archit*., 12(3), 1526–1539 (2024). https://doi.org/10.13189/cea.2024.120320

Nuruddin, M. F., Demie, S. and Shafiq, N., Effect of mix composition on workability and compressive strength of self-compacting geopolymer concrete, *Can. J. Civ. Eng.,* 38(11), 1196–1203 (2011). https://doi.org/10.1139/l11-077

Ogwang, G., Olupot, P. W., Kasedde, H., Menya, E., Storz, H. and Kiros, Y., Experimental evaluation of rice husk ash for applications in geopolymer mortars, *J. Bioresour. Bioprod*., 6(2), 160–167 (2021). https://doi.org/10.1016/j.jobab.2021.02.008

Onsongo, S. K., Olukuru, J., Munyao, O. M. and Mwabonje, O., The role of agricultural ashes (rice husk ash, coffee husk ash, sugarcane bagasse ash, palm oil fuel ash) in cement production for sustainable development in Africa, *Discover Sustain.,* 6(1), 62(2025). https://doi.org/10.1007/s43621-025-00841-6

Pacheco-Torgal, F., Carbon Dioxide Sequestration Through Innovative Cementitious Construction Materials: Strategic Relevance in the Context of the 2026 Global Energy Crisis, *MDPI AG,* (2026). https://doi.org/10.20944/preprints202604.0790.v1

Parvathikumar, G., Karthikeyan, P. B., Eswaramoorthy, K., Sahadevan, B. and Udaya, K. V., Optimizing mechanical properties of concrete with waste ceramic tiles and coconut shell charcoal as fine aggregate replacements: A Taguchi approach, *Matéria,* 30, 0461 (2025). https://doi.org/10.1590/1517-7076-rmat-2025-0461

Prakash, M. V. B., Advances in Geopolymer Concrete: A Comprehensive Review, *Int. J. Sci. Res*., 13(3), 985–990 (2024). https://doi.org/10.21275/sr24312141330

Putri, P. Y., Kamil, I. and Rizandi, A., The Effect of Rice Husk Ash as Cement Substitution on the Compressive Strength of Self-Compacting Concrete, *CIVED,* 11(2), 550–557 (2024). https://doi.org/10.24036/cived.v11i2.493

Ramineni, K., Boppana, N. K. and Ramineni, M., Performance Studies on Self-Compacting Geopolymer Concrete at Ambient Curing Condition, *Springer Int. Publish.,* 501–508 (2018). https://doi.org/10.1007/978-3-319-78175-4_64

Rashad, A. M., Effect of nanoparticles on the properties of geopolymer materials, *Mag. Concr. Res.,* 71(24), 1283–1301 (2019). https://doi.org/10.1680/jmacr.18.00289

Rezaie, M., Asl, M. M. and Kajabad, B. G., Enhancement of concrete performance through zeolite and nanoclay incorporation: An experimental study on mechanical properties, water permeability, and microstructure, *Constr. Build. Mater*., 495, 143650 (2025). https://doi.org/10.1016/j.conbuildmat.2025.143650

Shivasakthivadivelan, R. A., Geena, M. G., Reena, L., Manoj Prabhu, C., Kavitha, E. and Brindha, S., Strength and durability enhancement in geopolymer mortar incorporating nano-silica and nano-GGBFS, *J. Environ. Nanotechnol.,* 14(3), 495–504 (2025). https://doi.org/10.13074/jent.2025.09.2531719

Sujitha, V. S., Raja, S., Rusho, M. A., Yishak, S., Advances and developments in high strength geopolymer concrete for sustainable construction – A review, *Case Stud. Constr. Mater*., 22, e04669 (2025). https://doi.org/10.1016/j.cscm.2025.e04669

Tamilarasan, A., Sai, T. Y. and Manikandan, P., Effect of various nano materials in enhancing the strength, microstructural, mineralogical, and durability properties of geopolymer binder – a comprehensive review, *Compos. Interf.,* 33(8), 1695-1720(2025). https://doi.org/10.1080/09276440.2025.2593693

Thadathil, B. J. and Girdhar, S. R., Review on Research Progress of Geopolymer Concrete, *J. Prog. Civ. Eng.,* 6(6), 8–13 (2024). https://doi.org/10.53469/jpce.2024.06(06).02

Tian, Y. H., Tao, J. C., Luo, T. and Li, L., Workability of Nanomodified Self-Compacting Geopolymer Concrete Based on Response Surface Method, *Build.*, 14(11), 3610 (2024). https://doi.org/10.3390/buildings14113610

Varma, V. C., Nagaraju, T. V., Raju, J. N. S. S. N., Alisha, S. S. and Chaitanya, M. S. K., Understanding the potential role of precursor content in the geopolymer concrete strength development, *Mater. Today Proc.,* 8535(2023). https://doi.org/10.1016/j.matpr.2023.05.227

Verma, P., Goldar, D., Daniyal, M. and Singh, S., Effect of Rice Husk Ash on the Properties and Performance of Geopolymer Concrete, *Int. J. Civ. Eng*., 11(11), 11–22 (2024). https://doi.org/10.14445/23488352/IJCE-V11I11P102

Wang, Y., Wang, W., Zhao, Y., Li, N., Luo, J., Belete, A. M. and Ping, J., Modification Effect of Nano-Clay on Mechanical Behavior of Composite Geomaterials: Cement, Nano-Silica and Coastal Soft Soil*, Mater.*, 15, 8735 (2022). https://doi.org/10.3390/ma15248735

Wu, H., Chen, C., Zhang, W., Wang, R. and Zhang, W., Effect of Nano-Clay Dispersion on Pore Structure and Distribution of Hardened Cement Paste, *Build.,* 13(11), 2753 (2023). https://doi.org/10.3390/buildings13112753

Xie, T. and Fang, C., Nanomaterials Applied in Modifications of Geopolymer Composites: A Review, *Aust. J. Civ. Eng.,* 17(1), 32–49 (2019). https://doi.org/10.1080/14488353.2019.1614353

Xu, Z., Huang, Z., Liu, C., Deng, H., Deng, X., Hui, D., Zhang, X. and Bai, Z., Research progress on key problems of nanomaterials-modified geopolymer concrete, *Nanotechnol. Rev*., 10(1), 779–792 (2021). https://doi.org/10.1515/ntrev-2021-0056

Zhang, J., Low-Carbon Construction and Building Materials, *Mater.*, 19(9), 1726 (2026). https://doi.org/10.3390/ma19091726

Zhao, Z., Qi, T., Zhou, W., Hui, D., Xiao, C., Qi, J. and Zhao, Z., A review on the properties, reinforcing effects, and commercialization of nanomaterials for cement-based materials, *Nanotechnol. Rev*., 9(1), 303–322 (2020). https://doi.org/10.1515/ntrev-2020-0023