

Geopolymer Concrete as a Sustainable Alternative in Pavement Construction: Comparative Analysis with Conventional Concrete

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Abstract

The study examines the potential of utilising rice husk ash (RHA), metakaolin (MK), and cementitious solutions in the formulation of geopolymer concrete (GPC) as a replacement for conventional concrete in pavement applications. Conventional concrete made from OPC is not ecofriendly due to several factors, such as high CO₂ emissions, intensive energy consumption, depletion of natural resources, etc. This study necessitated the search for an alternative ecofriendly approach to address these limitations. The interaction between RHA, MK, and the cementitious solution for possible improvement in concrete pavement applications was investigated. RHA and MK were locally produced from the calcination of rice husk and kaolin at temperatures ranging from 600 to 800°C, while cementitious solutions were sourced in Ibadan. The constituent cementitious solutions—1M NaOH and 2M Na₂SiO₃ were solubilised in 1 litre of distilled water and 0.12% SP430. The experimental design applied RHA:MK (30:70, 50:50, 70:30) to a cementitious solution (kg/kg) at a 2:1 ratio, alongside fine and coarse aggregates. Laboratory tests conducted include compressive strength (CS), slump test (ST), and specific gravity (SG). The data were analysed using an ANOVA at the 0.05 significance level. The control and modified concrete were evaluated at 7, 14, and 28 days. The CS for control and modified concrete reached up to 40 MPa at 28 days. The 30:70 RHA:MK mix yielded the highest strength. This research indicates that GPC derived from RHA and MK has great potential to replace OPC-based concrete in pavement applications. Practical evaluation of geopolymer technology in greening intrastate road infrastructure is recommended.

1. Introduction

Pavement construction is a crucial component of transportation infrastructure, with concrete serving as a primary material for rigid pavement systems due to its high compressive strength, durability, and capacity to withstand heavy traffic loads. Concrete pavement design and material optimisation can encourage more effective transportation, cost savings, and higher sustainability while minimizing the effects of weather, fuel consumption, maintenance requirements, and pavement lifespan (Lei et al., 2024). Conventional concrete, primarily

composed of Ordinary Portland Cement (OPC), has long been the standard for pavement construction. However, the production of OPC is the second- largest source of carbon dioxide emissions, following the automobile industry, which contributes significantly to atmospheric pollution (Barbhuiya et al., 2024). The construction of roads using OPC concrete consumes substantial energy due to limestone calcination and fossil fuel combustion. OPC-based concrete pavement, especially in Nigeria, is susceptible to premature failure, costly maintenance, and environmental degradation (Abdulazeez & Sani, 2024). As OPC-based concrete is used extensively, a significant percentage of roads deteriorate quickly under severe conditions and heavy traffic, thereby needing frequent repairs and adding to the cost of construction (Olanrewaju, 2024). OPC manufacturing also contributes significantly to carbon emissions, making it a less sustainable option (Ahmad et al., 2024). It is estimated that 5%–8% of global man-made CO₂ emissions are produced through cement manufacture, which generates tremendous quantities of greenhouse gases and exacerbates climate change (Nejad & Enferadi, 2025; Khaiyum et al., 2022). As a result, various novel materials have been evaluated to reduce reliance on the ever-increasing manufacture of OPC (Saingam et al., 2024). The escalating environmental issues linked to the manufacture of OPC, such as elevated carbon dioxide emissions and energy consumption, have prompted the search for sustainable alternatives.

Among these, agricultural waste materials such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), palm oil fuel ash (POFA), and coconut shell ash (CSA) have gained prominence since they are valued raw material in the synthesis of geopolymer concrete (GPC) (Khalife et al., 2024). Such wastes contain significant proportions of silicon dioxide (SiO₂) and aluminium oxide (Al₂O₃), which are essential components of the geopolymerisation reaction to improve mechanical strength and durability properties (Raut & Patkar, 2023) Application of these waste materials not only mitigates the disposal problem of agricultural wastes but also ensures sustainable construction. Studies have confirmed that locally available agricultural wastes, i.e., RHA and POFA, are viable resources of aluminosilicate with ecological and economic advantages (Abdullah et al., 2022). Rice is one of the most widely cultivated staple foods across the globe, with an estimated annual production of about 400 – 800 million tonnes of paddy rice (equivalent to about 600 million tonnes of milled rice). During milling, approximately 20% of the paddy weight is removed as rice husk, resulting in a global generation of nearly 160 million tonnes of rice husk annually. This by-product is often regarded as agricultural waste and is either incinerated,

discarded, or left to accumulate, leading to environmental challenges. However, controlled combustion of rice husk produces Rice Husk Ash (RHA), a highly siliceous material with excellent pozzolanic properties. RHA has thus attracted significant attention in construction research as a sustainable supplementary cementitious material (SCM) that can partially replace Ordinary Portland Cement (OPC), reduce carbon emissions, and enhance the durability and performance of concrete, particularly in applications such as pavement construction.

Metakaolin (MK) is another widely recognized supplementary cementitious material (SCM) that has gained prominence in sustainable concrete research. It is produced through the calcination of kaolinite clay at temperatures between 650–800 °C, a process that transforms kaolin into an amorphous, highly reactive aluminosilicate. Unlike many industrial by-products, MK is a manufactured pozzolan, which ensures consistency in its physical and chemical properties. Rich in silica (SiO_2) and alumina (Al_2O_3), MK enhances the pozzolanic reaction when blended with cement, leading to the formation of additional calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) phases that refine pore structure and improve mechanical performance. Its incorporation in concrete has been shown to increase compressive, tensile, and flexural strength, while significantly improving resistance to sulphate attack, chloride penetration, and alkali–silica reaction (ASR). Furthermore, MK reduces cement demand and lowers the overall carbon footprint of concrete production, making it a valuable material in the development of high-performance and durable concretes, such as those required for pavement construction.

Geopolymers are based on thermally activated natural pozzolans, i.e., metakaolinite and rice husk ash, which are sources of required silicon (Si) and aluminium (Al). Geopolymer concrete (GPC) is a potential future alternative to OPC-based concrete as a sustainable and low carbon emission concrete. In contrast to OPC, which is reinforced by calcium silicate hydrate (C-S-H) gel, geopolymer concrete is manufactured by activating aluminosilicate content-containing substances like rice husk ash (RHA) and metakaolin (MK) with alkaline activators (NaOH, KOH, K_2SiO_2 , Na_2SiO_2) (Xinyan et al., 2022). The raw materials are typically industrial wastes or agricultural residues; hence GPC is an eco-friendly and cost-effective alternative. Though it has advantages, application of geopolymer concrete in pavement construction has been low. Furthermore, its application in Nigerian highway pavements remains to be investigated. While studies have evaluated the properties of GPC under laboratory conditions, literature on its field based performance evaluation is limited (Rambabu et al., 2022). While investigations have been

conducted on its mechanical behavior and chemical structure (Hamada et al., 2025), no comprehensive study is available comparing its overall performance with conventional OPC-based concrete. Therefore, this research seeks to bridge this knowledge gap through a comparative analysis of the mechanical strength and environmental sustainability of OPC- and GPC-based concrete. The findings will offer decision-making information on the uptake of sustainable and low-cost pavement material in Nigeria's road construction.

In this study, an effort is made to fill this gap by comparative study of geopolymer concrete and normal concrete for pavement construction, Specifically, the research investigated the performance of geopolymer concrete produced using RHA and MK in various proportions on the compressive strength of concrete and compared its strength with normal concrete to evaluate its suitability in modern pavement infrastructure.

2. Problem Statement

OPC-based concrete pavement, especially in Nigeria, is susceptible to premature failure, costly maintenance, and environmental degradation (Abdulazeez & Sani., 2024). As OPC-based concrete is used extensively, a significant percentage of roads deteriorate quickly under severe conditions and heavy traffic, thereby needing frequent repairs and adding to the cost of construction (Olanrewaju, 2024). OPC manufacturing also contributes significantly to carbon emissions, making it a less sustainable option (Ahmad et al., 2024). Geopolymer concrete (GPC) produced from industrial and agricultural by-products such as metakaolin and rice husk ash has been discovered to be one feasible alternative. However, its application in Nigerian highway pavements remains to be investigated. While there are researchers who have experimented with the properties of GPC under laboratory conditions, not much is recorded about performance in Nigerian pavements (Rambabu et al., 2022). This research seeks to bridge this knowledge gap through a comparative analysis of the mechanical strength, durability, and environmental sustainability of OPC- and GPC-based concrete. The findings will offer decision-making information on the uptake of sustainable and low-cost pavement material in Nigeria's road construction.

3. Methodology

This study adopted an experimental research design to evaluate the suitability of geopolymer concrete (GPC), synthesised from Rice Husk Ash (RHA) and Metakaolin (MK), for rigid pavement applications. The process involved systematic collection, preparation, mix proportioning, testing, and statistical analysis to assess mechanical behavior, fresh concrete properties, and pozzolanic characteristics of the binders. RHA (Figure 1) was sourced locally and subjected to calcination between 600°C and 800°C to enhance its pozzolanic reactivity. Metakaolin, a thermally activated clay, was also procured and similarly treated to ensure comparable levels of activation. Sodium hydroxide (NaOH) with a concentration of 12 Molar was prepared by dissolving solid pellets in distilled water and allowing it to stabilize for 24 hours. This was combined with sodium silicate (Na_2SiO_3) in a 2:1 ratio to produce the alkaline activator used in the geopolymer mixtures.

Three different binder ratios were prepared by varying the proportions of RHA to MK: 30:70, 50:50, and 70:30. The water-to-binder ratio was kept constant at 0.45 across all mixes to maintain uniformity. To accelerate geopolymerisation, specimens were heat-cured in an oven at 80°C for 24 hours. After curing, they were demolded and stored under ambient laboratory conditions until testing. Compressive strength tests were conducted on 100 mm cubes at 7, 14, and 28 days to assess load-bearing performance.



Figure 1: Rice husk



Figure 2: Kaolin residue in Lakiri Village, Ogun state

3.1 Material Preparation

The production of geopolymer concrete (GPC) began by acquiring the necessary materials. To convert kaolin and rice husks into metakaolin and rice husk ash, an electric muffle furnace was used to calcine the kaolin and rice husk samples at varying temperatures.

Calcination of Pozzolans

From previous studies rice husk was calcined at temperatures between 600-800°C, and kaolin was calcined at temperatures 550°C and 800°C (Ji et al., 2025; Torres-Ortega et al., 2024). In this study, we varied the calcination temperatures to determine which pozzolan temperature resulted in the highest reactivity. Kaolin clay was calcined, being subjected to temperatures of 650°C, 700°C, and 750°C to produce metakaolin (MK) shown in Figure 4, while rice husk was also being subjected to temperatures of 600°C, 700°C, and 800°C to produce rice husk ash (RHA) (Figure 3) using a muffle furnace in the laboratory (Figure 50. Samples were analysed using XRD to ascertain the optimal calcined temperature for metakaolin (MK) and rice husk ash (RHA), resulting in the most appropriate aluminosilicate component (Table 1). At 650°C, metakaolin exhibits the highest percentage of aluminosilicate, while RHA at 700°C shows an impressive 82%, indicating that rice husk ash is a promising pozzolanic material (Table 2). Additionally, the XRF test was determined to reveal the chemical components of the optimal temperature for MK at 650°C and RHA at 700°C, the chemical composition of rice husk ash and metakaolin at 700°C and 650°C. This result indicates that rice husk ash and metakaolin can be classified as Class-N pozzolan according to ASTM standards (Figures 4 and 5) (Hoai-Bao and Quoc-Bao, 2021). By being classified as Class N pozzolans, MK and RHA fall under the natural pozzolan category, meaning they are directly suitable for cement replacement (Afolayan et al., 2022; Sinngu et al., 2023). This classification supports their suitability in concrete, especially for sustainability goals and strength enhancement

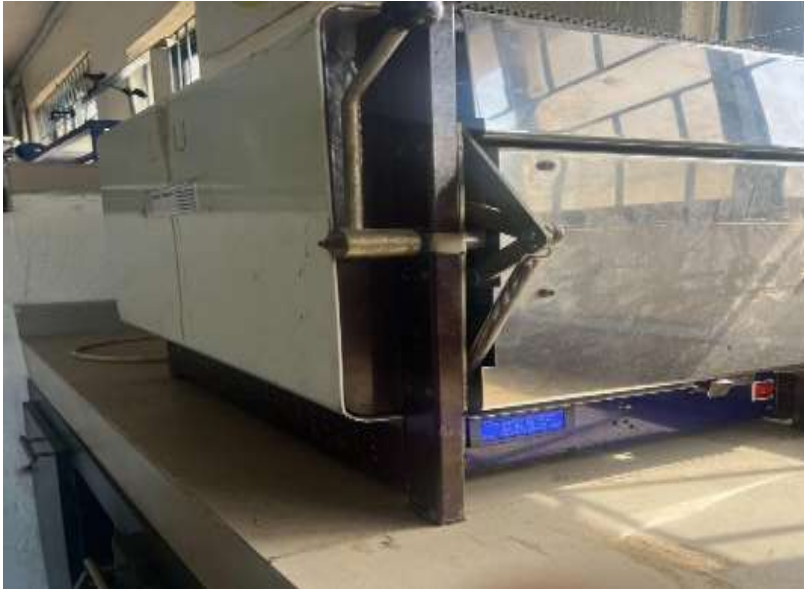


Figure 3: Calcination of rice husk using a muffled furnace



Figure 4: Calcined Metakaolin



Figure 5: Calcined Rice husk Ash

Table 1: Classification of Pozzolanic Materials based on the XRD result

Pozzolan Classification	Metakaolin (MK 650°C) Class N Pozzolan (ASTM C618)	Rice Husk Ash (RHA 700°C) Class N Pozzolan (ASTM C618)
Type	Alumino-siliceous pozzolan	Siliceous pozzolan
SiO ₂ (%)	52.94	82.76
Al ₂ O ₃ (%)	40.00	1.71
Fe ₂ O ₃ (%)	1.93	1.78

(SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃) (%)	94.87	86.25
CaO (%)	0.254	2.190
SO ₃ (%)	0.003	0.389
MgO (%)	0.000	0.000
Loss on Ignition (LOI)	<2%	<10%
Pozzolanic Reactivity	High (due to high Al ₂ O ₃ + SiO ₂ + amorphous)	High (due to high reactive SiO ₂)

Table 2: Chemical Composition of Rice husk Ash and Metakaolin at 650°C and 700°C, respectively

Oxides	MK 650°C (%)	RHA 700°C (%)
SiO ₂	52.94	82.76
Al ₂ O ₃	40.00	1.71
Fe ₂ O ₃	1.93	1.78
K ₂ O	0.14	3.21
CaO	0.25	2.19
TiO ₂	3.45	0.27
P ₂ O ₅	0.00	6.55
MnO	0.05	0.20
SO ₃	0.00	0.39
Cl	0.65	0.70

3.2 Specific Gravity of Aggregates

The specific gravity of the coarse and fine aggregates was determined to determine their suitability for concrete mix

Apparatus includes: Pycnometer (50 ml), Distilled water, Weighing balance (accurate to 0.01 g), tray, water supply, Oven

Procedures: A sample of aggregate was dried in an oven set at 105°C for 24 hours. After drying, the sample was allowed to cool to ambient temperature and weighed as W₁. Before the test, the pycnometer was thoroughly cleaned. The dry, empty pycnometer was weighed and recorded as W₂. The measured fine aggregate was loaded into the pycnometer, denoted as W₃. The pycnometer was then filled to the neck with water, ensuring that the fine aggregate was properly immersed,

and left for 3 hours. The weight of the pycnometer with aggregate and water was recorded as W_4 . The pycnometer was drained and cleaned thoroughly. The pycnometer was filled with water up to the neck and weighed at W_4 . To ensure precision, the experiment was performed at least twice, and the pycnometer was thoroughly cleaned before each repetition.

3.3 Particle Size Analysis of Aggregates

The aggregates underwent air drying and was subsequently weighed to evaluate material loss. The dried aggregate was introduced into the top of the sieve, which was equipped with the smallest sieve at the bottom (19 mm to 2.36 mm sieve size range for coarse aggregates; and 4.75 mm to 150 μm for fine aggregates) (Figure 6). The assembly was then sealed with the lid and subjected to the sieve shaker for a duration of 15 minutes.



Figure 6: Set of sieves arranged in the sieve shaker

Upon completion of the sieving process, the tray was removed from the sieve shaker. The stack of sieves was then disassembled and cleaned to eliminate any residual material. Subsequently, the mass of the aggregate retained in each sieve was recorded to the nearest 0.1 g.

Alkaline Activator

The alkaline activator, which is the key part of geopolymer concrete, includes sodium hydroxide and sodium silicate in a 1:2 ratio, and 12M of NaOH was considered for this study, where 1M is equal to 40 gm of NaOH. Hence, 12M = 480 g of NaOH was dissolved in 1 litre of water and mixed 24 hours earlier before use to cool down because it gets hot when mixed and to

allow the pellets to be fully dissolved; also added sodium silicate in liquid form at the chosen ratio, as shown in Figure 7.



Figure 7: Alkaline Activator NaOH

3.4 Mix Design Ratio

Researchers have not yet developed a universal mix design method for geopolymer production because of the complexity of mixture proportioning variables and the various factors that influence the properties of geopolymers. Currently, there are no mix design standard codes for geopolymers, as most designs depend on the trial-and-error approach because of the multiple and varying mix design variables. Varying proportions of MK and RHA have been used by other researchers: Because the influence of MK and RHA is nonlinear, different proportions of MK and RHA were compared.

- i. Rice husk Ash 70% + 30% Metakaolin
- ii. Rice husk ash 50% + 50% Metakaolin
- iii. Metakaolin 70% + 30% Rice husk Ash

3.4.1 Concrete Mix Design

A typical concrete mix design was utilised in accordance with the mix design technique outlined. A trial mix is indispensable for validating the design and making necessary adjustments to attain the desired strength and workability; several trial mixes were conducted to attain M40 (Table 3). The mix ratio that gave M40 for control was 1:1.6:2.7. Table 4 shows the proportion of each mix in 12 moulds of 150 mm x 150 mm x 150 mm. The aggregate was batched by weight and mixed manually with a 42.5R grade CEM II as binder, and a water-cement ratio of 0.45 was

considered. The fine aggregate was batched by weight, and the required amount of CEM II was measured with it until it was homogenous. Coarse aggregate was also added and mixed with the required amount of 0.45 water-cement ratio plus 1.2% by weight of the cement that was measured and added.

The mould, which was oiled and cleaned before use, was placed on a rigid horizontal surface and filled with concrete in such a way that it removed as much trapped air as possible. The concrete was placed in the old in layers approximately 50 mm deep and compacted in each layer with a compacting rod subjected to not less than 35 strokes per layer and filled in three layers. Samples were demoulded 24 hours later and immersed in a water curing tank for 7, 14, and 28 days. The trial mix cubes are shown in Figure 8. For geopolymer concrete, the materials for the concrete were mixed thoroughly and cast as per BS 1881 Part 108 (1983). The geopolymer concrete was kept in a rest period for 24 hours before it was cured in an oven to allow for proper polymerisation, then later cured in an oven at 80°C for 24 hours. The GPC mix was demoulded and cured at room temperature in ambient conditions ($23 \pm 5^\circ\text{C}$) for durations of 7, 14, and 28 days. Three cube samples were prepared for each mix variation, taking into account the testing age. The geopolymer concrete cubes are shown in Figure 9.

Table 3: Trial mix ratios for concrete

Trial mix	Result	28 days (MPa)
1	1:1.9: 3.2	36.02
2	1: 2.0: 3.3	34.23
3	1: 2.1: 3.4	32.74
4	1: 1.8: 3.1	38.56
5	1: 1.7: 2.9	37.77
6	1:1.6: 2.7	40.97

Table 4: Proportion of each material under different proportions in 12 moulds.

s/no	Materials	Control	30% RHA	50% RHA	70% RHA
		(kg)	+ 70% MK (kg)	+ 50% MK (kg)	+ 30% MK (kg)
1	Cement (CEM II)	13.33	0	0	0
2	sand	29.34	29.34	29.34	29.34
3	Rice husk Ash	0	3.03	5.04	7.05
4	Metakaolin	0	7.05	5.04	3.03
5	Coarse Aggregate	49.53	49.53	49.53	49.53
6	W/C or A/C	0.45	0.45	0.45	0.45
7	Activator	0	8.1	8.1	8.1
8	Additional Activator	0	0.78	1.36	2.87



Figure 8: Trail mix Cubes for M40



Figure 9: Cast geopolymer concrete

3.5 Compressive Test

The test cubes were placed in the compressive test machine, bearing surfaces were wiped clean, and no loose grit material was seen on the surface of the cubes which will be in contact with the platens. The cube was carefully centered on the lower platens and ensured that the load was applied in two opposite cast faces of the concrete. The load was applied and increased continually at a normal rate until no greater load could be sustained, as shown in Figure 10. The max load applied to the cube was recorded. This is done according to BS EN 12390-3. The compressive strength was then calculated with the formula given in Eqn. (1).

$$\text{Compressive Strength} = \frac{F}{A} \quad (1)$$

Where; F = Maximum load at which the cube crushed, A = Cross sectional area of the cube



Figure 10: Compressive strength test on concrete cubes

4. Results

The Preliminary tests carried out on the fine aggregates, coarse aggregates, rice husk, metakaolin and cement used for the preparation of the mortar specimens were specific gravity, and sieve analysis.

4.1 Specific Gravity and Particle Size Distribution of Aggregates

Determining the specific gravity of the constituent materials used in both geopolymer and conventional concrete mixes, is crucial, especially when plateuring out material proportions and the volume occupied by aggregates and binders. Table 4 presents the measured specific gravities of the materials used in this study. The results of the particle size distribution of aggregates are presented in Figures 11 and 12.

Table 4: Specific gravity of aggregates

Item	Specific Gravity
Fine aggregate	2.4
Coarse Aggregate	2.74

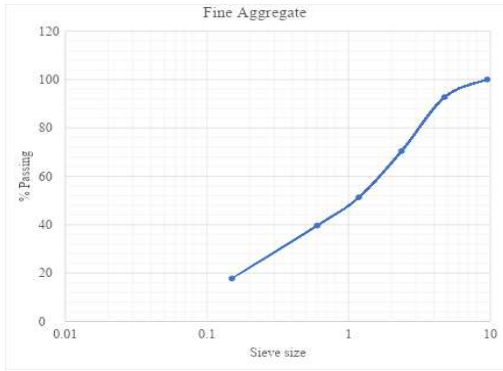


Figure 11: Particle Size Distribution of Fine Aggregate

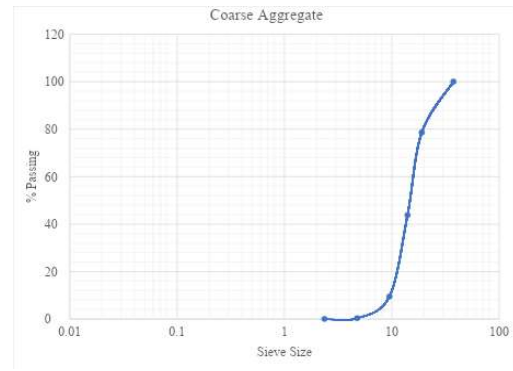


Figure 12: Particle Size Distribution of Coarse Aggregate

4.2 Compressive Strength Test on Concrete Cubes

The compressive strength test is a key mechanical property for evaluating the structural performance of concrete, particularly for pavement applications. The compressive strength test is shown in Figure 13.

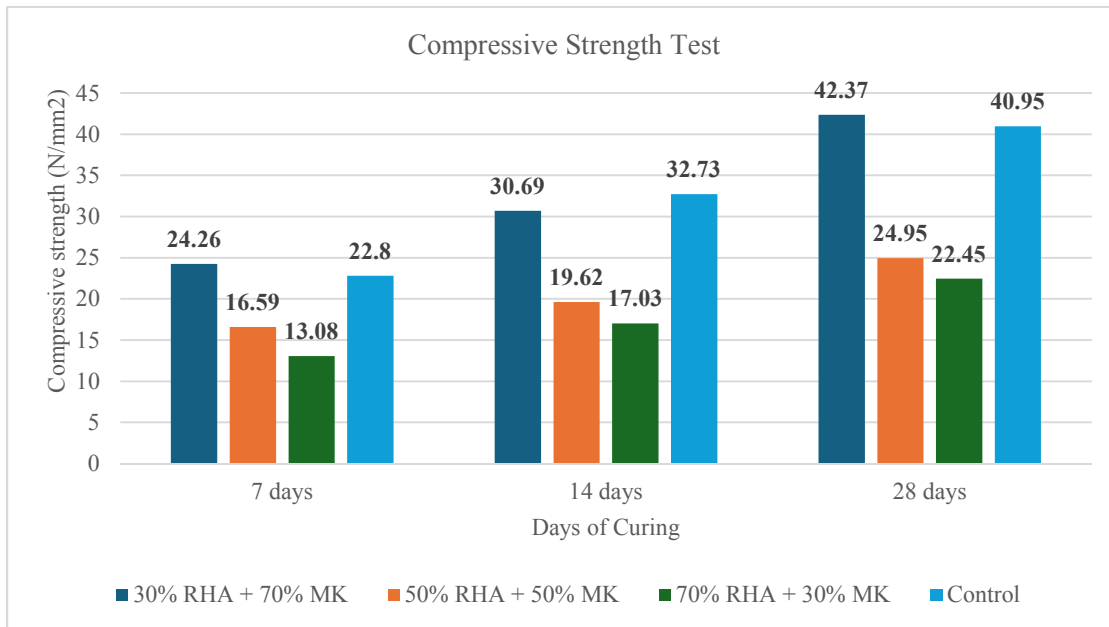


Figure 13: Compressive strength of concrete

4.4 One-Way Analysis of Variance on The Compressive of Geopolymer Concrete

The one-way ANOVA conducted on the 28-day compressive strength results across four different mix types (30% RHA + 70% MK, 50% RHA + 50% MK, 70% RHA + 30% MK, and conventional control) is shown in Table 5.

Table 5: Analysis of Variance of Treatment against the Compressive Strength of Geopolymer Concrete

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Treatment	3	496.3	165.45	3.84	0.057
Error	8	345.1	43.14		
Total	11	841.4			
Factor	Levels	Values			
Treatment	4	30% RHA + 70% MK, 50% RHA + 50% MK, 70% RHA + 70% MK, Control			

Significance level $\alpha = 0.005$. *Equal variances were assumed for the analysis*

5. Discussion of Findings

5.1 Specific Gravity

From Table 4, the specific gravity of fine aggregate (2.40) and coarse aggregate (2.74) are within the typical range expected for siliceous aggregates, indicating good quality and suitability for concrete production. The specific gravity values of 2.4 for fine aggregate and 2.74 for coarse aggregate fall within the normal range (2.4–2.9) for natural aggregates commonly used in concrete. These values suggest that the aggregates are of good quality and suitable for use in both conventional and geopolymer concrete mixtures.

5.2 Particle Size Distribution of Aggregates

The results are presented in Figure 11 and Figure 12. The fine aggregates sample shows a D_{10} of 0 mm, suggesting a lack of finer particles because none of the particles passed through the sieve size that corresponds to 10% passing. As a result, the Coefficient of Curvature (Cc) and Coefficient of Uniformity (Cu) were both computed to be zero, which technically implies that the material was not graded. However, the coarse aggregate is comparatively uniformly graded. In accordance with the standard classification, the coarse aggregate with a $Cu < 2$ is typically uniform graded, as it has a smooth gradation curve indicated by a Cc of 1.78 (between 1 and 3).

For both conventional concrete and geopolymer concrete in pavement construction, the well-graded nature ensures better packing, lower void ratio, and higher density. It supports

achieving higher compressive strength, better interlock, and reduced permeability, all important for pavements exposed to wheel loads, weathering, and potential chemical attacks. In geopolymer concrete, the interaction between the alkaline activator and reactive binder (e.g., metakaolin or rice husk ash) is more efficient with well-packed aggregates. The coarse aggregate used in this mix design is well graded with a desirable size distribution for pavement applications. Its properties suggest it will enhance mechanical performance, durability, and constructability of both conventional and geopolymer concrete mixes. Its compatibility with other materials like fine aggregates and binders will contribute positively to the overall quality and long-term performance of pavement concrete.

5.3 Compressive Strength Test on Concrete Cubes

At 7, 14, and 28 days of curing, concrete cube specimens containing varying amounts of Metakaolin (MK) and Rice Husk Ash (RHA) were tested. The control was a standard concrete mix. The results are presented in the appendix and summarised in Figure 13. After curing for 7 days, the 30% RHA + 70% MK mix outperformed the control at an early age, achieving an average strength of 24.46 N/mm² compared to 22.8 N/mm². The 70% RHA + 30% MK mix had the lowest strength (13.08 N/mm²), while the 50% RHA + 50% MK blend likewise performed competitively (16.59 N/mm²). Because of its high aluminosilicate reactivity under alkali activation, this suggests that a higher proportion of MK encourages the development of strength early on. At seven days, the geopolymer concrete with 30% RHA and 70% MK performed better than the control concrete, indicating better early-age strength development.

The same pattern persisted by the fourteenth day. The strength of the 30% RHA + 70% MK mix was the highest at 30.69 N/mm², followed by the 50% RHA + 50% MK blend at 19.62 N/mm². Once more, the 70% RHA mix had the lowest strength (17.03 N/mm²), confirming that too much RHA slows strength gain because it is less reactive than MK. Between 7 and 14 days, strength continued to increase noticeably, particularly in mixes with a higher MK content. At 28 days, the 30% RHA + 70% MK had a strength of 42.37 N/mm², which was higher than the control mix (40.95 N/mm²). 50% RHA + 50% MK had a strength of 24.95 N/mm², and the 70% RHA mix was the least strong (22.99 MPa). The 30% RHA + 70% MK mix was the most effective binder blend in this study, as evidenced by the fact that it continuously produced the highest strength at all curing ages.

In this study, the 30% RHA + 70% MK blend reached a compressive strength of 24.46 N/mm², outperforming the control mix (22.8 N/mm²). This early strength gain is attributed to MK's high aluminosilicate reactivity, which accelerates geopolymerization. Previous research aligns with this trend, as incorporating RHA (up to ~15%) into geopolymers has been shown to boost early strength by ~21%, particularly at repacked levels around 15 wt % (Hamada *et al.*, 2025). Also, higher Si-to-Al ratios, influenced by RHA content, also correlate with improved strength at early ages (Mohd Basri *et al.*, 2020). These observations confirm that blends with higher MK content notably enhance early compressive strength due to their reactive aluminosilicate content. At day 14, the 30% RHA + 70% MK mix continued to lead at 30.69 N/mm², with the 50:50 blend achieving 19.62 N/mm², and the 70% RHA blend trailing at 17.03 N/mm². The lower reactivity of RHA dampened strength development at higher proportions. This aligns with past studies showing decreased performance when RHA content exceeds optimal levels due to slower geopolymerization kinetics and incomplete network formation (El Naggari *et al.*, 2024).

According to the Nigerian Highway Design Manual (Vol. III), concrete strengths within the range of 30–40 MPa are typically suitable for medium-traffic pavements, corresponding to slab thicknesses between 150 mm and 250 mm (Pekede *et al.*, 2024). The mix containing 30% RHA + 70% MK, which achieved a 28-day compressive strength of 42.37 MPa, falls within this category. This indicates that the geopolymer concrete developed in this study can be reliably used for medium-traffic pavement applications, with slab thicknesses ranging from about 180 mm to 220 mm under favorable construction conditions such as adequate base preparation, doweled joints, and controlled joint spacing. This result demonstrates the potential of RHA–MK binders to not only provide sustainable alternatives to cement but also to meet structural requirements for pavement design

5.4 One-Way Analysis of Variance on The Compressive of Geopolymer Concrete

The one-way ANOVA conducted on the 28-day compressive strength results across four different mix types (30% RHA + 70% MK, 50% RHA + 50% MK, 70% RHA + 30% MK, and conventional control) yielded a P-value of 0.057 (as shown in Table 5). Although this result does not meet the stricter significance threshold of $\alpha = 0.005$, it is very close to the conventional threshold of $\alpha = 0.05$, which is commonly used in engineering and materials science research. This indicates a marginally significant effect of binder composition on compressive strength, suggesting

that the type of pozzolanic blend used does, in fact, influence the performance of geopolymer concrete. The difference observed demonstrates a clear trend, as the compressive strength decreases as the proportion of RHA increases beyond 30%. This pattern is consistent with the known chemical behavior of RHA and MK in geopolymerisation. MK has a higher aluminosilicate reactivity, while excessive RHA can reduce the binder's gel-forming ability due to lower reactivity, (especially when over crystalline), high unburnt carbon content (in less refined ash), and increased porosity and water demand. While the statistical evidence at $\alpha = 0.005$ is not definitive, the numerical trend, supported by a P-value of 0.057 (close to 0.05), provides strong practical evidence that binder ratio is a key factor influencing compressive strength.

6. Conclusion

The study supports the use of agro-industrial by-products, like RHA, in the building sector because they provide waste reduction and a decrease in carbon emissions associated with cement without sacrificing performance. Among the mixes tested, 30% RHA and 70% MK demonstrated superior performance, attaining a 28-day compressive strength of 42.37 MPa. The findings support the viability of GPC as an environmentally sustainable alternative to OPC for rigid pavement construction, particularly within the framework of sustainable infrastructure development in Nigeria. This study concludes that RHA and MK in a 30:70 ratio should be used for optimal strength and reactivity in geopolymer concrete intended for rigid pavement applications.

7. Recommendations

The following recommendations are given for future studies

- i. **Durability Testing:** It is advised that future research assess GPC's long-term durability performance under real-world pavement service circumstances, such as chemical resistance, abrasion resistance, and freeze-thaw resistance and explore other laboratory testing.
- ii. Other pozzolans beyond Rice husk ash (RHA) and metakaolin (MK) should be exploited and compare their potentials in the production of geopolymer concrete (GPC). Advanced analysis can help uncover specific materials responsible for reacting in GPC.

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