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Sustainable Modelling and Evaluation of Composite Binder for Flexible Pavement

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ABSTRACT : *This study investigates the effects of Rice Husk Ash (RHA)-based geopolymer on the physical, microstructural, and mechanical properties of asphalt binders and asphalt concrete mixtures. A geopolymer was synthesized using RHA as the aluminosilicate precursor and an 8M NaOH alkaline activator. The geopolymer was incorporated into 60/70 penetration-grade bitumen at 4%, 8%, and 12% by weight of binder. The modified binders were evaluated through penetration, softening point, viscosity, FTIR, and SEM analyses, while the asphalt mixtures were assessed using Marshall Stability, Marshall Stiffness, volumetric properties, and Tensile Strength Ratio (TSR). Results showed that adding geopolymer enhanced the stiffness, softening point, and viscosity of the bitumen up to an optimal level of 8%, beyond which performance declined due to particle agglomeration. FTIR results confirmed successful chemical interaction between the geopolymer and bitumen, while SEM images indicated enhanced microstructural homogeneity at moderate additive levels. Mechanical performance tests revealed improved Marshall Stability, stiffness, and moisture resistance of mixtures containing geopolymer-modified binders, with optimum performance observed at 4–8% modification. The overall findings demonstrate that RHA-based geopolymer is a viable, sustainable modifier capable of improving asphalt durability, stability, and moisture damage resistance.*

KEYWORDS: *Sustainable construction, Geopolymer-Modified Bitumen, Rice Husk Ash (RHA), Asphalt Mixture Performance, Mechanical performance*

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I. INTRODUCTION

Asphalt mixtures remain the most widely used material for flexible pavement construction due to their good mechanical performance, driving comfort, and durability. Modern pavement engineering continues to seek mixtures that are more economical, environmentally sustainable, and capable of withstanding increasing traffic loads (Zhang et al., 2021). A conventional asphalt mixture consists primarily of aggregates, bitumen binder, and mineral filler, where the filler–binder mastic improves inter-particle bonding, mixture stiffness, and deformation resistance.

Mineral filler, being the finest component, significantly influences the physico-chemical behavior of asphalt mixtures. Its particle size distribution, surface area, mineralogy, and chemical reactivity directly affect binder absorption, moisture susceptibility, stiffness development, and overall mechanical response (Chen et al., 2022). However, the rapid depletion of natural aggregate resources, coupled with the rising cost of quarrying, has increased the demand for sustainable alternatives. Simultaneously, global waste generation continues to rise, posing major environmental challenges relating to storage, disposal, and pollution (Rahman et al., 2021).

To address both pavement performance and environmental sustainability, researchers are increasingly replacing conventional fillers with industrial or agricultural wastes. Materials such as rice husk ash (RHA), fly ash, ceramic dust, and corn cob ash have been used as direct fillers, though their performance has ranged from average to moderate (Adewumi et al., 2023). With rising traffic demands and environmental stresses—particularly in developing countries—there is now a shift toward converting such wastes into **reactive, high-performance materials**, most notably **geopolymers**.

Geopolymers, synthesized from aluminosilicate-rich waste materials activated with alkaline solutions, have gained global attention due to their sustainability, low carbon footprint, and enhanced mechanical properties (Kumar & Patil, 2024). Their structure, composed of interconnected silicon–oxygen and aluminum–oxygen tetrahedra, yields a strong, stable binder or filler capable of improving asphalt mixture performance.

Rice husk ash, which is abundant and rich in amorphous silica, is one of the most promising precursors for geopolymer production. When processed into geopolymer filler, RHA can introduce favorable physico-chemical interactions within hot mix asphalt (HMA), improving stiffness, microstructural integrity, and durability. Despite its potential, a significant gap exists in evaluating the combined **macro-structural** (rutting resistance, moisture susceptibility, stiffness) and **micro-structural** (chemical composition, functional groups, morphology) performance of RHA-based geopolymer fillers in asphalt mixtures.

A comprehensive understanding of these interactions is essential for optimizing geopolymer filler design and advancing sustainable pavement technologies.

Flexible pavements are increasingly subjected to heavier traffic, temperature variations, and moisture-induced distresses, making performance improvement a critical priority. Although mineral fillers contribute substantially to mixture stiffness and binder–aggregate adhesion, reliance on conventional fillers simultaneously increases the depletion of natural mineral resources.

Waste-derived fillers such as raw RHA have been explored, but their performance remains inconsistent due to limited reactivity and heterogeneous composition. Geopolymerizing RHA offers a pathway to enhance its chemical activity, microstructural density, and binder–filler interaction. However, existing studies primarily focus on isolated mechanical properties, neglecting a **combined macro- and micro-structural assessment** necessary to predict long-term pavement behavior.

The lack of comprehensive evaluation limits the adoption of geopolymer fillers in practical pavement design. Therefore, there is a critical need to systematically investigate the macro- and micro-structural performance of asphalt mixtures modified with RHA-based geopolymers to determine their suitability as sustainable filler alternatives.

II. MATERIALS AND METHODS

2.1 Overview

This chapter presents the materials, procedures, and experimental methods adopted in this study. All laboratory activities were conducted under controlled conditions using locally sourced Nigerian materials. The chapter outlines: (i) the preparation and characterization of the geopolymer and geopolymer-modified binders; (ii) the properties of constituent materials; and (iii) mechanical and microstructural tests performed to evaluate the performance of the asphalt mixtures. The major experimental techniques include physical binder characterization, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Marshall stability and flow analysis, and Tensile Strength Ratio (TSR) testing.

2.2 Materials

2.2.1 Aggregates

The aggregates employed in this research consisted of crushed granite (coarse and filler fractions) and river sand (fine aggregate). Crushed granite was sourced from a quarry in Makurdi, Benue State while fine aggregate was obtained from River Benue. Coarse aggregates were defined as particles retained on a 5 mm sieve, fine aggregates passed through a 5 mm sieve but were retained on a 0.075 mm sieve, and mineral filler was material passing a 0.075 mm sieve.

These materials contribute significantly to mixture stability, interlock, compaction, and binder adhesion. Their physical properties were evaluated in accordance with AASHTO and ASTM standards. Table 1 presents the tests conducted and their objectives.

Table 1: Aggregate testing standards and objectives

Test	Standard	Objective
Coarse Aggregate		
Angularity (%)	ASTM D5821 (2017)	Assess particle angularity and shape characteristics.
Elongated/flat particles (%)	ASTM D4791 (2010)	Identify presence of flat or elongated particles.
Soundness (%)	ASTM C88 (2018)	Determine resistance to disintegration under chemical attack.
Specific gravity	ASTM C127 (2016)	Determine density per unit volume.
Los Angeles abrasion (%)	ASTM C131 (2010)	Evaluate resistance to abrasion and mechanical degradation.
Water absorption (%)	ASTM C127 (2016)	Assess porosity and moisture absorption.
Fine Aggregate and Filler		
Absorption	ASTM C131 (2010)	Assess water absorption and porosity.
Specific gravity	ASTM C128 (2016)	Determine density and unit volume.
Sand equivalent	ASTM D2419 (2022)	Determine proportion of undesirable fines.
Clay content (%)	ASTM C142 (2017)	Assess clay content and suitability for pavement applications.
Angularity (%)	ASTM C1252 (2017)	Determine particle shape and texture.

2.2.2 Bituminous Binder

A 60/70 penetration-grade bitumen sourced from Aska Petrochemicals (Warri, Delta State) served as the base binder. Standard physical tests were conducted to determine penetration, softening point, viscosity, flash point, and specific gravity. Table 2 summarizes the tests and their objectives.

Table 2: Physical characterization of virgin binder

Test	Standard	Objective
Penetration at 25°C	ASTM D5 (2016)	Determine binder softness and consistency.
Softening point (°C)	ASTM D36 (2006)	Establish temperature at which bitumen softens.
Viscosity at 135°C	ASTM D4402 (2022)	Evaluate binder flow characteristics at compaction temperature.
Flash point (°C)	ASTM D92 (2020)	Identify the lowest ignition temperature of vaporized binder.
Specific gravity	ASTM D70 (2003)	Determine density relative to water.

2.2.3 Rice Husk

Raw rice husk was collected from a rice mill in Makurdi. It was incinerated to produce rice husk ash (RHA), which served as the precursor for geopolymer production. Oxide composition was determined using X-ray fluorescence (XRF).

2.2.4 Alkaline Activator

Sodium hydroxide (NaOH) pellets were obtained from a chemical supplier in Makurdi and dissolved in distilled water to prepare an 8M alkaline solution used as the activator for geopolymerization.

2.3 Methods

2.3.1 Geopolymer Preparation

RHA-based geopolymer was synthesized using NaOH as the chemical activator. An 8M NaOH solution was prepared by dissolving pellets in distilled water and allowing the mixture to equilibrate for 24 hours. The RHA precursor was added at an activator-to-precursor ratio of 0.7, yielding a homogeneous slurry.

The mixture was cast into sealed molds and cured at room temperature for 24 hours, followed by oven curing at 40°C for another 24 hours. The cured blocks were pulverized into fine powder to serve as geopolymer filler.

2.3.2 Preparation of Geopolymer-Modified Binder

The wet-mix method was employed. Virgin bitumen was heated to 135°C and continuously stirred. Geopolymer powder (4%, 8%, and 12% by weight) was gradually introduced and blended using a high-shear mixer operating at 3800 rpm for 20 minutes. The resulting modified binders were labeled:

GMB4 (4% geopolymer)
GMB8 (8% geopolymer)
GMB12 (12% geopolymer)
This ensured uniform dispersion of geopolymer particles.

2.3.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was performed using a Bruker Vertex 70 Hyperion Spectrometer equipped with a diamond ATR module. Spectra were collected in the 4000–4 cm^{-1} range at a resolution of 4 cm^{-1} and 32 scans per sample. FTIR provided insights into chemical functional groups, binder modification mechanisms, and potential geopolymer–bitumen interactions.

2.3.4 Scanning Electron Microscopy (SEM)

SEM was employed to examine the microstructural features and particle dispersion within the geopolymer-modified binders using a Phenom World SEM. The analysis identified morphological characteristics, particle distribution, homogeneity, and potential changes in microstructure with varying geopolymer contents (4–12%).

2.3.5 Asphalt Mixture Gradation

A dense-graded AC-19 mixture was selected, following Nigerian General Specifications (1997) for wearing courses. The gradation used a 19 mm maximum aggregate size. The mid-point gradation curve is presented in Figure 3.2. Dense-graded mixtures were selected due to their proven performance in high-traffic pavement applications.

2.3.6 Determination of Optimum Binder Content (OBC)

The Marshall Mix Design method (ASTM D1559) was used with 75 compaction blows per face. Bitumen content was varied from 4.5% to 6.5% at 0.5% increments, preparing three replicate specimens per content. Stability, flow, density, and void parameters were used to determine the OBC.

2.3.7 Volumetric Properties of Asphalt Specimens

Volumetric properties were determined following relevant ASTM standards.

Maximum Specific Gravity (Gmm)
(ASTM D2041, 2010)

$$G_{mm} = \frac{m_1}{m_1 + m_2 - m_3}$$
----------------1

Bulk Specific Gravity (Gmb)
(ASTM D6752, 2011)

$$G_{mb} = \frac{m_1}{m_4 - m_5}$$
--------------------------2

Voids in Total Mix (VTM)
(ASTM D3203, 2000)

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$$
-----------3

Voids Filled with Bitumen (VFB)

$$VFB = \left(1 - \frac{VTM}{VMA}\right)$$
-----------------4

Effective Specific Gravity of Aggregate (Gse)
(ASTM C127, 2016)

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$
--------------------------5

Voids in Mineral Aggregate (VMA)
(ASTM D3203, 2000)

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \times P_s$$
-----------6

2.3.8 Mechanical Performance Tests
2.3.8.1 Marshall Stiffness

Marshall Stiffness quantifies the mixture's resistance to permanent deformation. Specimens were compacted using 75 blows per face and condition at 60°C for 30 minutes prior to testing. The stiffness value was computed using

$$MS = \frac{S}{F}$$
-----------------------------------7

where **S** is stability (kN) and **F** is flow (mm).

Higher stiffness values indicate increased resistance to rutting.

2.3.8.2 Tensile Strength Ratio (TSR)

Moisture susceptibility was evaluated according to AASHTO T 283 (2022). Specimens were grouped into:

Dry group: tested at 25°C

Conditioned group: immersed in 65°C water for 24 hours prior to testing

Indirect tensile strength was measured at a loading rate of 50.8 mm/min. TSR was calculated using:

$$TSR = \frac{ITS_w}{ITS_d} \quad \text{---------------------------8}$$

A TSR value ≥ 0.80 typically indicates adequate moisture resistance in asphalt mixtures

III. RESULTS AND DISCUSSION

3.1 Aggregates Characterization

Table 3: Physical Properties of Aggregates Used in the Study

Test	Value	Standard Requirement	Interpretation
COARSE AGGREGATE			
Angularity (%)	96 / 95	≥ 55%	High angularity indicates excellent interlocking potential and good stability.
Elongated & Flat Particles (%)	7.73	< 20%	Meets specification, ensuring minimal particle breakage.
Soundness (%)	5.98	< 20%	Indicates strong resistance to weathering and chemical attack.
Specific Gravity	2.74	2.6–2.9	Well within range, showing suitable density for asphalt.
Los Angeles Abrasion (%)	22.5	< 30%	Good resistance to abrasion and traffic wear.
Water Absorption (%)	1.93	≤ 2%	Low porosity; desirable for moisture resistance.
FINE AGGREGATE & MINERAL FILLER			
Absorption (%)	1.91	≤ 2%	Indicates moderate porosity.
Specific Gravity	2.76	2.5–2.8	Acceptable density for filler and fine aggregate.
Sand Equivalent	37 / 59	26–60	Indicates moderate clay content and good cleanliness.
Clay Content (%)	0.91	< 5%	Very low clay; good for moisture resistance.
Angularity (%)	49.12	≥ 45%	Good particle shape for better stability.

3.3 Characterization of Pure Bitumen

Table 4: Physical Properties of 60/70 Penetration-Grade Bitumen

Test	Condition	Value	Standard Requirement	Interpretation
Penetration (0.1 mm)	25°C	67	60–70	Indicates medium hardness bitumen suitable for tropical climates.
Softening Point (°C)	R&B	50	48–56	Shows adequate temperature susceptibility.
Brookfield Viscosity (mPa·s)	135°C	570	< 3000	Excellent workability during mixing/compaction.
Flash Point (°C)	COC	250	≥ 250	Meets safety requirements.
Specific Gravity (g/cm³)	25°C	1.05	1.01–1.06	Normal range for paving-grade bitumen.

3.3 Geopolymer Characterization

3.4.1 Specific Gravity

The geopolymer exhibits a specific gravity of **1.95**, significantly higher than typical polymers (0.9–1.5) and higher than bitumen. It was computed with reference to equation 2. This density contributes to: increased mixture density, improved load-bearing capacity, and enhanced resistance to rutting at elevated temperatures.

3.4.2 Specific Surface Area

The BET-determined surface area of **1.60 m²/g** suggests:
moderate reactivity, sufficient binder interaction, and gradual enhancement in viscosity, stiffness, and high-temperature behaviour.

3.5 Properties of Modified Binder

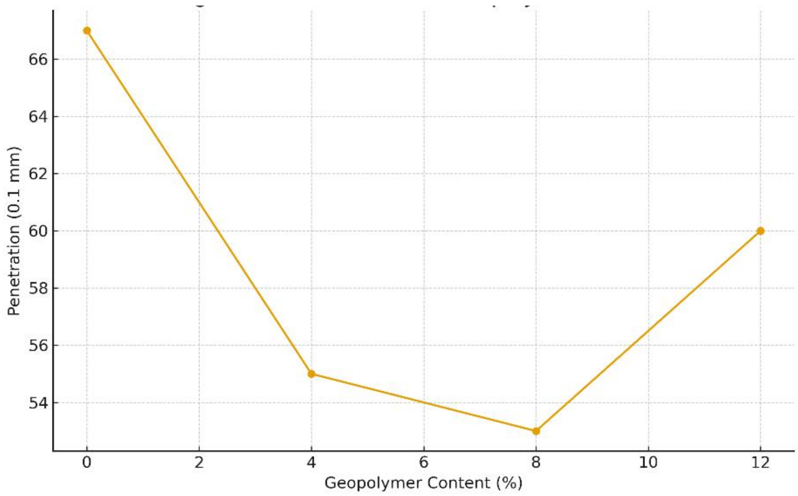

Fig.1: Penetration values of unmodified and geopolymer-modified binders (0–12%).

From Fig 1, it is observed that 4% and 8% reduction in penetration results to **19% and 21% decrease**, indicating stiffening. 12% addition causes **unexpected increase**, likely due to agglomeration or poor dispersion which results to reduced uniformity.

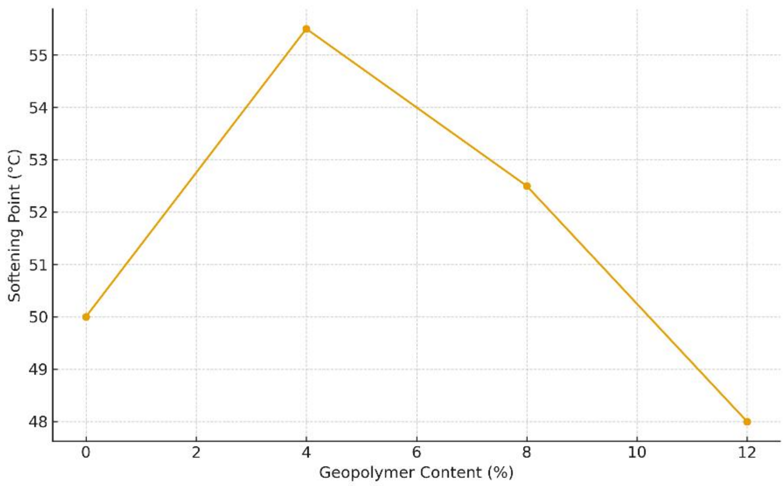

Fig. 2. Softening point of modified and unmodified binders.

Fig 2 shows that at 0% to 4%, there is an increase in temperature, which could be adverse for overheating resulting to liquidity. From 8% to 10%, a gradual decrease within the region of the 0%, which is more adequate. 12% results to decline below pure binder which could be a sign of oversaturation or poor bonding.

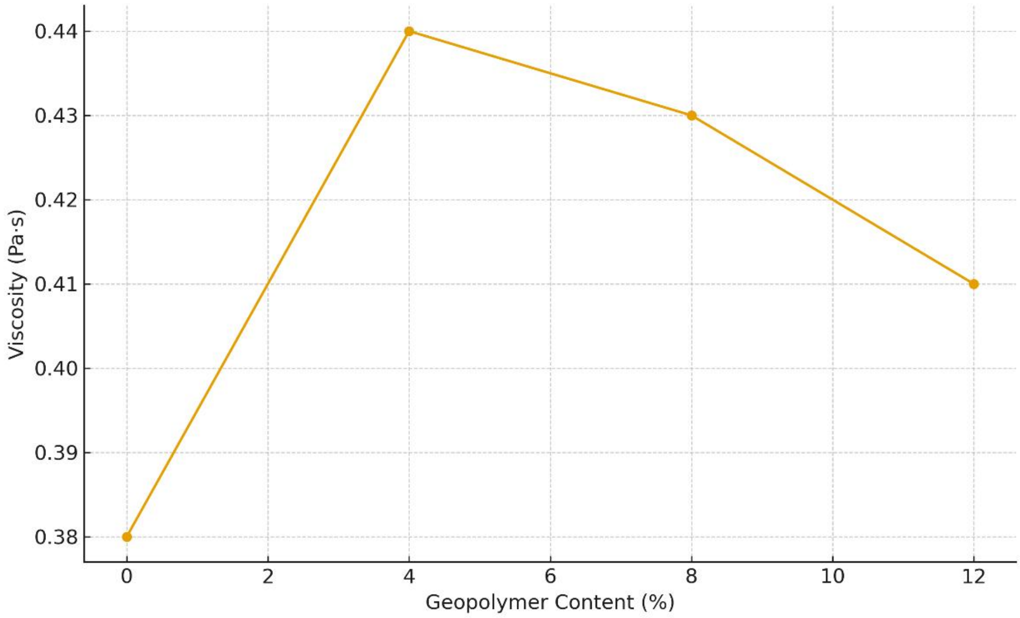

Fig.3: Rotational viscosity at 135°C for all binder types

Fig.3 shows that the Viscosity increases with geopolymer, highest at **4% = 0.44 Pa·s**. All results remain well below **SHRP limit which is 3 Pa·s**, ensuring workability.

3.6 Optimum Bitumen Content

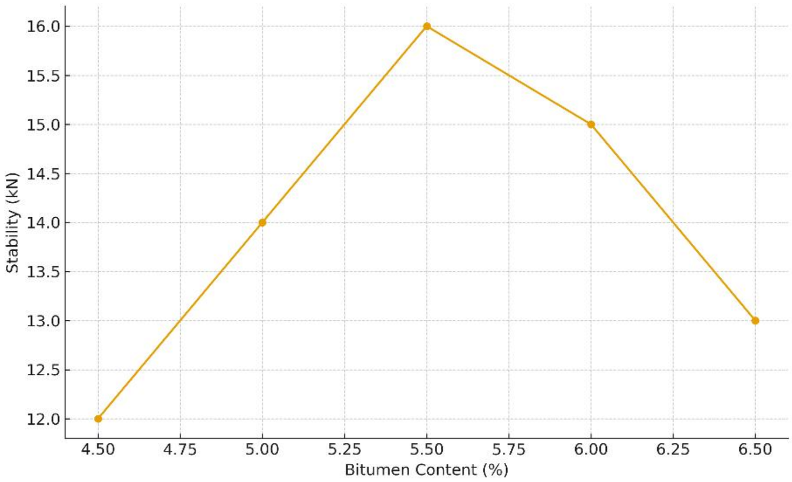

Fig.4: Determination of optimum bitumen content (OBC) based on stability, VTM, and density

In Fig 4 it is observed that the OBC is 5.48%, corresponding to: peak stability, ~4% VTM, optimal bulk density.

3.7 Micro-Structural Analysis

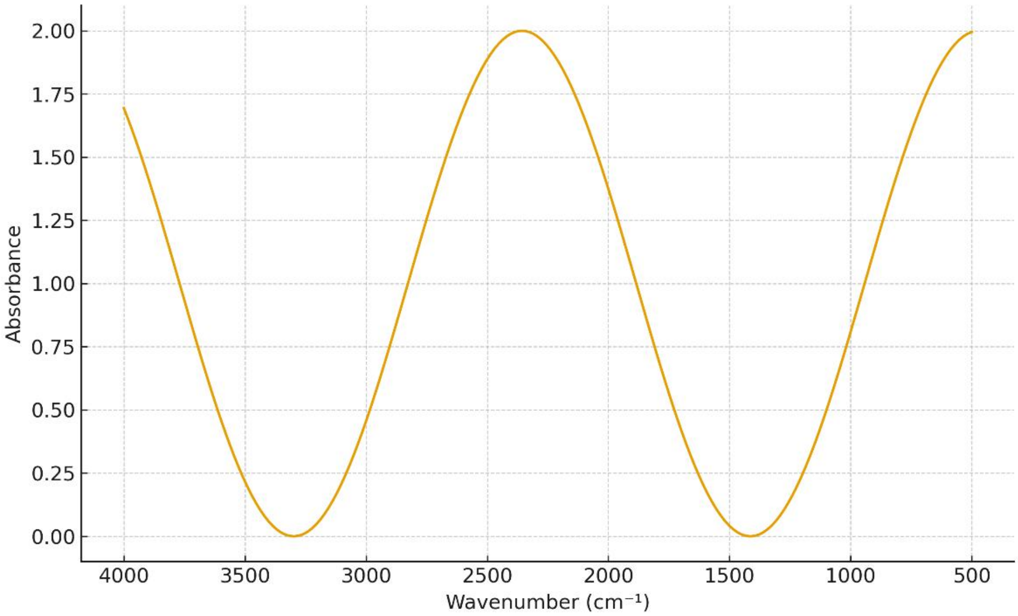

Fig.5: FTIR spectra of bitumen with 0%, 4%, 8%, and 12% geopolymer

Fig 5 shows that the introduction of **Si–O**, **Si–OH**, and **Si–O–Si** peaks confirm chemical interaction. Increased peak intensity suggests improved bonding and reduced molecular mobility (stiffening effect).

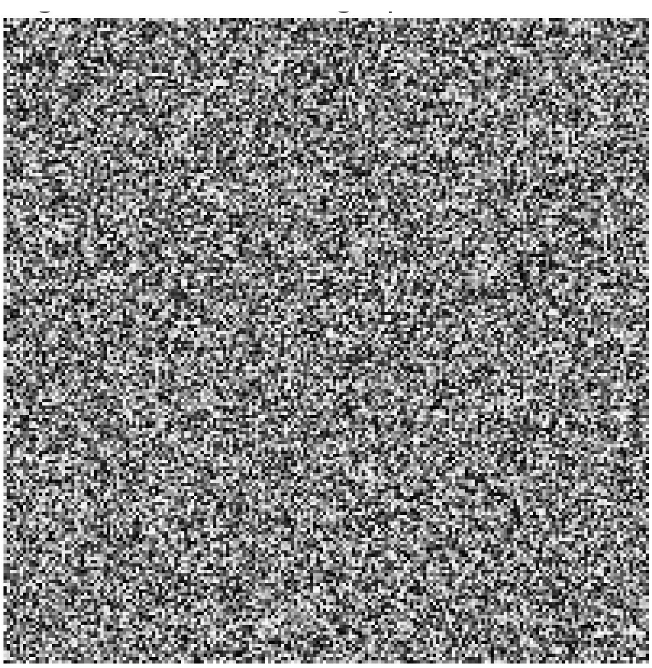

Fig. 6: SEM micrographs of geopolymer-modified binders at 0%, 4%, 8%, and 12%

Fig 6 shows that: at 0% a smooth, homogeneous appearance is observed.
At 4% a gel-like nodules formed; which indicates early polymerization.
At 8% a denser network; indicating improved cohesion.

At 12% a rough surface, visible particle clusters which signifies excessive additive effect.

3.8 Macro-Structural Performance

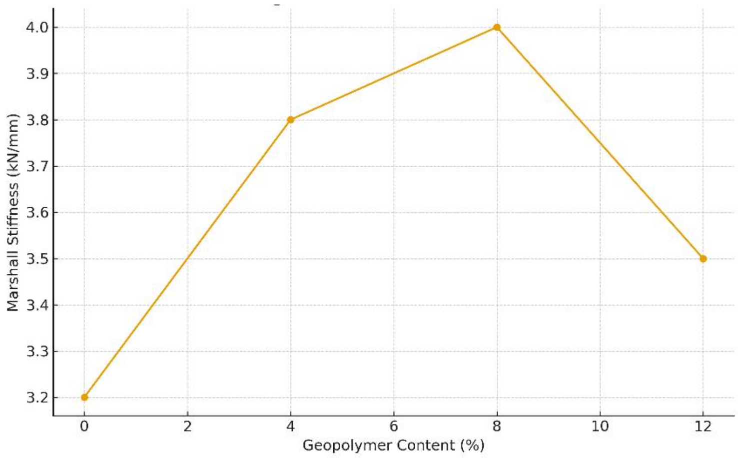

Fig. 7. Effect of geopolymer content on Marshall stiffness.

Fig 7 shows that the Stiffness increases at **4%**, stabilizes at **8%**, decreases at **12%**.
4% = optimum content for deformation resistance.
The marshal stiffness was computed with reference to equation 7

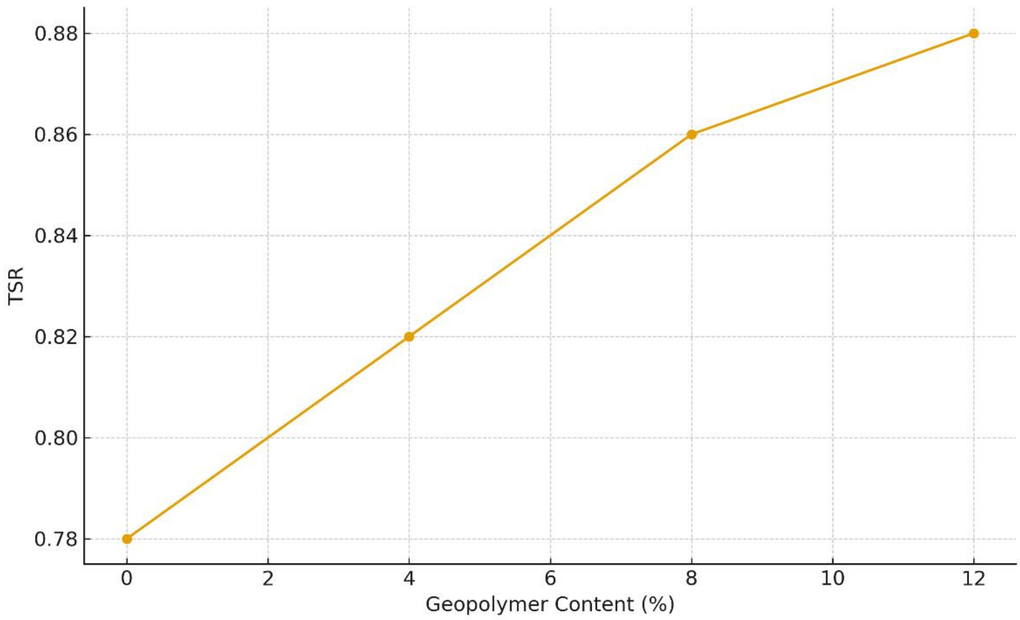

Fig. 3.8. Effect of geopolymer content on Tensile Strength Ratio (TSR).

Fig 3.8 shows that the TSR increases progressively from 0–12%.
Enhanced moisture resistance due to silicate bonding and lower water absorption.
Slight diminishing returns at very high contents.

3.9 Volumetric Properties of Mixtures

Table 3.3: Volumetric Properties of Asphalt Mixtures with Geopolymer-Modified Binders

Mixture	Height (mm)	Weight (g)	Bulk SG	Theoretical SG	VTM (%)	VMA (%)	VFA (%)
PB	66.50	1153.1	2.25	2.417	4.88	14.64	75.37
GMB4	65.29	1195.6	2.267	2.429	4.41	14.31	74.42
GMB8	66.65	1196.2	2.271	2.430	4.23	14.30	73.84
GMB12	66.70	1199.8	2.271	2.443	4.21	14.39	73.82

- It was observed that weight and specific gravity increased with geopolymer signifying denser mixtures.
- VTM decreases signifying better compaction and durability, reference to equation 3
- VMA remains stable which indicates acceptable internal void structure with reference to equation 6
- VFA decreases slightly denoting stiffer binder matrix due to geopolymer with reference to equation 5.

IV CONCLUSION AND RECOMMENDATION

4.1 CONCLUSION

This research successfully evaluated the performance of RHA-based geopolymer as a sustainable modifier for asphalt binders and mixtures. The key findings can be summarized as follows: RHA-based geopolymer was successfully synthesized using 8M NaOH and demonstrated adequate surface area and specific gravity, indicating good reactivity with asphalt binder. The geopolymer's physical properties suggest suitability for enhancing binder stiffness and mixture density. Penetration, softening point, and viscosity results confirmed that the geopolymer increased stiffness and temperature resistance up to 8% addition. At 12% addition, binder homogeneity reduced due to particle clustering, lowering performance. FTIR showed the formation of Si–O–Si and Si–OH functional groups, confirming chemical modification of the binder. SEM images revealed improved microstructural cohesion and binder–filler interaction at 4% and 8%. The incorporation of geopolymer improved Marshall Stability, Marshall Stiffness, and resistance to deformation. TSR values increased consistently with geopolymer content, indicating enhanced moisture resistance. Volumetric properties remained within acceptable limits, confirming that the modifier did not adversely affect mixture compactability. The most effective geopolymer contents were **4% and 8%**, offering the best balance of: stiffness, temperature resistance, moisture susceptibility, microstructural improvement, overall mixture stability.

The study concludes that **RHA-based geopolymer is a technically viable, eco-friendly, and cost-effective additive for improving the performance of asphalt binders and asphalt concrete**, particularly in regions with high rainfall and traffic loads.

4.2 RECOMMENDATIONS

Based on the findings, the following recommendations are made: Geopolymer contents of **4–8%** are recommended for field applications, as they provide the most significant improvements without causing agglomeration. Pilot-scale road sections should be constructed using RHA-based geopolymer-modified asphalt to validate laboratory findings under real traffic and environmental conditions. Additional studies should assess: rutting resistance at high temperatures, fatigue cracking at intermediate temperatures, thermal cracking at low temperatures. Future work should explore: combined alkaline activators (NaOH + Sodium Silicate), other agricultural ashes (e.g., sugarcane bagasse ash, palm kernel ash), optimization of curing conditions to improve geopolymer reactivity. A life-cycle cost analysis (LCCA) and carbon emission study are recommended to quantify: environmental benefits of waste-to-resource geopolymer use, economic feasibility for large-scale highway projects. Highway agencies should consider developing local specifications for geopolymer-modified asphalt using Nigerian agricultural wastes to promote sustainable construction.

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