Evaluating the Effect of Waste Rice Straw Ash-Based Geopolymer on the Physical Properties of Bitumen

[1]Abdulfatai A. Murana, [2]Joshua J. Ochepo, [3]Bello A. Gidadawa and [4]Kenneth E. Ibedu
[1,2]Department of Civil Engineering, Ahmadu Bello University, Zaria Nigeria.
[3]Department of Civil Engineering, Umaru Ali Shinkafi Polytechnic, Sokoto, Nigeria
[4]Department of Civil Engineering, Baze University, Abuja, Nigeria
fatinoyi2007@gmail.com | ochepo1@gmail.com | bgidadawa@gmail.com | ibedukenneth@gmail.com

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ORIGINAL RESEARCH

Abstract— The asphalt pavement industry is increasingly embracing sustainability through the incorporation of waste materials as alternative modifiers. This study evaluates the effect of waste rice straw ash-based geopolymer (WRSABG) on the physical properties of conventional 60/70 penetration-grade bitumen. The geopolymer was synthesized by activating waste rice straw ash with alkaline solutions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The resulting WRSABG was then blended with bitumen at varying dosages of 0, 2, 4, 6, and 8% by weight of bitumen. Physical properties including penetration, softening point, ductility, viscosity, flash point, and fire point were determined. Chemical characterization of both the WRSABG and modified bitumen was performed using Fourier Transform Infrared Spectroscopy (FTIR). Results showed that the addition of WRSABG produced a stiffer bitumen, evidenced by reduced penetration and increased softening point. Improvements were also observed in ductility, viscosity, flash point, and fire point compared to the unmodified control bitumen. FTIR analysis revealed that WRSABG is an inorganic polymer characterized by Si-O-Si and Al-O-Al bonds, while the modified bitumen exhibited typical hydrocarbon functional groups (N-H, C-H, C=O, and C=C). The findings demonstrate the potential of waste rice straw ash-based geopolymer as an effective bitumen modifier. An optimum dosage range of 2–4% WRSABG is recommended, as it significantly enhances the engineering properties of bitumen while promoting environmental sustainability through waste utilization.

Keywords— Bitumen, Geopolymer, Physical Properties, Sustainable Materials, Waste Straw Ash.

1 INTRODUCTION

Bitumen is extensively used as a binder in asphalt concrete production for road pavements worldwide due to its excellent adhesion, waterproofing properties, good viscosity, and overall versatility (Murana, et al., 2023). However, the growing demand for high-performance pavements under increasing traffic loads and harsh climatic conditions has necessitated the modification of conventional bitumen to mitigate common distresses such as cracking, rutting, corrugation, and stripping. One effective approach to enhancing bitumen performance is through polymer modification, using either virgin or waste-derived polymers. In recent years, research efforts have shifted towards a waste-to-wealth strategy, promoting sustainable waste management and resource recovery (Eziefula, et al., 2025). Modified bitumen is typically produced by incorporating various additives into bituminous binders or mixtures to improve mechanical properties and extend pavement service life. This practice has become essential in modern road engineering as it addresses the limitations of conventional bitumen and reduces the frequency of maintenance and rehabilitation of flexible pavements. (Yalcin & Demirbag, 2022). In developing economies such as Nigeria, waste disposal has emerged as a rapidly growing environmental challenge, with approximately 55% of waste deposited in open dump sites, 15% discarded into rivers, and 30% incinerated (Ibedu & Murana, 2024). To address this issue, waste materials are increasingly being repurposed as valuable resources in pavement construction. This approach helps conserve natural resources while promoting sustainability and enhancing overall pavement performance.

Rice is one of the oldest cultivated crops in human history, with cultivation dating back thousands of years. Today, it is grown in over 100 countries and serves as a staple food for more than half of the world's population. Over the past two decades, global rice production has increased by nearly 50% (Zou & Yang, 2019). According to the Food and Agricultural rice market monitor as cited in Endale, et al., (2022), the projected world paddy rice production for 2021–2022 was approximately 714.2 million tons. During rice harvesting, large quantities of rice straw are generated as a major agricultural byproduct. When calcined at 600°C for 2 hours in a muffle furnace, rice straw is converted into rice straw ash (RSA), which is rich in silica. This high silica content makes it a promising precursor for geopolymerisation. Geopolymers are inorganic aluminosilicate polymers formed by the polymerization of aluminosilicate monomers in the presence of alkaline activators. Their chemical composition is similar to that of zeolites; however, they exhibit an amorphous rather than a crystalline structure (Tee & Mostofizadeh, 2021). Various aluminosilicate precursors have been used in geopolymer synthesis. Ibedu et al., (2026) synthesized and characterized metakaolin-based geopolymers for industrial applications using Fourier Transform Infrared (FTIR) spectroscopy, X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), and Differential

Corresponding Author:
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Thermal Analysis (DTA). Their results demonstrated improved thermal stability. Kankia et al., (2021) investigated the use of petroleum sludge ash (PSA) and fly ash in geopolymer mortar production. They reported that the incorporation of 20% PSA with 16 M NaOH reduced the workability of the mortar while increasing its hardened density. However, a mix containing 10% PSA, a Na_2SiO_3/NaOH ratio of 2.0, and 12 M NaOH yielded an optimum unconfined compressive strength (UCS) of 31.01 MPa. The study concluded that the inclusion of PSA in fly ash-based geopolymer mortar offers a sustainable and eco-friendly solution that can help alleviate petroleum sludge disposal problems. Similarly, Yaro et al., (2023) evaluated the effect of biochar-based geopolymer composite on asphalt binder modification and the permanent deformation resistance of asphalt concrete using the Response Surface Methodology (RSM). Their findings revealed that the addition of the biochar-based geopolymer composite significantly improved the rutting resistance of asphalt concrete. Although extensive research has been conducted on the use of geopolymers in mortar, cement concrete, and asphalt concrete, limited studies have explored their application in bitumen modification. This study aims to bridge this gap by investigating the effect of waste rice straw ash-based geopolymer (WRSABG) on the physical properties of bitumen. The objective followed are characterisation of waste rice straw ash based geopolymer (WRSABG) and WRSABG-modified bitumen using Fourier transform infrared (FTIR) and determination of the physical properties of bitumen modified with waste rice straw ash (WRSABG).

2 MATERIAL AND METHODS

2.1 MATERIALS

The materials used in this study include waste rice straw ash, 60/70 penetration-grade bitumen, and alkaline activators. The 60/70 bitumen was procured from MotherCAT Construction Company, Palladan, Samaru, Nigeria. Waste rice straw was collected from a farmland in Sokoto State, Nigeria, and calcined to obtain rice straw ash. The alkali activator was prepared using sodium hydroxide (NaOH) pellets (99% purity) and sodium silicate solution (Na_2SiO_3), both locally sourced from Samaru market, Zaria, Nigeria.

2 METHODS

2.2.1 PREPARATION OF WASTE RICE STRAW-BASED GEOPOLYMER (WRSABG)

The preparation of waste rice straw ash-based geopolymer (WRSABG) was adopted from the procedure reported by Ibedu et al., (2026) and validated by previous studies (Gambo et al., 2020; Hauruna et al., 2018). The alkali activator solution was prepared by dissolving sodium hydroxide (NaOH) pellets in distilled water to obtain an 8 Molar (8M) concentration. This solution was then mixed with sodium silicate (Na_2SiO_3) at a ratio of 2:1 (sodium silicate to sodium hydroxide) and stirred continuously for 5 minutes to ensure homogeneity. The resulting alkali activator was thoroughly mixed with the waste rice straw ash to form the geopolymer paste. The fresh paste was poured into 50 × 50 × 50 mm cube molds and allowed to cure at room temperature for 48 hours. After demolding, the geopolymer cubes were further oven-cured at 40°C for 24 hours. The cured samples were subsequently crushed, ball-milled into fine powder, and sieved through a No. 200 sieve (75 µm). Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the functional groups present in the synthesized WRSABG.

2.3 EXPERIMENTAL INVESTIGATIONS

The following tests were performed on both the control and WRSABG-modified bitumen samples in accordance with relevant ASTM standards:

1. **Penetration:** Evaluates the consistency and stiffness of the bitumen. Conducted in accordance with ASTM D5/D5M-20 (2020).
2. **Softening point**: Determines the temperature at which the bitumen reaches a specified degree of softening. Performed according to ASTM D36/D36M-14 (2020).
3. **Ductility:** Measures the ability of the bitumen to undergo tensile deformation without fracturing, indicating its cohesion and elasticity. Tested per ASTM D113-17 (2017).
4. **Flash and Fire Point:** Assesses the safety characteristics of the bitumen by determining the lowest and highest temperatures at which it ignites under specified conditions. Conducted in accordance with ASTM D92-18 (2018).
5. **Viscosity:** Determines the apparent viscosity of the binders at elevated temperatures relevant to mixing, handling, and compaction. Carried out according to ASTM D4402 (2023).
6. **Fourier Transform Infra-Red (FTIR)**: Used to identify functional groups and detect possible chemical interactions between WRSABG and bitumen. Analysis was performed in accordance with ASTM D6348-12 (2020).

3 RESULTS AND DISCUSSIONS

3.1 FTIR of WRSABG

Figure 1 depict the infrared spectrum of WRSABG. The FTIR analysis of WRSABG showed that the wave numbers 3403, 2885, and 2383.1 cm^{-1} indicates the presence of hydroxyl groups (O-H stretching vibrations), methyl/hydrocarbons (C-H stretching vibrations) and silicate (Si-O-Si asymmetric stretching vibrations) respectively. Also, the wavenumbers ranging from approximately 1341 – 2120 cm^{-1} indicates the presence of Si-O-Si and Si-O-Al stretching vibrations, which is a characteristic of silicate and aluminosilicate structures that are fundamental to the geopolymer matrix. More also, the wavenumbers of 726.8, 776.3 and 954.2 cm^{-1} indicates the presence of Si-O-Si bending vibrations, Si-O-Al bending vibrations, and Al-O-Al bending vibrations, respectively. The outcome of these findings showed that the geo-polymer used in this study is rich in silicate and aluminate and can be used to enhance properties of bitumen. Similar findings were reported by Mavilia, et al., (2024); Kankia, et al., (2021); (Oladele, et al., 2023)

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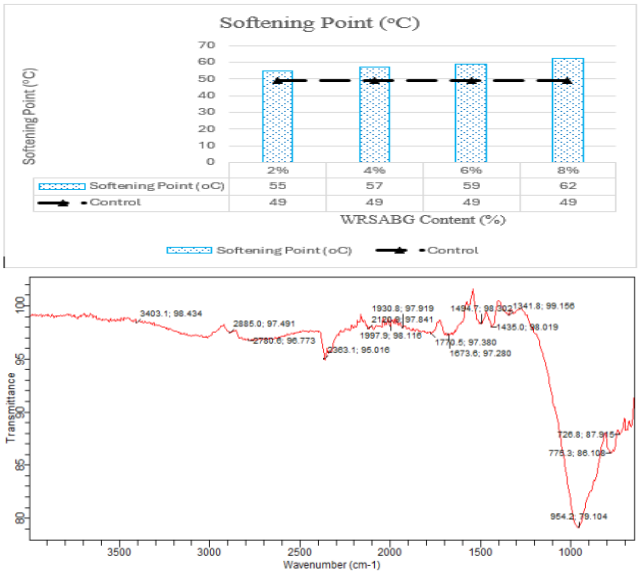

Fig. 1. FTIR Spectrum of WRSABG

3.2 FTIR OF WRSABG-MODIFIED BITUMEN

The result from Figure 2 showed that the modified bitumen wavenumber of 3335.7 cm^{-1} indicates the presence of amine/amide groups (N-H stretching vibrations), whereas the wavenumbers of 2855.1 and 2922.2 cm^{-1} indicates C-H stretching vibrations, and the wavenumbers ranging from approximately 1595 – 2161 cm^{-1} indicates the presence of unsaturated carbons (C=C stretching vibrations); carbonyl groups (C=O stretching vibrations); and nitriles (C≡N stretching vibrations). The sharp peak drops with wavenumbers 1457.4 and 1028.7 cm^{-1} also indicates the presence of C-H bending vibrations and C-O stretching vibrations respectively. The prominence of these peaks is expected as bitumen is composed of hydrocarbons with about 81% of carbon and 10% of hydrogen. Similar findings were reported by Nivitha, et al., (2019); Ngezahayo, et al., (2023); Murana, et al., (2023).

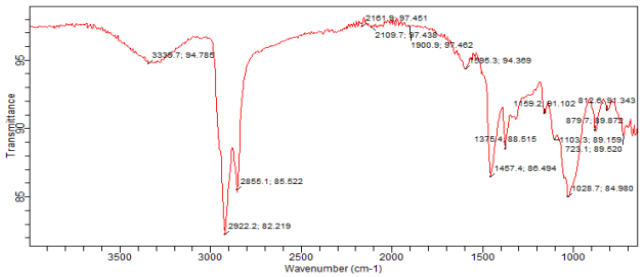

Fig. 2. FTIR Spectrum of WRSABG-modified Bitumen

3.3 PHYSICAL PROPERTIES OF WRSABG-MODIFIED BITUMEN

3.3.1 Penetration

As shown in Figure 3, the penetration values of WRSABG-modified bitumen decreased progressively with increasing WRSABG content, with the highest value of 59 mm recorded at 2% WRSABG. This reduction is primarily attributed to the ability of WRSABG to absorb the lighter molecular fractions of bitumen, leading to stiffening of the binder matrix and restricted molecular mobility. The presence of Al-O-Al and Si-O-Si functional groups in the WRSABG further contributes to this stiffening effect. These findings are consistent with previous studies by Rosyidi, et al., (2020); Ibrahim, Yusoff, et al., (2016). From an engineering perspective, the reduced penetration values indicate improved resistance to temperature susceptibility, higher stiffness, and better suitability for heavy traffic loading (Murana, et al., 2023); Nivitha, et al., (2019).

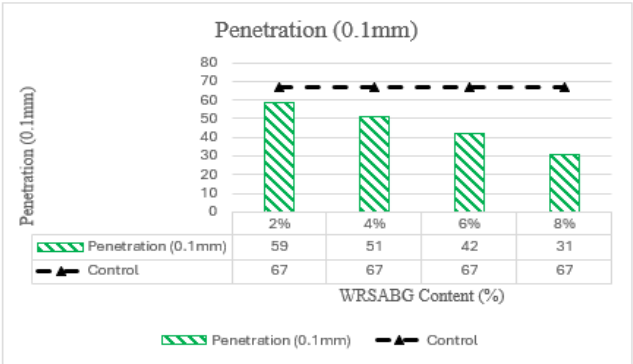

Fig. 3. Penetration of WRSABG-modified bitumen

3.3.2 Ductility

Figure 4 presents the ductility results of WRSABG-modified bitumen. The ductility decreased continuously with increasing WRSABG content, consistent with the stiffening effect observed in the penetration test. Nevertheless, the modified bitumen containing 2% and 4% WRSABG satisfied the minimum ductility requirement of 100 cm stipulated by the Federal Ministry of Works and Housing (FMWH, 2016). This indicates that the modified binders retained adequate adhesive and tensile properties at these dosages. From an engineering standpoint, the reduction in ductility suggests decreased temperature susceptibility and enhanced rutting resistance of the WRSABG-modified bitumen.

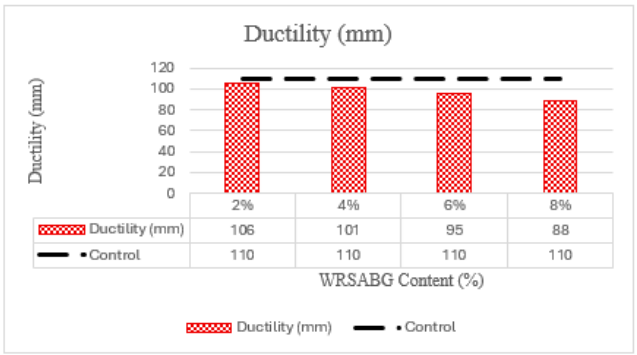

Fig. 4. Ductility of WRSABG-modified bitumen

3.3.3 Softening Point

The softening point results of WRSABG-modified bitumen are presented in Figure 5. All modified samples exhibited higher softening points than the unmodified (control) bitumen. This increase is attributed to the chemical interaction between WRSABG and bitumen, which alters the internal structure of the binder. The presence of C–H aliphatic functional groups in WRSABG is believed to contribute to the enhanced hardness and melting point of the modified bitumen (Murana *et al.*, 2023). Among the tested samples, only the bitumen modified with 2% WRSABG satisfied the FMWH (2016) specification range of 48–56°C. Softening point is closely related to bitumen viscosity, which in turn is strongly linked to penetration value. From an engineering perspective, the increased softening point enhances the bitumen's resistance to rutting at high service temperatures.

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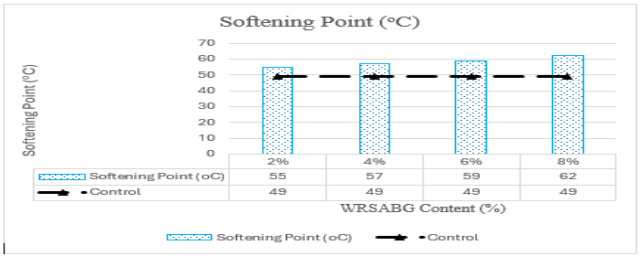

Fig. 5. Softening Point of WRSABG-modified bitumen

3.3.4 Viscosity

Figure 6 shows that the viscosity of bitumen increased with increasing WRSABG content. Viscosity measures the resistance to flow of the bitumen binder. This increase is primarily attributed to the effective dispersion and gelling of WRSABG particles within the bitumen matrix, resulting in a stiffer binder. Additionally, chemical interactions between WRSABG and bitumen, facilitated by key functional groups such as Si–O–Al (aluminosilicate), C–H (aliphatic), and C=C (carbonyl), further contribute to the enhanced matrix rigidity. The higher viscosity of WRSABG-modified bitumen indicates improved coating and adhesion to aggregates, thereby enhancing resistance to wear, tear, and deformation under heavy traffic loads and high-temperature conditions.

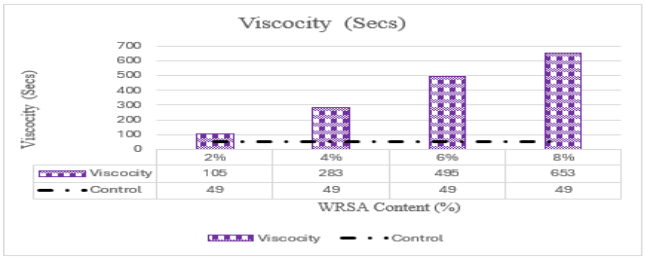

Fig. 6. Viscosity of WRSABG-modified bitumen

3.3.5 Flash Point and Fire Point

Figures 7 and 8 present the flash and fire points of WRSABG-modified bitumen, respectively. Both parameters increased compared to the unmodified control bitumen. This improvement is attributed to the incorporation of WRSABG, which enhances the thermal stability of the binder and reduces its volatility. Notably, the fire point of all modified samples satisfied the minimum specification of 250°C stipulated by the Federal Ministry of Works and Housing (FMWH, 2016). From an engineering perspective, the higher flash and fire points indicate improved safety during storage, handling, and high-temperature application, while also suggesting better resistance to ignition and thermal degradation under service conditions.

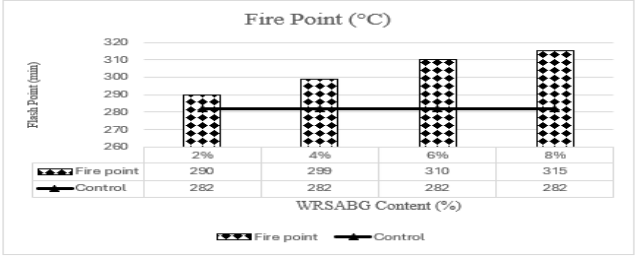

Fig. 7. Flash Point of WRSABG-modified bitumen

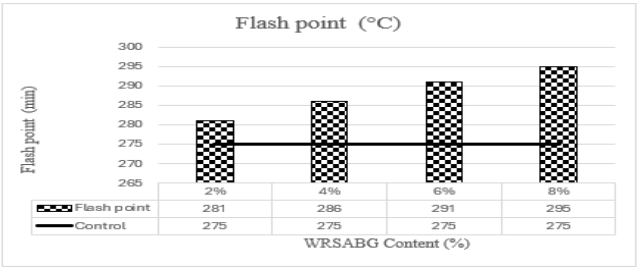

Fig. 8. Flash Point of WRSABG-modified bitumen

4 CONCLUSIONS

This study investigated the effect of waste rice straw ash-based geopolymer (WRSABG) on the functional groups and physical properties of bitumen. Based on the experimental findings, the following conclusions are drawn:

1. Chemical characterization revealed that WRSABG contains key functional groups such as C–H, O–H, Si–O–Si, and Al–O–Al, confirming its inorganic aluminosilicate nature and suitability as a bitumen modifier. The incorporation of WRSABG into bitumen resulted in structural changes, as evidenced by the presence of N–H, C–H, C=O, and C=C functional groups in the modified bitumen.
2. The addition of WRSABG significantly altered the physical properties of bitumen. Penetration and ductility decreased; while softening point, viscosity, flash point, and fire point increased with higher WRSABG content. These results indicate that WRSABG is an effective modifier capable of improving key performance characteristics of bitumen.
3. Based on the overall performance, a modification dosage of 2–4% WRSABG is recommended for practical application. At these dosages, the modified bitumen showed increased hardness (lower penetration), greater resistance to rutting (ductility), reduced temperature susceptibility (higher softening point), improved adhesiveness and consistency (viscosity), and enhanced safety, storage, and handling properties (fire and flash points). These improvements largely complied with relevant standards and specifications.

5 RECOMMENDATIONS

To enhance the performance of bitumen, it is recommended that a blend containing 2% WRSABG be used for modification, as the properties of the modified bitumen improved and largely fell within the relevant standards and code specifications.

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