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EVALUATING THE MECHANICAL PERFORMANCE OF SORGHUM STALK ASH AND SORGHUM HUSK ASH AS A SUSTAINABLE MINERAL FILLER IN WARM MIX ASPHALTIC CONCRETE

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Abstract

The performance of road construction materials has prompted research into alternative fillers. Concerns about the need to mitigate depletion of natural resources and environmental degradation became a dire need. The high production temperature of Hot Mix Asphalt (HMA) which results in significant energy consumption, greenhouse gas emissions, and occupational health risk has driven research into alternative Warm Mix Asphalt (WMA) technologies. Thus, this study investigated the mechanical performance of WMA incorporating Sorghum Stalk Ash (SSA) and Sorghum Husk Ash (SHA) as sustainable fillers. The study adopted bitumen of 60/70 penetration grade. Sasobit proportion of 3.5 wt. % of the bitumen was adopted, which serves as an additive to produce WMA samples. Aggregates and filler were added to unmodified and modified WMA concrete samples. The samples were produced by incorporating SSA and SHA at a proportion of 0 – 100 wt. % at 10% intervals. Marshall Stability and Flow (MSF), Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) properties of the WMA samples were evaluated. The optimum replacement level was found at 40 wt.% (SSA and SHA) for the MSF resulting in 18.85 kN and 4.30 mm, respectively, exceeding the minimum of 8 kN and 4 mm, respectively. Furthermore, ITS and TSR recorded 40 wt.% replacement resulting in 250 kN/m² and 82.7%, respectively, exceeding the minimum recommended TSR of 80%. This study is limited to mechanical performance without considering the Microstructural analysis of the concrete. These finding revealed that incorporating SSA and SHA enhance pavement construction properties and promote sustainability.

Keywords
Warm Mix Asphaltic Concrete, Sorghum Stalk Ash, Sorghum Husk Ash, Indirect Tensile Strength, Tensile Strength Ratio

1. INTRODUCTION

In flexible pavement construction, the adoption of conventional Hot Mix Asphalt (HMA) concrete is due to its superior structural performance, workability, and durability [1]. However, the production temperature ranging between 140 and 180 °C and its high compaction requirement, which results in significant energy consumption, greenhouse gas emissions, and occupational health risks prompted an alternative mixture [1]. In relation to conventional HMA concrete, Warm Mix Asphaltic (WMA) concrete represents a modern advancement in pavement technology, characterized by its ability to reduce mixing and compaction temperatures by 20 – 40 °C [2]. Its lower energy consumption, reduced emissions, and improved working conditions results from its reduced temperature. The rheological and mechanical properties of bituminous mixtures depend on the fillers, affecting stiffness, workability, void structure, and moisture susceptibility [3, 4]. Limestone dust, cement, and hydrated lime are examples of conventional mineral fillers which have been extensively used but their production is energy-intensive and contributes to environmental degradation [5].

Significant research was prompted due to the pursuit of sustainable construction practices which led to incorporation of agro-industrial wastes as viable alternatives to conventional construction materials [6]. Highway engineers have incorporated numerous waste-derived materials such as Rice Husk Ash (RHA), bottom ash, fly ash, Reclaimed Asphalt Pavement (RAP), marble dust, and steel slag, into asphalt production which have demonstrated promising potential as supplementary cementitious or filler materials [7]. This innovation of incorporating waste by-products in asphalt pavement addresses and buttress the current global efforts to lower the carbon footprint of infrastructure development, while maintaining and enhancing material performance and durability characteristics [8]. However, the following deficiencies in these materials are notable; i. the quality consistency is difficult to achieve at scale for RHA due to its requirement of controlled incineration temperatures for optimal pozzolanic activity, ii) the availability of fly ash is increasingly constrained due to transition away from coal fired plant globally, iii) limited pozzolanic reactivity exhibited by Marbel dust which dependent highly on the size of particle and chemical composition, iv) the possession of free lime and magnesia expansion in steel slags poses risks of volumetric instability, necessitating careful pre-treatment before use [9]. Therefore, the need for more consistent, environmentally sustainable alternatives and locally available materials is essential.

Sorghum stalk and Sorghum husk, an under-utilised agricultural resource with significant potential for improving the performance ability of bituminous mixtures [10]. Sorghum production in Nigeria in 2018 was 6.9 million tonnes, accounting for 50% of the total cereal production and occupying about 45% of the total land area devoted to cereal crop production in Nigeria [11]. Although Sorghum is utilised in food production, animal feed, and biofuel generation. However, the post-harvest residues; Sorghum Stalks and Sorghum husks, are often improperly disposed of through open-air burning or indiscriminate dumping [12] which contributes to environmental degradation through the emission of greenhouse gases and particulate matter.

In pursuit of substitutes to partially or wholly replace limestone, fillers derived from sorghum ash, with their finer particle size distribution and reactive oxide compositions, offer the potential. Sorghum ash is characterised by a high content of amorphous silica, with studies reporting up to 89.3% pure silica yield after acid leaching and calcination, which removes heavy metals and impurities [13]. The extracted silica from sorghum ash exhibits nanoscale particle size (~77 nm), high surface area (723 m²/g), and porous structure, all favorable for pozzolanic activity [13]. Additionally, the incorporation of agro-waste based fillers enhance the microstructural integrity and the interfacial bonding between the bitumen and aggregates [14, 15]. Emphasizing the increasing global sustainable pavement materials and the urgent solution for resource efficient. This study investigates the performance of SSA and SHA as enhanced fillers in WMA concrete. Large amounts of sorghum agricultural residues are produced in Nigeria and other sub-Saharan regions, often disposed of by open burning or landfilling, which harms the environment [11]. These materials, when processed into ash, contain key oxides like silica, alumina and calcium that enhance the filler performance in bituminous concrete. The typical presence of silica and other minerals in Sorghum biomass contribute to its reactivity and suitability as a filler material [16, 17].

The presence of these properties makes sorghum ash a promising sustainable substitute for conventional mineral fillers in pavement constructions, bolstering resource efficiency and waste valorization efforts in Nigeria and similar regions [17]. Hence, this study aims to investigate the mechanical performance of WMA concrete incorporating SSA and SHA as sustainable filler alternatives. The objectives of this study include: i) characterization of the materials ii) Marshall mix design for 1:1 mixture of SSA and SHA specific iii) mechanical properties of engineered asphalt.

2. MATERIALS AND METHOD

2.1. Materials

The materials used during the research are described in the subsequent sections.

2.1.1. Aggregates

The aggregates used in this study were sourced from Salung quarry Obaagun, Osun State, Nigeria. Aggregate crushing was performed in accordance with BS 812 specifications. In accordance to British Standard (BS) and American Society for Testing and Materials (ASTM) specifications, the properties of aggregates including specific gravity, abrasion resistance, crushing value, impact value, flakiness index, and elongation index were assessed.

2.1.2. Bitumen

Bitumen of 60/70 penetration grade was sourced from an FSK asphalt plant, Iragberi, Osun State, Nigeria. Penetration, softening point, viscosity, ductility, specific gravity, flash and fire point, and loss on heating were used to characterised the bitumen. All the aforementioned tests were conducted in accordance with ASTM standards.

2.1.3. Filler

The SSA and SHA used in this study were sourced from local farms in Osogbo, Osun State. The materials were air-dried, burned in controlled conditions and subsequently calcined at 700 °C for 2 hours to obtain reactive ash. To achieve fine particle size suitable for use as filler material, the ashes passed through 75 µm sieve.

2.1.4. Sasobit

To facilitate WMA production, Sasobit, a Fischer-Tropsch wax-based organic additive, was incorporated at a dosage of 3.5% by weight of bitumen. This result in reduction of binder viscosity at higher temperature, enabling lower mixing and compaction temperatures while maintaining adequate performance. The selection of 3.5 wt.% Sasobit as an additive dosage typically improves asphalt workability and high-temperature performance while reducing viscosity and compaction temperatures [1, 18-19].

2.2. Method

2.2.1. Material characterization

Figure 1 presents the particle size distribution curve of the coarse aggregates which followed a typical S-shaped profile, suggesting a smooth and continuous distribution of aggregates sizes from coarse to fine. This distribution is indicative of a well-graded aggregate system, which is generally favourable for achieving dense packing, enhanced load distribution, and reduced void content in asphalt mixtures.

Specific gravity, abrasion, crushing, and impact tests were determined following [20-23] respectively. Bitumen characterisation included penetration, Softening point, Viscosity, Ductility, Flash and fire points and specific gravity followed [24- 29], respectively.

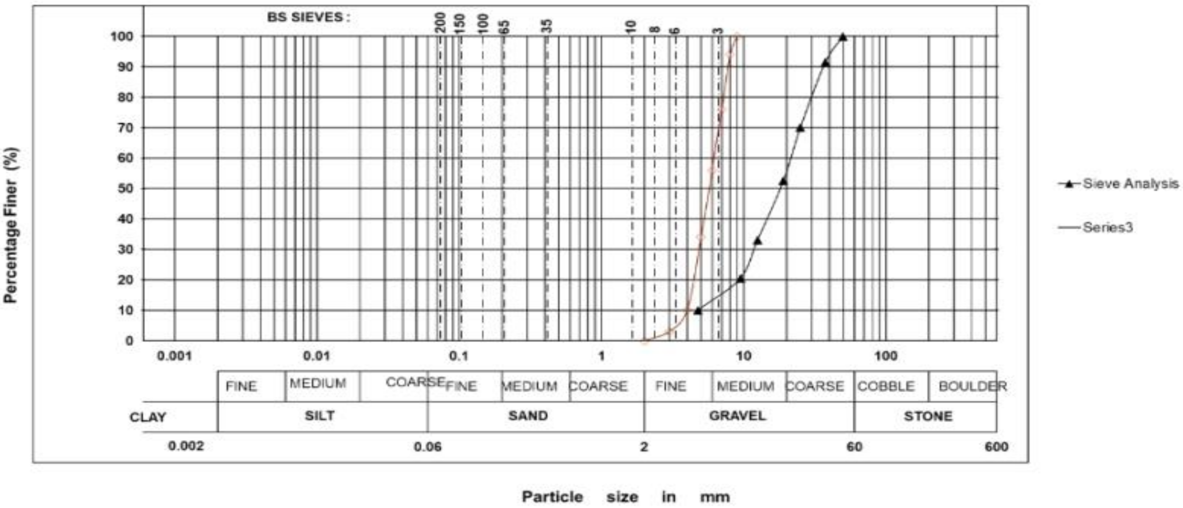

Figure 1: Particle Size Distribution

2.2.2. Marshall mix design

Marshall Mix Design procedure was employed to determine the Optimum Binder Content (OBC) and evaluate the mechanical properties of the asphalt mixtures. Cylindrical specimens (101.6 mm diameter × 63.5 mm height) were prepared at varying binder contents (4.5 to 6.5% at 0.5% interval) and compacted using 75 blows on each face. The SSA and SHA were blended at different proportions: 10 - 100% in a step of 10% by weight of mineral filler content. The OBC was identified as the binder content corresponding to 4% air voids, which also satisfied criteria for stability (minimum 8 kN), flow (minimum 4 mm), VFB (70-80%), and VMA (minimum 14% for 19 mm nominal maximum aggregate size). Tables 1 and 2 display the Marshall Mix design for ordinary bitumen and the Optimum Mix for OBC 5.9 %, respectively, while Figures 2 and 3 shows Asphalt Samples and Marshall Test Set-up, respectively.

Figure 2: Asphalt Samples

Figure 3: Marshall Test Set-up

Table 1: Marshall Mix Design

BC	Weight of Coarse Aggregates (g)	Weight of Fine Aggregates (g)	Weight of filler (g)	Weight of bitumen (g)	Weight of SSA and SHA (g)
7.5	696	240	162	90	54
7	690	240	162	84	54
6.5	684	240	162	78	54
6	678	240	162	72	54
5.5	672	240	162	66	54
5	666	240	162	60	54

Table 2: Optimum Mix Table for OBC at 5.9 %

Bitumen Content (%)	Coarse Aggregate (g)	Fine Aggregate (g)	Mineral Filler (g)	Crushed Coarse Aggregate (g)	Bitumen (g)
5.9	673.2	240	162	54	70.8

2.2.3. *Durability Performance Tests*

Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) tests were conducted to assess moisture susceptibility and durability. Specimens were prepared at OBC and divided into two sets: dry specimens and conditioned specimens subjected to moisture conditioning (saturation at 60 °C for 24 hours followed by freezing at -18 °C for 16 hours and thawing at 60°C for 24 hours). Indirect Tensile Strength was determined using the equation 1:

$$ITS = \frac{2P}{\pi t D}. \qquad (1)$$

Where; P = maximum load (N), t = specimen thickness (mm), D = specimen diameter (mm). The ratio of wet ITS to dry ITS was used to calculate Tensile Strength Ratio (TSR) expressed in percentage, where 80% minimum TSR value is generally required for adequate moisture resistance [30].

3. RESULTS AND DISCUSSION

3.1. Properties of Materials Used

The properties of materials used are presented in the subsequent sections.

3.1.1. *Properties of Aggregates*

The summary of aggregate properties is presented in Table 3. All parameters measured conform to the recommended standard for wearing course asphalt mixtures, possess adequate resistance to impact, crushing, and deformation under traffic loading.

3.2. Marshall Properties

The Marshall properties are elucidated in the following sections.

3.2.1. *Voids Filled with Bitumen*

Figure 4 presents the VFB results. A 73.4% VFB was recorded for the control mixture, aligning with the recommended value of 65-75% for dense-graded asphalt mixtures. Variable results were noted with the introduction of SSA and SHA, with a notable peak of 77.7% at 20% replacement, representing 5.9% increase over the control. The increase in VFB indicates enhanced binder distribution and reduced air void connectivity, which improves resistance to oxidative aging and mixture durability.

At 40% replacement, the lowest VFB value of 67.0% was recorded, despite this composition exhibiting superior stability and TSR performance. This apparent contradiction suggests that, rather than simply maximizing binder content in voids, the 40% mixture achieves its exceptional mechanical properties through enhanced particle interlocking and binder-filler chemistry. This may actually indicate that, the relatively lower VFB at this level is an optimal balance that maintains sufficient flexibility while maximizing strength.

3.1.2. *Bitumen Properties*

The penetration grade 60/70 bitumen exhibited a penetration value of 64 mm, softening point of 53 °C, specific gravity of 0.98, viscosity at 135 °C of 2587 Pas., ductility at 25°C of 113 cm, flash point and fire point of 276°C, and loss on heating of 0.19%. All properties as shown in Table 4 conformed to ASTM specifications for paving-grade bitumen. These results are consistent with the findings of [1, 31, 32].

Table 3: Summary of Index properties Tests on Aggregates

Test Type	Parameter	Average Value (%)	ASTM, 2018 Specification	BS, 1992 Specification	Remarks
Abrasion	Aggregate Abrasion Value (AAV)	21.6	40% maximum	25 - 50% range	Satisfactory
Crushing	Aggregate Crushing Value (ACV)	14.32	30% Maximum	30% Maximum	Satisfactory
Impact	Aggregate Impact Value (AIV)	16.74	45% Maximum	40% Maximum	Satisfactory
Shape	Flakiness Index	23.5	45% Maximum	40% Maximum	Satisfactory
	Elongation Index	21.87	45% Maximum	50% Maximum	Satisfactory
Specific Gravity	Fine Aggregate (FA)	2.6	3 Maximum	3 Maximum	Satisfactory
	Coarse Aggregate (CA)	2.8	3 Maximum	3 Maximum	Satisfactory
	Mineral Filler	1.9	3 Maximum	3 Maximum	Satisfactory

Table 4: Summary of Bitumen test results

Parameters	Average Results	Specification	Test Method
Penetration @ 25 °C	64	60-75	EN1426, IS1203 and ASTM D-5
Ductility @ 25 °C	113	100min.	IS1208 and ASTM D-113
Softening Point	53	52-60	EN1427, IS1S1205 and ASTM D-36
Loss On Heating (wt.) %	0.19	0.2max.	ASTM D-6
Specific Gravity	0.98	0.98-1.06	ASTM D-70
Viscosity	2587	2400 min.	IS1206(PART2) and ASTM D-2171
Flash and Fire Point	276	≥250	EN ISO2592 and ASTM D-92

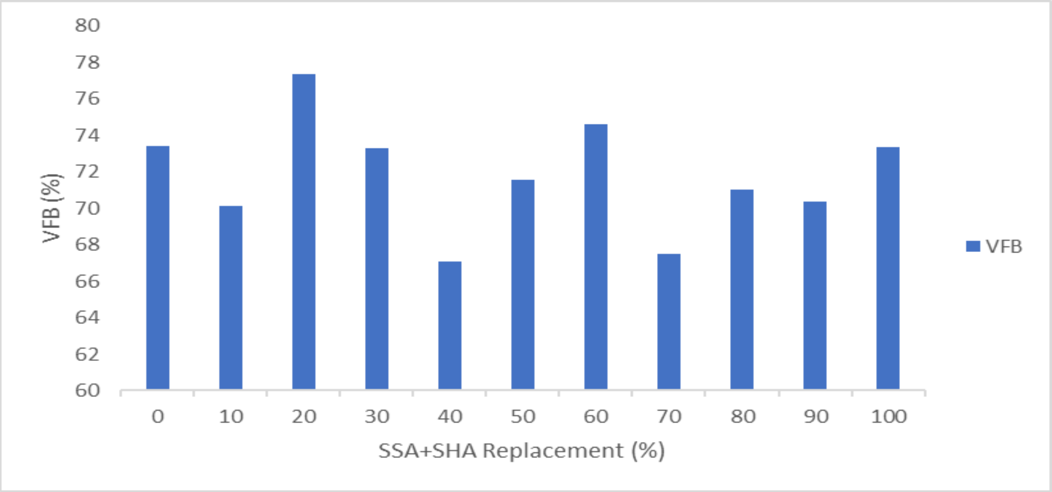

Figure 4: Voids filled with Bitumen

The VFB values stabilised at higher replacement levels of 70 - 100 % around 67-74%, indicating acceptable binder distribution despite the increasing ash content. However, excessive ash content may interfere with binder coating efficiency, potentially due to the high absorption capacity of the ash particles competing with void-filling requirements. This may be as a result of declining trend beyond 20% replacement. [33 – 35] reported similar trend for Fine-Volcanic-Ash in HMA, CCA in WMA and Cement Kiln Dust-Rice Husk Ash in HMA.

3.2.2. Voids in Mineral Aggregates

Void in Mineral Aggregates (VMA) results are presented in Figure 5, with a VMA value of 18.08% for the control mixture, which conform to the minimum (13-15%) specified for dense-graded mixtures. At 10% SSA+SHA replacement, VMA of 18.59% was observed, followed by a decrease to 17.08% at 20%. At 80% replacement, the maximum VMA of 19.25% occurred, representing a 6.5% increase over the control. The fine particle size and irregular morphology of SSA and SHA attributed the increasing VMA trend at higher ash content, which reduce packing efficiency compared to conventional limestone filler. While higher VMA provides space for satisfactory binder content, poor compaction or insufficient aggregate contact can occur due to excessive values, potentially compromising mixture stability. When conventional filler is completely replaced, the minimum VMA of 16.82% at 100% replacement suggests altered packing dynamics.

Important mixture characteristics were revealed through the relationship between VMA and other volumetric properties. The exhibition of moderate stability and acceptable Tensile Strength Ratio (TSR) at compositions with higher VMA (70-80% replacement), indicating that increased void space did not severely compromise performance. This is likely due to effective void filling by the asphalt binder. Conversely, the 20% SSA+SHA mixture combined high VFB with relatively low VMA, which suggest optimal packing density that contributes to its superior performance metrics. [33 – 35] reported similar trend for Fine-Volcanic-Ash in HMA, CCA in WMA and Cement Kiln Dust-Rice Husk Ash in HMA.

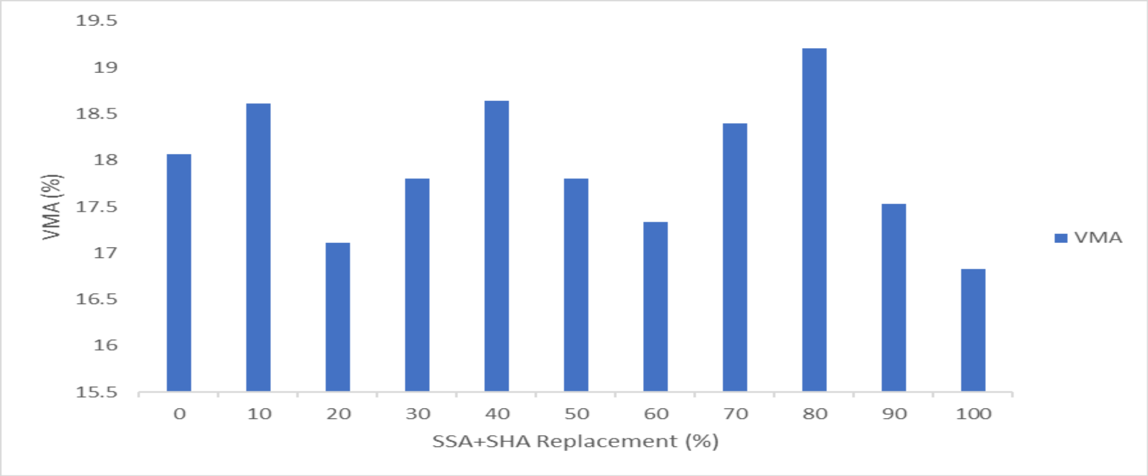

Figure 5: Voids in Mineral Aggregates

3.2.3. Marshall flow

Figure 6 presents the Marshall Flow results for WMA concrete blended with SSA and SHA. The control mixture (0% replacement) satisfies the acceptable minimum specified for flexible pavement design of 4 mm with a flow value of 4.28 mm. The introduction of the substitute (SSA+SHA) initially had no significant effect on the flow value at lower replacement level of 10 - 20%, recording 4.28 mm and 4.19 mm, respectively. However, 30% replacement recorded a notable reduction with flow value of 3.99 mm followed by a peak at 40% replacement (4.30 mm). At 60% replacement, the most significant decline occurred where flow decrease to 3.80 mm, representing an 11.2% reduction compared to the control mixture.

Enhanced resistance to permanent deformation was indicated by the reduction in flow, attributed to the pozzolanic properties of the ashes which improve the stiffness of the binder-filler matrix. Beyond 60% substitute, flow values at 70% and 80% showed marginal recovery to 4.20 mm and 3.99 mm, respectively. At higher level replacement of 90% and 100%, a decline occurred with flow value of 3.80 mm and 3.99 mm, respectively. Complex interaction between ash content and mixture rheology could be suggested due to the fluctuating trend, potentially influenced by changes in binder film thickness and aggregate coating efficiency. Literature on Fly ash for asphalt modification [36], Walnut Shell Ash and Limestone Filler in HMA [37], and Modelling and optimization of locust bean pod ash content in asphalt mixture using surface response methodology [38], reported similar result.

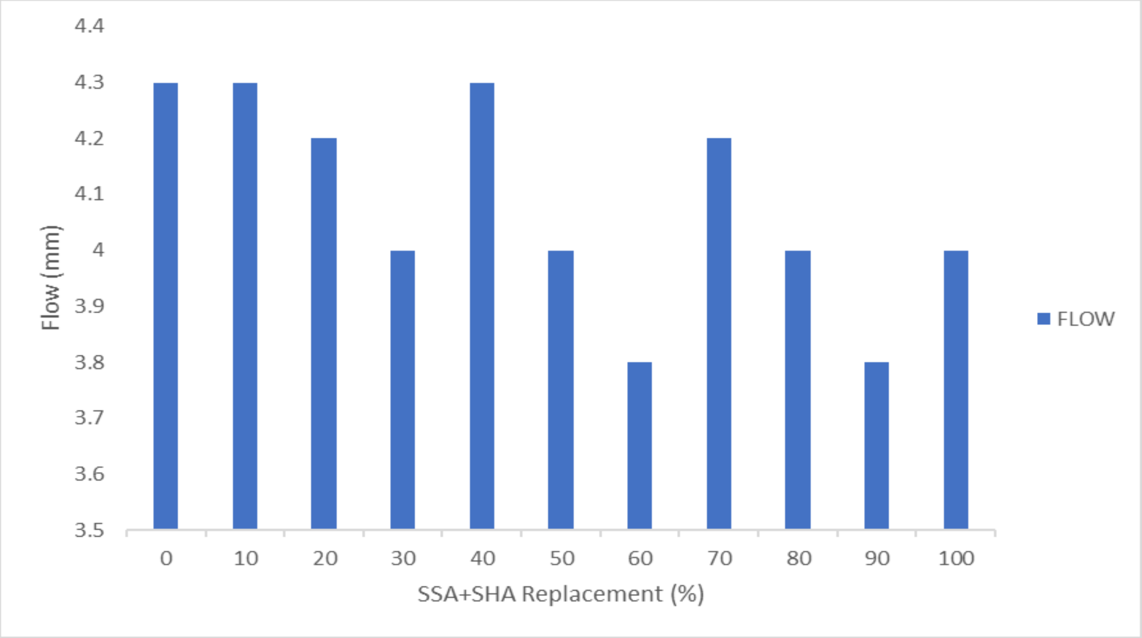

Figure 6: Marshall Flow

3.2.4. *Marshall stability*

Figure 7 presents the Marshall Stability results, where the minimum specification of 8 kN for flexible pavement construction was exceeded by the control mixture of 10.46 kN. The engineered asphalt with SSA+SHA at 10% and 20% replacement recorded a Marshall stability of 10.28 kN and 11.13 kN, indicating that low replacement levels do not significantly compromise load-bearing capacity. The 40% replacement recorded a substantial improvement with peak stability of 18.85 kN; an 80.2% increase compared to the control mixture, which is attributed to multiple synergistic mechanisms. The SSA and SHA fine particle size distribution reduces void spaces, enhancing filler packing density, and creating a more compact mixture. In addition, the enhancement of binder-filler adhesion through increased contact points is as a result of the high surface area of the ash particles. Furthermore, the superior in mechanical interlocking was promoted by the angular particle morphology. The high silica content in sorghum ashes contributes to pozzolanic reactions that strengthen the binder matrix over time.

Beyond 40% replacement, a notable progressive decline from 15.60 kN at 50% to 7.35 kN at 100% replacement is attributed to excessive ash content disrupting binder continuity and reducing the effective binder film thickness on aggregate surfaces. Literature on Fly ash for asphalt modification [36], Walnut Shell Ash and Limestone Filler in HMA [37], and Modelling and optimization of locust bean pod ash content in asphalt mixture using surface response methodology [38], reported similar result.

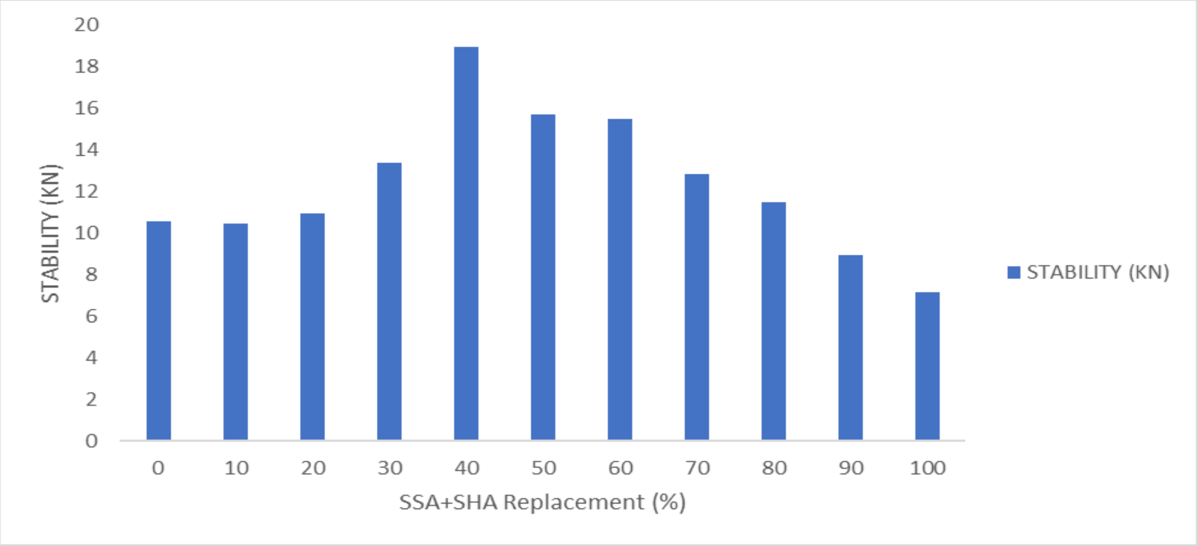

Figure 7: Marshall Stability

3.3. Durability Properties

The durability properties are elucidated in the following sections.

3.3.1 Indirect tensile strength

The **Indirect Tensile Strength (**ITS) behaviour of WMA mixtures under both wet and dry conditions was presented in Figure 8, with the control mixture demonstrating ITS values of 258 kN/m² (wet) and 421 kN/m² (dry). A 20.4% increase compared to the control was noticed at 10% replacement of dry ITS, reaching a maximum of 507 kN/m², attributed to the high silica and alumina content in the ashes. The enhancement resulted from the promotion of stronger chemical bonding with the asphalt binder through acid-base interaction. The improvement in cohesive strength resulted from the pozzolanic activity of SSA and SHA, which facilitated the formation of additional binding sites. However, beyond 10% replacement, a declining trend to 227 kN/m² at 20% was noticed in dry ITS, followed by stabilizing trend around 350 - 440 kN/m² for 30-80% replacement levels before attaining 507 kN/m² at 100% replacement.

Figure 8: Indirect Tensile Strength

For wet ITS, an initial improvement to 288 kN/m² at 10% was noticed, which was followed by a decline trend to 162 kN/m² at 20%. At 40% replacement, a notable peak of 250 kN/m² was observed, where the wet ITS reached its highest value among all mixtures, indicating optimal moisture resistance at this composition. The exhibition of superior performance at 40% replacement level under moisture conditioning may be attributed to an optimal balance between pozzolanic activity and binder film thickness, which minimize moisture infiltration pathways. Similar trend was reported by [38 - 40] when Crushed Bottom Ash was used as Filler in Polymer-Modified Asphalt Concrete Mixtures.

The most notable dry ITS is 10% and wet ITS is 40% because they are govern by different mechanism; mechanical bonding is reflected by dry ITS while moisture resistance is reflected by wet ITS. Although, the highest dry strength is achieved at 10%, however, it fails the [30] threshold, disqualifying it as optimum. Since the most critical property for field performance is moisture resistance, threshold, disqualifying it as the optimum. Since moisture resistance is more critical for field performance, 40% is identified as the recommended optimum, supported by the highest wet ITS.

3.3.2. Tensile strength ratio

The Tensile Strength Ratio (TSR) values across different replacement levels were presented in Figure 9. The control sample achieved a 61.3% TSR, which satisfies 80% minimum recommendation for moisture damage resistance [30]. Across all replacement levels, 40% substitute exhibited a maximum of 82.7% TSR, representing a 35% improvement over the control, indicating substantially enhanced resistance to moisture-induced damage. The 40% superior performance is attributed to the; pozzolanic compounds in the ashes which react with moisture to form stable hydration products that enhances bonding rather than weaken it. It is also attributed to the formation of a robust binder-filler interface that resists water penetration and stripping. Similar result was reported by [41].

Mixes which fall below the recommended standard of 80% i.e., 10, 30, 50, 70, 80, 100%, are moisture susceptible. Only the mix with 40% replacement level passed with 82.7%, but this value barely exceeds the minimum recommended value, making the acceptable replacement range narrow. Practically, SHA/SSA replacement should be limited to around 40% for adequate moisture resistance. Table 5 present properties of Engineered asphalt.

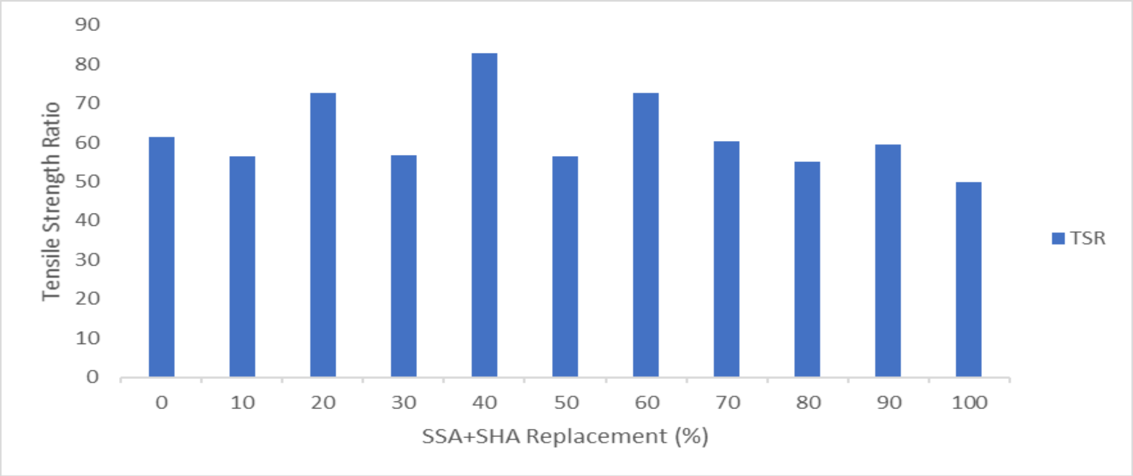

Figure 9: Tensile Strength Ratio

Table 5: Properties of Engineered Asphalt

% (SSA and SHA)	Corrected Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	VMA (%)	VFB (%)
0	10.55	4.3	2.4	18.07	73.39
10	10.49	4.3	2.5	18.61	70.15
20	10.98	4.2	2.6	17.11	77.35
30	13.37	4	3.4	17.8	73.29
40	18.94	4.3	4.5	18.64	67.07
50	15.71	4	3.9	17.8	71.58
60	15.49	3.8	4.1	17.33	74.63
70	12.87	4.2	3.1	18.4	67.5
80	11.49	4	3	19.21	71.05
90	8.96	3.8	2.4	17.53	70.38
100	7.18	4	1.8	16.83	73.34

4. CONCLUSION

The mechanical performance of warm mix asphaltic concrete incorporating sorghum stalk ash and sorghum husk ash as sustainable filler was evaluated in this study. This study has been able to determine the suitability of sorghum stalk ash and sorghum husk ash as mineral filler enhancement. This study has evaluated the production of sorghum stalk ash and sorghum husk ash as enhanced warm mix asphaltic concrete with enhanced mechanical properties. The Marshall stability, Indirect Tensile Strength and Tensile Strength Ratio of the asphaltic concrete increased with an increased sorghum stalk ash and sorghum husk ash dosage of 1:1 of the mineral filler. There was a 20.4% increase in the Indirect Tensile Strength compared to the asphaltic control mixture. The SSA and SHA improved the moisture resistance (Tensile Strength Ratio) of the asphaltic concrete mixtures by 40 wt. % compared to the control sample. This finding is significant as it reveals that the adoption of sorghum stalk ash and sorghum husk ash at 40 wt.% optimal substitution enhances enhance pavement construction properties and promote sustainability. Further studies should investigate the microstructural analysis of engineered asphalt incorporating SSA+SHA a sustainable mineral filler and the cost implication of these materials.

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