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Sustainable Utilization of Rice Husk Ash and Biochar as Eco-Friendly Fillers in Hot Mix Asphalt for Enhanced Thermal Stability and Environmental Performance

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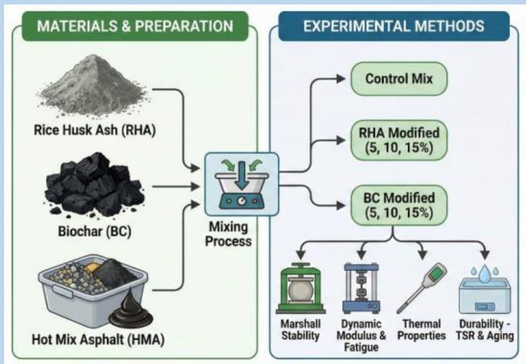
Abstract: This paper has discussed the application of rice husk ash (RHA) and biochar (BC) as environmentally friendly additive in hot mix asphalt (HMA) to enhance their mechanical, thermal, and durability characteristics. There were seven asphalt mixtures prepared; one control mix and 6 modified mixes with 5, 10, and 15 % RHA or BC as partial replacements. The mixtures were tested in the form of marshal stability, dynamic modulus, fatigue life, thermal conductivity, specific heat capacity, tensile strength ratio (TSR) and aging resistance (RTFOT and PAV). The findings indicated great improvements as compared to the control mix. The uppermost values of the mixtures were RHA10% and BC10% with a Marshall stability value of 10.7 kN and 10.4 kN respectively compared to the control value of 12.6 and 9.5 respectively. RHA10% enhanced the dynamic modulus of fatigue life as much as 4.8 and 20% respectively. Thermal conductivity decreased to 0.743 W/m2.K in BC10% as compared to 0.872 W/m2.K (control), and specific heat capacity increased to 1024 J/kg K as compared to 923 J/kg K, indicating improved thermal insulation. The durability parameters were also improved with the TSR improving to 89.3% and long-term aging resistance (PAV) improving to 77.9%. These findings indicate that both RHA and BC are both environmentally friendly fillers that would help to strengthen and sustain asphalt pavements making them eco-friendly and reducing carbon emissions.



Keywords: Hot Mix Asphalt, Rice Husk Ash, Biochar, Filler Replacement, Sustainability.

Introduction

Owing to international concerns regarding climate change, natural resource depletion, and the necessity of sustainable structures, there has been mounting pressure on the infrastructure sector to adopt environmentally friendly approaches. Road construction businesses consume many non-renewable resources and emit large amounts of greenhouse gases (GHGs) owing to the utilization of petroleum products (particularly hot mix asphalt or HMA). With growing concerns about environmental regulations and increased sensitivity of the population towards sustainability, there has been a shift towards the use of renewable and waste materials, which have ecological and engineering advantages [1-3].

The most popular alternative is the application of agricultural byproducts, namely rice husk ash (RHA) and biochar (BC), to partially substitute traditional mineral fillers in HMA (in some portions). The biomass is pyrolyzed into biochar, which is rich in carbon, surface area, and porosity (insert reference). This makes it appropriate for enhancing the binder-aggregate interface and mechanical behavior of asphalt mixtures [4-6]. A byproduct of rice milling and combustion, rice husk ash contains amorphous silica with pozzolanic activity, which enhances the rigidity and density of matrices. These are physical and chemical materials that are compatible and capable of strengthening asphalt mixtures, making them more resistant to high temperatures and more environmentally friendly [5-7].

Traditional fillers, such as cement, hydrated lime, and limestone dust, consume a lot of energy and cause carbon emissions to the atmosphere. They also exhaust mineral resources. In contrast, RHA and BC are easily obtained agricultural waste materials, especially in rice-cultivating regions. A good example of a circular economy, where waste is converted into useful building materials, is the use of waste materials in asphalt [7]. These bio-based fillers are environmentally and economically friendly; however, they are not popular in asphalt applications. This is because very few studies have been conducted on how they communicate with binders, their optimum dosage levels, and their efficacy under varying service conditions over time [8-10].

This study addresses the immediate need for sustainable asphalt mixes by evaluating the synergistic use of RHA and BC

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as green fillers in HMA. The current study aims to fill an enormous knowledge gap pertaining to their influence on mechanical, thermal, and durability properties, resulting in new information on waste valorization and low-carbon pavement designs. The experimental program systematically investigated how different replacement rates of RHA and BC (5, 10, and 15 %) could affect important asphalt performance parameters, such as stiffness, fatigue resistance, moisture sensitivity, and thermal behavior, under hot and humid conditions [8,11,12].

This study was conducted for a number of reasons. Rice husk ash (RHA) is one of the most widespread forms of agricultural waste worldwide. It is believed that over 100 million tons are manufactured annually. This ash is burned or disposed of in landfills, contaminating air and soil. The long-term solution to this waste management problem is the use of RHA with a high silica content in the asphalt matrix, which also offers a solution that is more powerful in withstanding heat and holding heat [4,7]. Second, the porous and hydrophobic microstructure of biochar makes it more resistant to fatigue, less likely to conduct heat, and less permeable to water. This renders it an excellent additive to pavements that undergoes considerable temperature changes [5,8].

In this study, the mechanical properties were also analyzed, and environmental measurements, including life cycle analysis and carbon footprint calculation, were used to determine the overall sustainability potential of RHA and BC in HMA [6,13,14]. This combined strategy is in line with the global trend of circular materials and promotes the making of informed decisions concerning infrastructure decarbonization based on facts.

The scientific significance of this study is that it provides an in-depth evaluation of the two bio-based fillers in a single experiment. Most previous studies have dealt with one material or a few performance parameters. In contrast, this study simultaneously considers mechanical, thermal, and environmental factors at the same time [5,8,9]. These findings assist in comprehending the actions of RHA and BC as a unit and how they can be employed in asphalt systems to improve their performance. The results provide specific design suggestions for implementing the design in practice and promote the application of environmentally friendly and economically reasonable asphalt technologies for engineers and authorities [15,16].

This study also promotes the United Nations Sustainable Development Goals (SDGs), namely, Goal 9 (Industry, Innovation, and Infrastructure), Goal 11 (Sustainable Cities and Communities), and Goal 12 (Responsible Consumption and Production), as it advocates the use of agricultural waste in construction. The application of such materials not only benefits the environment but also strengthens local economies by transforming waste materials into something useful and creating new methods for producing materials.

In addition to the environmental benefits, the inclusion of RHA and BC in asphalt can be further beneficial to the economy in the long run. Waste products are cheap and readily available; thus, the country does not have to depend on imported mineral fillers and cementitious additives that consume much energy. Moreover, the superior thermal insulation of BC and RHA may enhance the pavement life in hot climates, thereby reducing the maintenance expenses and cost of the overall life of the pavement in hot climates [18,19].

In summary, the research indicates the presence of a life-size research and application gap because the proposal fills it by assessing the capabilities of RHA and BC as sustainable fillers in HMA to enhance the mechanical strength, thermal resistance, and environmental performance. This study aims to assist the asphalt industry in transitioning to low-carbon, bio-integrated formulations that comply with the circular economy concept. The mixture of these materials fosters innovation, durability, and sustainability in present-day infrastructure systems, which is positive for the future of pavement engineering [20].

Materials

The three major ingredients of the asphalt mixtures manufactured in this study were bitumen binders, aggregate, and filler. A typical penetration-grade (60/70) asphalt binder was employed. The aggregates were composed of well-graded crushed limestone selected according to the specifications of the local road authorities. The Job Mix Design (JMD) was prepared to prepare dense-graded HMA of maximum aggregate size of 1/2 inch (19 mm) based on ASTM D1559 and AASHTO M323 specifications. The optimum binder content was considered to be approximately 4 percent air pores, thereby ensuring that stability and flow were on the boundary of specifications. The other components of this filling material derived from agriculture are biochar (BC) and rice husk ash (RHA).

The filler materials underwent several steps to achieve homogeneity, as required for use in a laboratory setting. Rice husk ash was prepared through several steps, including gathering raw rice husks, washing them in distilled water to clean them of any residues, and allowing them to dry. The husks were dried in a muffle furnace at 600 °C and then burnt for two hours to produce a homogenous powder. The ash was then left to cool and sieved using a mesh screen with a diameter of 75 µm. Biochar was produced by heating agricultural biomass that had been dry dried to 400-500 ºC and then slow pyrolysis under a limited oxygen atmosphere. To grind the resulting solid, a planetary ball mill was used to achieve the required fineness, and finally, it was sieved through a 75 µm sieve. Both filling materials were packed inside airtight containers and stored under conditions that prevented contamination and absorption of moisture before their final application.

To identify the basic material properties of RHA and BC, the chemical composition was determined using X-ray fluorescence (XRF) spectroscopy, which was used for testing essential elements such as Si, Ca, and C, and many more. The results revealed that RHA was mainly composed of SiO_2 (87.5), but there were slight traces of Al_2O_3 (0.35), Fe_2O_3 (0.25), CaO (0.85), MgO (0.41), K_2O (2.30), Na_2O (0.14), TiO_2 (0.09), and P_2O_5 (0.12). This indicates that the silica content of RHA is high and the reactive metal oxides are low. In contrast, BC consisted of a high percentage of carbon (69.8%), SiO_2 (11.3%), K_2O (4.5%), CaO (3.6%), MgO (2.1%), Al_2O_3 (1.2%), and Fe_2O_3 (1.0%). The LOI indicated a medium value of volatile residues of BC, which was approximately 5.8%. These values denote variations based on the feedstock, burning conditions, and sources of minerals used. To model and control the mix design, it is imperative to comprehend these compositional patterns, as indicated by [12, 14].

Laboratory hot mix asphalts with varying degrees of filler replacement were developed to examine the feasibility of using rice husk ash and biochar as alternative sustainable fillers for hot mix asphalts. Six different modified mix asphalt specimens containing RHA or BC at weight percentages of 5, 10, and 15, each, were prepared and used for experimentation. In addition, a control mix containing only limestone dust was used.

Each blend was designed using the Marshall mix design procedure to identify the optimal bitumen content required, based on the standards, to obtain sufficient workability, density, and stability. The mixture and compaction temperatures were slightly altered depending on the type of filler material used, based on the viscosity, for equal blending of all mixtures. Each blend had only one variable, which was the type and content of each filler, while the asphalt and aggregates remained constant.

Table 1 shows the mix ID, type of filler, replacement rate, and description of each mix used in this study. It provides a summary of the composition of the asphalt mix and the percentage of each type of filler used.

Table (1): Mix Design of Asphalt Samples with Varying Filler Types and Contents.

Mix ID	Filler Type	Filler Replacement Level (% by weight)	Description
C	Limestone Dust	100	Control mix (conventional)
RHA-5	Rice Husk Ash	5	5% RHA + 95% Limestone Dust
RHA-10	Rice Husk Ash	10	10% RHA + 90% Limestone Dust
RHA-15	Rice Husk Ash	15	15% RHA + 85% Limestone Dust
BC-5	Biochar	5	5% BC + 95% Limestone Dust
BC-10	Biochar	10	10% BC + 90% Limestone Dust
BC-15	Biochar	15	15% BC + 85% Limestone Dust

The 5%, 10%, and 15% replacement levels of both RHA and BC were selected based on previous studies (Senadheera et al. 2023; Zhang et al. 2022), which reported that these levels offered the best balance between workability and degree of enhancement strength. The content below 5% tended to improve with increasing temperature. The material can lose cohesiveness and become brittle when the values exceed 15. The reason behind This range was selected to systematically evaluate the effects of RHA and BC on the mechanical and thermal characteristics of the HMA mixtures.

Each mix was prepared using standardized laboratory procedures, which ensured that the mix was weighed accurately, the aggregates and fillers were fully mixed, and the correct amount of hot bitumen was applied. Before testing, the specimens were preconditioned for 24h at room temperature and compacted with a Marshall compactor to the required number of blows on both sides.

Sample Preparation and Testing Procedures

Each mixture was homogenized in a laboratory-scale mechanical mixer to create an equal distribution of the constituents for preparing the asphalt specimens. The slab and cylindrical samples were subjected to testing of the durability, heat, and mechanical properties of the mixtures by compacting the heated mixtures using a typical Marshall compactor. Three performance tests (n = 3) were conducted for each mixture to ensure statistical reliability and repeatability.

The mechanical performance of the mixtures was tested using a series of standardized tests. The Marshall Stability and Flow Test according to ASTM D6927 [21] was conducted on cylindrical specimens with a diameter of 101.6 mm (4 in.). in diameter and 63.5 mm (2.5 in) in height, and provided information regarding the plastic flow characteristics and load-bearing capacity of the mixes [7]. A Dynamic Modulus Test was conducted on cylindrical samples with a diameter and height of 100 and 150 mm, respectively, to establish the behavior of the asphalt when it was loaded in a cyclic axial manner at various temperatures and frequencies. The test was performed according to AASHTO TP62 [16, 22]. Fatigue resistance was evaluated using the four-point bending beam test, as specified by AASHTO T321 [23]. Fatigue tests of these mixtures were carried out on prism-shaped beams with dimensions of 380 mm, 63 mm, and 50 mm, respectively, in length, width, and height, and they helped to evaluate the resistance to crack initiation and propagation of mixtures subjected to repeated loads [15].

The thermal characterization of asphalt mixtures was conducted by measuring the thermal conductivity and specific heat capacity. The thermal conductivity was evaluated based on the guarded hot plate method, as per ASTM C177 [24], on slab specimens of dimensions 300 mm × 300 mm × 50 mm, and the specific heat capacity was evaluated through Differential Scanning Calorimetry (DSC), as per ASTM E1269 guidelines [25] on small powdered samples of mass 2050 mg.

The durability and moisture susceptibility of the mixtures were analyzed in two major ways. As AASHTO T283 [26] suggests, the Tensile Strength Ratio (TSR) test is used to measure the impact of water on the mechanical integrity of the mix. This test was performed using six cylindrical specimens 101.6 mm across and 63.5 mm tall. Three specimens were moistened and conditioned, and three specimens were dry-tested to determine the loss of tensile strength owing to the damage caused by moisture (6). To simulate short-term aging, the Rolling Thin Film Oven Test (RTFOT) in accordance with ASTM D2872 [27] was implemented, and the Pressure Aging Vessel (PAV) test described in ASTM D6521 [28] was applied to simulate long-term aging. To maintain the consistency and comparability of the results, the experiments were performed in a controlled laboratory environment. The thermal conductivity and specific heat capacity tests were performed at a standard temperature of 60 ± 2 °C, which represents the mean temperature of asphalt pavement surfaces in hot climates. This temperature matches well with the known test procedures, such as ASTM E1269 for the specific heat capacity using differential scanning calorimetry (DSC), and ASTM C177 for steady-state thermal transmission. Mechanical tests, that is, Marshall Stability, Flow, and Fatigue Resistance, were performed at 25 °C as specified in ASTM D6927 and AASHTO T321, which represent ambient conditions of service. These temperature ranges ensured that the resulting performance indicators could be applied and that there was a reliable evaluation of sustainable asphalt mixtures based on biochar and rice husk ash.

The relevance of the differences between the mixtures, as well as the types of suitable fillers and their quantities, was considered. This ensured that the findings had relevance and scientific validity.

In addition to these tests, other sustainability metrics were used to rate and compare the environmentally friendly standards of each asphalt composition. According to traditional life cycle inventory methods, the carbon footprint of each mix was calculated using the embodied energy and emission factor of material extraction and processing, as well as material transportation [2, 7]. A resource circularity index was used to measure the percentage of agricultural waste, namely rice husk ash and biochar, which was successfully diverted to asphalt mixtures rather than being disposed of [3, 13]. Moreover, to include all mechanical, thermal, environmental, and economic factors in a single assessment method for the feasibility of the proposed materials, a multi-criteria sustainability index was designed. To ensure that all environmental impacts, either direct or indirect, are comprehensively documented, a holistic assessment was conducted based on the principles of Life Cycle Thinking (LCT) and those of a circular economy [1, 3, 20].

Results and Discussion

This section presents and discusses the experimental results of asphalt mixtures partially replaced with biochar (BC) and rice husk ash (RHA) as substitutes for limestone filler. Marshall stability and flow values, dynamic modulus, fatigue performance, thermal conductivity, specific heat capacity, tensile strength ratio (TSR), and aging performance were considered as performance indicators. To examine the effect of bio-fillers on the mechanical, thermal, and durable performances of hot mix asphalt (HMA), a control mix was considered.

Table 2 presents all the tested variables for all mix types. The performance variables were significantly influenced by the addition of RHA and BC, depending on the type and replacement level. To highlight the significance of the findings in relation to the broad context of research on sustainable paving materials, a discussion of the findings is presented in the following subsections.

Table (2): Summary of Asphalt Mix Test Results.

Test Type	Control	RHA5%	RHA10%	RHA15%	BC5%	BC10%	BC15%	Specification Limits (ASTM/AASHTO)
Marshall Stability (kN)	9.5	10.1	10.7	10.3	10.2	10.4	9.8	Agency/Project criterion: typically ≥ 8–12 kN (dense-graded, 75 blows)
Marshall Flow (mm)	3.4	3.5	3.6	3.8	3.4	3.5	3.6	2–4 mm (ASTM D6927)
Dynamic Modulus (MPa)	4813	4967	5042	4975	4928	5006	4912	≥ 80% (AASHTO T283)
Fatigue Resistance (cycles)	110397	124889	132518	129218	119812	126812	124263	Within design range (AASHTO T342)
Thermal Conductivity (W/m·K)	0.872	0.824	0.795	0.812	0.768	0.743	0.772	no fixed limit
Specific Heat Capacity (J/kg·K)	923.4	961.7	979.2	968.6	998.3	1024.1	992.9	no fixed limit
Tensile Strength Ratio (TSR, %)	81.4	85.2	87.8	86.6	88.5	89.3	87.5	Common requirement: ≥ 80% (some agencies ≥ 85%)
Aging Resistance (RTFOT, %)	73.8	76.1	78	75.4	77.7	79.4	76.7	≥ 8.0 kN (ASTM D6927)
Aging Resistance (PAV, %)	69.5	72.8	74.6	73.3	75.4	77.9	74.2	2–4 mm (ASTM D6927)

Discussion of Marshall Stability and Flow

In normal situations, the Marshall Stability and Flow tests (figure 1 and 2) provide the necessary details about the load-bearing capacity and deformation capability of asphalt mixtures. The control mix had a stability value of 9.5 kN, as indicated in Table 2, and it increased with the introduction of both RHA and BC fillers up to a certain replacement level.

The RHA-modified mixtures were found to be most stable at 10% replacement, with the highest value of 10.7 kN, which was a 12.6 percent increase compared to the control. This improvement is attributed to the pozzolanic activity and fine particle structure of RHA, which promote increased stocking in the asphalt matrix and a stronger bond between the filler and binder [4, 5]. However, stability decreased slightly to 10.3 kN at 15% RHA, presumably due to overfilling, which disturbed the good binder-filler ratio and reduced cohesion.

The mixes modified with biochar also increased, with a peak of 10.4 kN for 10% BC. As is well known, biochar, with its porous and carbon-rich structure, facilitates increased load distribution and binder absorption [5, 9]. However, a value of 9.8 kN was observed at 15% BC, indicating that there was a point beyond which the use of filler was harmful.

The stated value of The Marshall flow of the control mix was 3.4 mm, which was permissible in all modified mixes. The increase in flow with higher RHA content was small and was at 3.8 mm at 15 percent, which implied a moderate increase in plastic deformation with the applied load. RHA can cause a decrease in the stiffness of the mixture when it is applied in excess due to the fine nature and even agglomerated particles [4]. Instead, the high level of structural rigidity and dimensional stability of BC particles is likely to have caused the high deformation resistance of the biochar mixes, which remained stable with flow values of 3.4–3.6 mm [8].

Both RHA and BC tended to stabilize Marshall more at moderate dosages, with slight trade-offs in the higher dosage, with both being stable at about 10 per cent replacement. These findings are similar to those of Senadheera et al. [5] and Zhang et al. [9], who demonstrated that bio-based fillers enhanced the mechanical strength of HMA when used in small amounts. This creates problems with the filling of these substances to overflow; however, it weakens the performance of the binder and compromises its integrity [12].

These findings highlight the advantages of RHA and BC as sustainable partial fillers in asphalt mixtures, provided that their dosage is adjusted for the structural performance and deformation control.

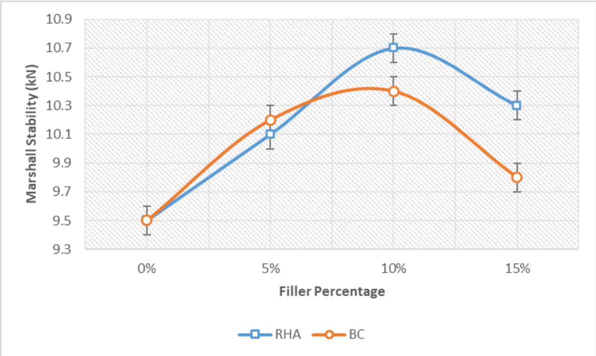

Figure (1): Marshall Stability Results.

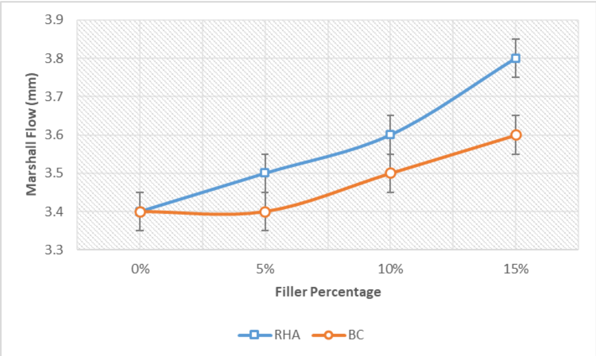

Figure (2): Marshall Flow Results.

Discussion of Dynamic Modulus

The dynamic modulus is an essential parameter that reveals the stiffness and viscoelastic properties of asphalt mixtures subjected to cyclic or repeated loading. This shows that the mixture is resistant to deformation owing to traffic loadings, particularly at intermediate and higher service temperatures. As shown in Table 2, the dynamic modulus of the control mix was 4813 MPa. However, based on the modified mixtures, improvements were observed at all replacement levels of the asphalt mixture.

The mixture with RHA-10% had the highest dynamic modulus of 5042 MPa, indicating an increase of 4.8% compared to that of the control mixture. This improvement is attributed to the fine silica content of rice husk ash that contributes to the stiffening of the binder-filler matrix by physical densification and possible chemical interactions at the interface between the binder [4, 6]. However, the modulus was reduced slightly to 4975 MPa at 15% RHA, which implies that an excessive amount of RHA may weaken the binder phase and lead to slight softening or low load transfer.

The biochar-modified mixtures had a maximum modulus of 5006 MPa with 10 percent BC. The porous microstructure of biochar results in improved stiffness and rutting resistance, allowing the absorption of viscous binders and enhancing the mechanical interlocking of biochar with surrounding aggregates [8, 9]. However, the modulus decreased slightly to 4912 MPa at 15% BC, which is comparable to that of RHA and confirms the optimal filler content.

The values of the modulus of the mixture with 5% and 15% replacement of each of the filler materials, compared to the control, were significantly higher, indicating a positive effect of these sustainable materials on the stiffness of the mixture. This is consistent with Cavalli et al.'s view that bio-based components can be added proportionally to enhance the stiffness and viscoelastic behavior of bio-based fillers [1] and Gulec et al., who observed that bio-based components can be added proportionally [16].

Lastly, both RHA and BC positively affected the dynamic modulus of the asphalt mix, and the highest value was achieved at a replacement of 10%. It is also of great value for sustainable pavement design, as it can help reduce rutting and extend the life of road surfaces subjected to heavy traffic loads.

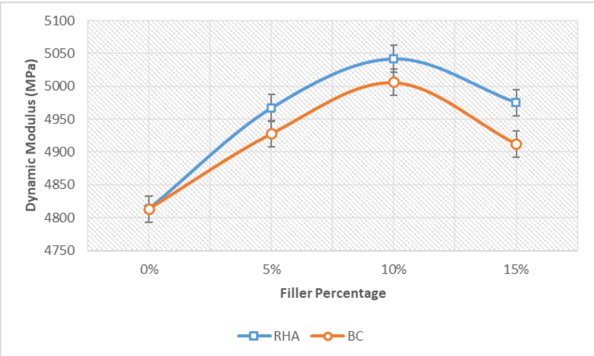

Figure (3): Dynamic Modulus Results.

Discussion of Fatigue Resistances

Fatigue resistance is one of the most important criteria used to determine the resistance of asphalt mixes to traffic and cracking failure due to vehicular trafficking. Fatigue resistance indicates the material resistance and its failure threshold. Both RHA and BC additions showed a remarkable improvement in the fatigue resistance of the control mix, attaining a value of 110,397 cycles, as shown in Table 2 and Figure 4.

However, with 132,518 cycles, the blend containing 10% RHA had the highest value of fatigue resistance, which was an improvement of 20% compared to the control mix. This can be explained by its pozzolanic behavior and finer size, which contribute to improved interaction between the binder and fillers, as well as the absorption of cyclic energy loads [4, 5]. Additionally, despite having a value slightly below that of the mix containing 10% RHA, the other two mixtures containing 15% and 5% RHA showed improved fatigue resistance of 129,218 and 124,889 cycles, respectively, indicating that 10% is the most critical content for improving its strength resistance capability.

Furthermore, corresponding trends were observed for mixtures made based on biochar additive modifications, and the mix, BC-10%, achieved a cycle count of 126,812, indicating a 15% improvement over that of the control. The elasticity and porosity of biochar allow it to act as a microbuffer within an asphalt mix, thereby delaying the formation of cracks within the material [8, 9, 16]. Moreover, the BC-15% and BC-5% mixtures also showed an improvement in cycle counts compared to the control mix, attaining 124,263 and 119,812 cycle counts, respectively.

This is in line with the findings of Beluhan et al. [10] and Bado et al. [14], who showed that fillers produced from agricultural waste materials can improve the fatigue strength by improving the binder-filler compatibility and modifying the stresses. This small loss of performance in mixtures at 15% replacement levels, however, could be related to the mix compositions that had too much filler material above 10%.

Therefore, based on the findings, the fatigue resistance of hot mix asphalt was improved by both RHA and BC, specifically at a 10% replacement rate. This implies that bio-fillers delay the degradation of road infrastructure, ensuring that the road lifespan is extended by increasing the short-term road performance. Thus, hot-mix asphalt based on bio-fillers is a technically feasible material for present-day asphalt technology.

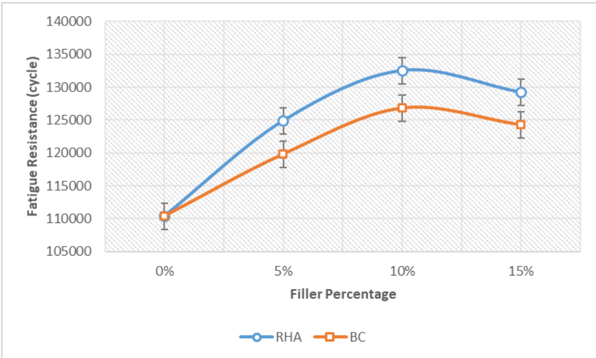

Figure (4): Fatigue Resistance Results

Discussion of Thermal Properties (Thermal Conductivity & Specific Heat Capacity)

The thermal Properties of Asphalt Mixtures are one of the factors that need to be considered in asphalt mixtures because they can influence their performance in terms of heat dissipation in hot weather conditions. Table 2 and Figures 5 and 6 indicate that the ash and biochar influenced the thermal conductivity and specific heat capacity of the mixture.

The control mix exhibited a thermal conductivity of 0.872 W/m·K, although this showed a slow reduction as the additions of RHA and BC continued. Among all the mix designs, BC10% exhibited the lowest value of thermal conductivity at 0.743 W/m·K, thus making it the best for heat retention. This is because it is a lightweight material that is porous at the microlevel, thereby interfering with heat transfer paths within the asphalt matrix [15, 18, 24]. Second, its amorphous silicon components make its conductive paths non-uniform, whereas its carbon matrices form microvoids and closed porosities that trap large amounts of air, which is not an effective heat conductor. Thus, its components work in a manner that prevents heat from easily undergoing smooth flows within it, as proven by the 15% decrease in thermal conductivity compared to that of the control mix materials [5, 8].

The specific heat capacity increased steadily with increasing additive concentration. The control showed the lowest value of 923.4 J/kg·K, whereas BC10% showed the highest value of 1024.1 J/kg·K. This suggests that a higher amount of heat energy was retained by the modified mixtures without a substantial increase in their temperature. A study in materials science noted that the porous carbon structure in BC behaves as a micro-reservoir that traps heat within its inner cavities. In contrast, the high specific surface area of the siliceous component of RHA allows it to trap higher amounts of heat energy. This makes it a thermally inert material, which means that its surface temperature remains unchanged. This is because when it is subjected to heat for an extended period, its tendency to rut is low [15].

This phenomenon is in line with previous studies related to the ability of composite materials of silica and biochar to control temperatures in pavement technology [8, 9]. In addition, the use of RHA and BC increased the longevity of the materials under hot conditions, as they resisted degradation. This results in a cooler city, as less heat is produced by the buildings.

When the amorphous silicon in RHA and the carbonaceous porous structure in BC acted in a complementary manner, it led to better performance of the modified-asphalt mixtures. They not only prevent the flow of heat but also provide a more stable and environmentally friendly road system because of their ability to absorb higher energies. This outcome indicates that bio-fillers play a crucial role in creating an asphalt road system that is climate-resilient and energy-efficient, as it should be for a sustainable asphalt road system [18, 20].

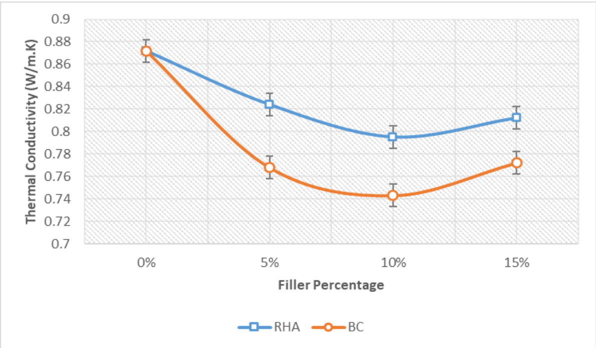

Figure (5): Thermal Conductivity Results

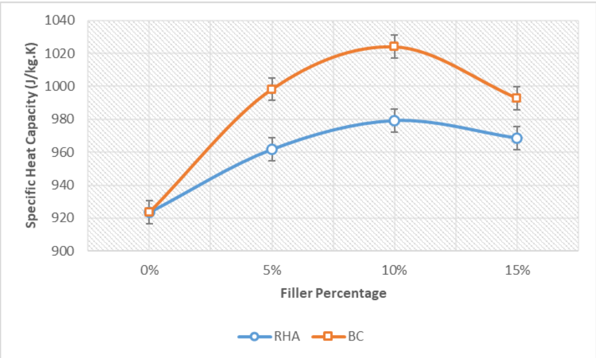

Figure (6): Specific Heat Capacity Results

Discussion of Moisture Susceptibility (Tensile Strength Ratio – TSR)

Moisture sensitivity is a criterion that influences the performance of asphalt mixtures. In this study, the Tensile Strength Ratio (TSR) test described in AASHTO T 283-14 [26] was utilized to measure the resilience of the asphalt mix to damage caused by moisture. From Table 2 and Figure 7, it is evident that the TSR of all mixed samples.

The TSR of the control mix was 81.4%, which is the lowest acceptable value. With the addition of 5%-15% RHA and BC, the TSR increased slowly. In the BC10% mix, the TSR was the highest (89.3%), followed by TSR in the RHA10% mix (87.8%). This signified that it was more resistant to moisture than the other two. The pozzolanic action of RHA and the hydrophobic property of BC contributed to this improvement.

From a microstructural viewpoint, the small silica particles in RHA occupy the microvoids around the binder-aggregate interfacial region and react with bituminous materials to produce a greater number of silicate bonds. This chemical compaction of the interfacial bonding region resists the flow of capillary water [1, 4, 7]. Conversely, biochar has a highly porous surface that is rich in carbon, giving it a high affinity and preventing water infiltration. Additionally, a network of carbon pores acts as a barrier that restricts water passage, increasing its tortuosity [5, 8, 9].

In fact, its coarse texture helps it mechanically adhere well to the asphalt mastic, which, in turn, helps to improve the interfacial strength of the mastic-aggregate interface and thereby enables efficient load transfer during rainy conditions. This was due to its reinforced composition, resulting in the BC 10% mix performing better than the RHA10% mix based on the TSR value. It is hydrophobic and mechanically stable because of the carbon material. Moreover, owing to the complementary actions of RHA and BC, the stickiness of the mixture was improved, thereby avoiding stripping.

All of these modified mixtures had a TSR value above the required threshold of 80% as specified by AASHTO T283 [26]. Based on these observations, it can be noted that biochar increases hydrophobicity and physical bonding, whereas RHA increases chemical bonding owing to its capability to interact with silicon.

Based on these observations, it is proven that a combination or semi-modified technology can be of great benefit, as it can develop asphalts that have a longer lifespan, can resist more moisture, and are environment-friendly [5, 7, 9, 18].

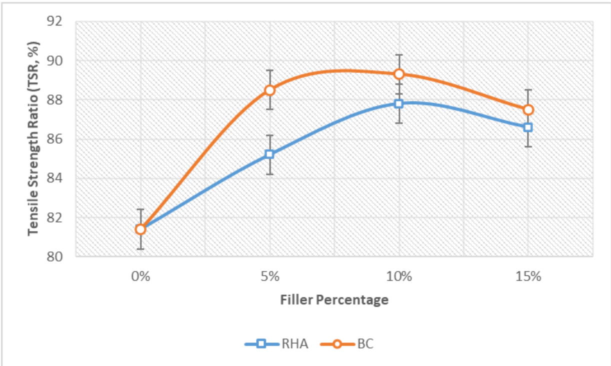

Figure (7): Tensile Strength Ratio Results

Discussion on Aging Resistance (RTFOT and PAV)

Aging resistance is a critical property of asphalt mixtures that is required to maintain their functionality and integrity. Two standardized techniques are commonly used to test it. One is the Pressurized Aging Vessel (PAV) for long-term oxidation aging in field conditions, and it is performed in conjunction with the Rolling Thin Film Oven Test (RTFOT) for short-term aging in mixing as well as compacting phases. Both were carried out according to the ASTM D2872-19 and ASTM D6521-19 standards, respectively," as illustrated in Table 2 and Fig 9.

The baseline susceptibility to oxidation and thermal degradation was embodied by the control mixture, whose

RTFOT resistance and PAV values were 73.8% and 69.5%, respectively. In all cases, the addition of RHA and BC increased the mixing sensitivity to oxidation reactions. Among all of them, the mixture with 10% BC showed the highest resistance to oxidation in the RTFOT (79.4%) and PAV (77.9%) tests. Similarly, an improvement was observed in all RHA mix designs, which was 78.0% in the RTFOT and 74.6% in the PAV.

The antioxidant properties of biochar, arising from carbon-containing materials and stable aromatic rings that prolong the weatherability of asphalt, contribute to enhancing the aging properties of asphalt [5, 8, 9]. Moreover, RHA is rich in reactive silica materials that may react with asphalt components to enhance the thermal stability of asphalt against heat conditions [1, 4, 11].

These findings are consistent with previous studies that have shown that fillers based on biomass, such as biochar, act as barriers to oxygen diffusion and thermal degradation of asphalt materials [2, 5, 9]. This performance indicates that such additives are suitable for use in the manufacture of sustainable asphalt materials.

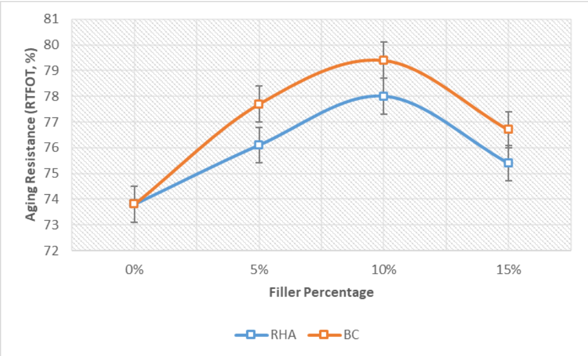

Figure (8): Aging Resistance (RTFOT) Results.

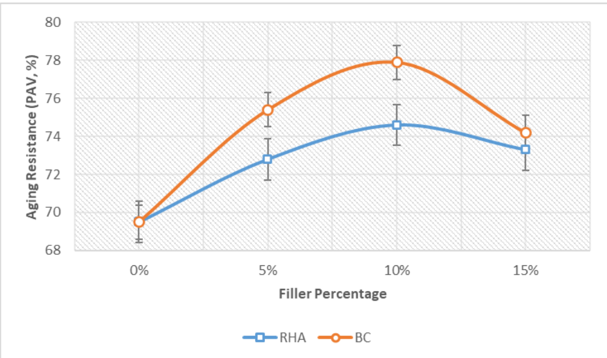

Figure (9): Aging Resistance (PAV) Results.

Comprehensive Comparison of All Mixtures

Table 2 presents all the performance indicators evaluated in this study and enables a collective analysis of the influence of biochar (BC), Rice Husk Ash (RHA), and other partial fillers on the hot mix asphalt (HMA) mix design to identify an optimal mix composition and all considerations entailed within finding a balance between strength, toughness, and thermal resistance.

Both RHA and BC increased the Marshall Stability value in terms of mechanical performance, and the highest value of 10.7 kN was recorded in the RHA10% mixture, signifying that it would resist a higher load. In contrast, the Marshall Flow values of the mixtures remained within acceptable ranges and were satisfactory in terms of flexibility.

Mixtures of RHA10% and BC10% have the longest fatigue life as far as fatigue characteristics are concerned (132,518 and 126,812 cycles, respectively), thus proving that these replacement percentages have been optimized in order to maximize such a property. Similarly, all modified mix materials exhibited a considerable improvement in dynamic modulus values, with the highest improvement in stiffness represented by RHA10% at 5042 MPa.

Improvement was also noted in terms of the indexes of durability, including aging resistance and Tensile Strength Ratio (TSR). In all modified mixtures, the TSR was above 85%, with a value of 89.3% recorded for BC10%, making it highly durable against moisture. In terms of aging resistance, all mixtures recorded higher values than the control in terms of RTFOT and PAV, with indices of 79.4% and 77.9% in BC10 %, respectively.

BC10% recorded the lowest value of 0.743 W/m•K in terms of thermal performance, signifying an improvement in insulation properties that may help combat temperature stress within the pavement layers. This is in addition to the improvement in the specific heat capacity, which may result in improvements in the thermal mass. In this group, BC10% also recorded better performance in specific heat capacity at 1024.1 J/kg•K.

In terms of mechanical, durability, and thermal performance, the RHA10 and BC10% mixtures provided the best overall balance of these properties. BC performs better in terms of thermal stability and aging resistance, whereas RHA is more effective in enhancing the strength and fatigue. According to these results, pavement sustainability and performance can be improved by combining agro-industrial by-products, which is consistent with the principles of the circular economy [1, 3, 5, 7].

The sustainability assessment showed that the use of RHA and BC had a much smaller effect on the environment than the use of limestone filler. Previous life-cycle studies [2, 6, 13] showed that limestone use requires approximately 40–60% more energy and releases more CO_2 (approximately 0.22–0.25 kg CO_2/kg) than RHA and BC (approximately 0.09–0.12 kg CO_2/kg). The fact that RHA and BC come from farms means that they require very little processing and store carbon. Replacing 10% of the limestone filler with RHA or BC on a mixture scale can reduce the total embodied energy by up to 15% and the CO_2 emissions by approximately 18%. This demonstrates that they are better for the environment and align well with the goals of the circular economy.

Analysis of Variance (ANOVA)

Table (3) above shows the two-way ANOVA analysis outcome concerning the variations in different parameters of tests and mix composition. Statistical analysis of two-factor ANOVA indicates that the ‘row’ variable, symbolically indicating the type of test, is highly significant, having F of 2058.91 and significantly larger than the critical value of $F_{(crit)}$ (2.14), followed by a small P-value of 3.81×10^{-58}, significantly smaller than the least threshold of 0.05. This indicates that large variations exist in the tested parameters of Marshall stability, Marshall flow, dynamic stiffness, resistance to fatigue, thermal conductivity, specific heat, tensile strength ratio (TSR), and aging resistance (RTFOT and PAV), and these differences are significantly more than mere experimentation, determining that each of these parameters measures a distinct property of these modified asphalt mixtures and that its extent and trend are significantly different from those of other tests.

However, for the column factor, or mixture composition, of 5%, 10%, and 15% of modifying RHA and BC, there are no statistically significant differences between the means, as indicated by the calculated F-value of 1.03, which is less than $F_{(crit)}$ = 2.29, and P-value of 0.418, which is greater than 0.05. Although some numerical increments have been observed for the values-for example, an improvement in Marshall stability and resistance to fatigue for mixtures containing RHA10% and BC10%)–the changes can be considered as falling within the range of experimental errors and, thus, can neither be statistically ascertained nor differentiated at a 95% confidence level. But based on engineering considerations, these observed trends generally point towards a significant engineering value and stability towards utilizing these two materials, namely, RHA and BC, as potential modifiers of asphalt mixtures and as environmentally friendly supplements. Both materials significantly improved the mechanical and aging parameters of the mixtures without impairing any other essential characteristics, indicating a promising trend as eco-friendly supplements and modifiers. In addition, this lack of statistical significance generally indicates that these two supplementary materials are relatively comparable for most of their characteristics and have ascertained their balance of properties through all these tests. Moreover, a value of 5,743,915 still (relatively speaking) embodies a low value of error variance and generally confirms the reliability of experimental observations and, thus, generally confirms that all these tests have generally ascertained some dependency and consistency through these tests and this testing process. In addition, ANOVA generally shows that, although none of these mixtures have any significant inter-differences, these generally observed trends generally lead to ascertaining engineering value and stability towards these two potential modifiers of asphalt mixtures, namely, RHA and BC.

Table (3): ANOVA: Two Factor Without Replication.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	94609659298	8	11826207412	2058.910561	3.80616E-58	2.138228827
Columns	35461931.02	6	5910321.837	1.028970965	0.418259748	2.294601313
Error	275707923.6	48	5743915.076			
Total	94920829153	62				

Conclusions

This study is useful for determining the mechanical, thermal, and resilient properties of hot mix asphalt (HMA) using rice husk ash (RHA) and biochar (BC) as alternative materials. The addition of such materials enables the mixture to behave more effectively. For instance, RHA10% and BC10% increased the Marshall stability by 12.6% and 9.5%, respectively, compared to that of the control mix. In addition, BC10% provided a higher Tensile Strength Ratio (TSR) of 89.3%, increasing by 9.7% compared to the control mix, whereas that of RHA10% was 87.8%. BC10% provided a higher TSR value than the control mix, with an increase of 9.7%. This also showed a decrease of up to 15% in the thermal conductivity of BC10%, proving that it is a better insulator. Another property that increased was the specific heat capacity by 10–11%, indicating that it could contain more heat than the control. Moreover, it was 11% more durable than the control mix because it was non-carbonaceous compared to bitumen.

From the above findings, it is clear that both RHA and BC are capable of enhancing the long-term durability of asphalt mixtures and at the same time ensuring that they meet performance criteria. Second, this technology can minimize the use of non-renewable fillers, thereby contributing to a 15%-18% decrease in embodied energy and CO2 emissions compared with limestone fillers.

The results are most useful for hot and humid areas, where problems with heat and moisture are common. However, to improve its performance in colder climates, the binder grade and filler content must be changed to stop cracking at low temperatures. This study showed that adding agricultural waste to modern asphalt pavement technologies has both environmental and performance-related benefits.

Suggestions

Given the promising results of this study, future research should examine the long-term field performance of asphalt mixtures incorporating RHA and BC under actual traffic and environmental conditions. Furthermore, these bio-fillers may interact better with asphalt binders and improve the mixture stability if their particle sizes and surface treatments are optimized. A cost-benefit analysis and life cycle assessment (LCA) should also be conducted to assess the viability of large-scale implementation from an economic and environmental standpoint. Additionally, the synergistic advantages of combining RHA and BC in hybrid formulations may outperform those of using each filler individually. Standardization efforts should be encouraged to incorporate bio-based fillers into national asphalt design specifications. Finally, investigating additional agro-industrial byproducts in conjunction with RHA or BC may pave the way for completely sustainable pavement.

Disclosure Statement

- **Ethics approval and consent to participate:** Not applicable
- **Consent for publication:** Not applicable
- **Availability of data and materials:** The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.
- **Author's contribution:** Author's contribution should be added, for example. The authors confirm contribution to the paper as follows: study conception and design: Smith, J2, theoretical calculations and modeling: Smith, J3; data analysis and validation, Smith, J2, Smith, J3. draft manuscript preparation: Smith, J3, Smith, J4. All authors reviewed the results and approved the final version of the manuscript.
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