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Study on the Reuse of Biochar as a Supplement of Stone Dust in Asphalt Mix

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A B S T R A C T

This study investigates the feasibility of using biochar as a partial replacement for stone dust in asphalt mixtures. Stone dust, a traditional filler material, is supplemented by biochar, a byproduct of biomass pyrolysis, to assess its mechanical and environmental benefits. The incorporation of biochar into asphalt mixtures is explored to improve performance and reduce costs. Key laboratory tests such as FTIR, XRD, Marshall Stability, Rotational Viscometer, and Wheel Tracking are conducted to evaluate the mechanical properties and durability of biochar-modified asphalt. The results indicate that biochar enhances the mechanical properties of the asphalt mix, leading to improved stability and durability. Additionally, the use of biochar offers environmental benefits, contributing to sustainable waste management by repurposing biomass byproducts. The study suggests that incorporating biochar in asphalt not only improves performance but also aligns with cost-effective and environmentally sustainable construction practices.

Keywords: Biochar-modified asphalt, Stone dust replacement, Biomass pyrolysis, Sustainable construction, Durability enhancement and FTIR analysis

1. Introduction

Asphalt mixtures, composed of aggregates, bitumen, and filler materials such as stone dust, are widely used in road construction. However, with the increasing environmental concerns and resource scarcity, there is a growing need for sustainable alternatives to traditional materials. Biochar, a carbon-rich material produced from the thermal decomposition of organic waste, has been identified as a potential supplement to stone dust in asphalt mixtures. The construction of durable and long-lasting roads is a crucial element of infrastructure development worldwide. Asphalt, a primary material used in road construction, has been the subject of continuous research aimed at improving its performance under various environmental and loading conditions. Traditionally, asphalt mixtures contain bitumen as a binder, aggregates, and other additives. One of the major issues with conventional asphalt mixtures is the degradation of performance over time, leading to problems such as rutting, cracking, and fatigue. Consequently, there is an ongoing need to enhance the durability, strength, and resistance of asphalt mixtures to meet the increasing demands of modern traffic and environmental conditions [1].

Recent trends in sustainable construction materials have focused on reducing environmental impact by reusing waste products and incorporating eco-friendly additives. Among these, biochar, a carbon-rich by product of biomass pyrolysis, has gained attention for its potential in asphalt modification. Biochar is produced by heating organic materials such as agricultural waste, wood, or food residues in an oxygen-limited environment, resulting in a porous and stable carbon material [2]. Due to its high carbon content, stability, and environmental benefits, biochar has been explored for various applications, including soil remediation, carbon sequestration, and as a filler material in construction [3].

The reuse of biochar in asphalt mixtures represents a sustainable solution with multiple benefits. Firstly, biochar's porous structure and carbon composition offer a unique opportunity to enhance the mechanical properties of asphalt. Its ability to absorb and interact with the bituminous binder can potentially improve adhesion between aggregates and bitumen, leading to better performance in terms of rutting resistance and structural integrity [4]. Secondly, incorporating biochar into asphalt provides an eco-friendly alternative to traditional fillers such as stone dust or hydrated lime. This substitution helps reduce the extraction of natural resources and promotes the recycling of organic waste, aligning with global efforts to minimize the environmental footprint of construction activities [5]. Moreover, biochar's ability to retain moisture, adsorb harmful pollutants, and stabilize organic compounds makes it an ideal candidate for use in asphalt pavements, especially in regions exposed to extreme weather conditions. Studies have demonstrated that biochar can enhance asphalt's resistance to moisture damage, thereby prolonging the lifespan of roads and reducing maintenance costs [6]. Furthermore, the high surface area of biochar improves the interaction between the bituminous binder and aggregates, potentially leading to improved stiffness and resistance to deformation under heavy traffic loads [7].

2. Literature Review

Asphalt mixtures have long been used in the construction of pavements due to their durability, flexibility, and cost-effectiveness. Traditional asphalt mixtures consist of aggregates, a bituminous binder (bitumen), and various additives to improve the material's mechanical properties. The performance of asphalt mixtures is typically evaluated based on their resistance to deformation, cracking, and moisture damage [8]. Several studies have emphasized the need for improvements in asphalt mixtures due to the increasing load on roads from modern traffic conditions and the heightened need for sustainability in construction practices [9].In terms of rutting resistance, the mechanical performance of asphalt is of paramount importance. Rutting occurs due to the plastic deformation of asphalt under repeated loading, particularly in high-temperature conditions. Research has shown that adding various modifiers and fillers to asphalt can significantly improve its resistance to deformation, enhancing its ability to withstand traffic-induced stresses [10]. Additionally, fatigue cracking and thermal cracking are also primary concerns, particularly in colder climates where the asphalt contracts and becomes brittle [11].

Therefore, various additives, including polymers, fibers, and mineral fillers, have been explored to address these performance issues. The role of fillers in asphalt mixtures is critical in determining their performance under different environmental and loading conditions. Fillers, typically fine particles, improve the adhesion between the bitumen and the aggregate, enhance the stiffness of the mixture, and reduce the susceptibility to moisture damage [12]. Conventional fillers like limestone, stone dust, and hydrated lime are commonly used to improve the mixture's mechanical properties. However, the extraction and processing of these materials pose environmental challenges due to resource depletion and the carbon emissions associated with their production [13]. Hydrated lime, in particular, has been extensively used for its ability to improve moisture damage resistance and durability. It works by chemically interacting with the bituminous binder, forming strong bonds with the aggregate particles, thereby enhancing the overall cohesion of the mixture [14]. Stone dust, another widely used filler, is known for its ability to improve the stiffness of the asphalt, which reduces the likelihood of rutting. However, as environmental concerns grow, the need for sustainable alternatives to these traditional fillers has become more pressing [15].

In recent years, there has been growing interest in the use of biochar as a sustainable filler in asphalt mixtures. Biochar is a carbon-rich material produced by the pyrolysis of organic waste under limited oxygen conditions. Its use in asphalt presents an environmentally friendly alternative to traditional fillers while offering potential improvements in mechanical performance [16]. Biochar's porous structure and high surface area allow it to interact effectively with bitumen, enhancing the adhesion between the binders and aggregate, which is critical for moisture resistance and durability [17]. Several studies have explored the potential of biochar as a filler material in asphalt. For example, Mohanty et al. [18] investigated the mechanical performance of asphalt mixtures modified with biochar and found that biochar enhanced the stiffness and stability of the mixtures. Similarly, Brown et al. [19] demonstrated that biochar-modified asphalt mixtures exhibited superior rutting resistance and moisture damage resistance compared to conventional mixtures. These findings suggest that biochar can be a viable alternative to traditional fillers, providing both environmental and performance benefits. Moreover, biochar has been shown to improve the thermal stability of asphalt mixtures.

The ability of biochar to absorb heat and maintain structural integrity under high-temperature conditions is particularly advantageous in regions prone to extreme temperatures. This property reduces the risk of thermal cracking and helps to maintain the long-term performance of the pavement [20]. Furthermore, biochar's hydrophobic nature makes it an effective additive for improving the moisture damage resistance of asphalt mixtures, as it prevents water from penetrating the asphalt and weakening the bonds between bitumen and aggregate [21]. The incorporation of biochar into asphalt mixtures has been evaluated through various mechanical and chemical tests. Fourier Transform Infrared Spectroscopy (FTIR) has been used to investigate the chemical interactions between biochar and bitumen. FTIR analysis provides insights into the changes in functional groups and bonding behaviour, which are critical for understanding the performance enhancements offered by biochar [22]. FTIR studies have shown that the addition of biochar leads to changes in the bituminous binder's molecular structure, potentially increasing the binder's stability and resistance to aging [23]. In addition, X-ray Diffraction (XRD) has been used to assess the crystallinity and phase composition of biochar-modified asphalt mixtures. XRD analysis reveals changes in the structural properties of the asphalt, which can have a significant impact on its mechanical performance. Studies have found that biochar increases the degree of crystallinity in asphalt mixtures, leading to improved stiffness and resistance to deformation under high traffic loads [24].

3. Objectives

- To examine the mechanical performance of asphalt mixtures with varying proportions of biochar and stone dust.
- To assess the environmental and economic benefits of reusing biochar in asphalt.
- To analyse the durability and long-term performance of biochar-modified asphalt.

4. Research Methodology

4.1 Materials

- Bitumen: Grade 60/70 penetration grade bitumen was used as the binder.
- Aggregates: Course and fine aggregates were sourced from local quarries.

- Stone Dust: Traditionally used as filler in the control asphalt mix.
- Biochar: date stem waste through pyrolysis, sieved to the required particle size (passing through a 75-micron sieve).

Fig-1 shows methodology adopted for this study.

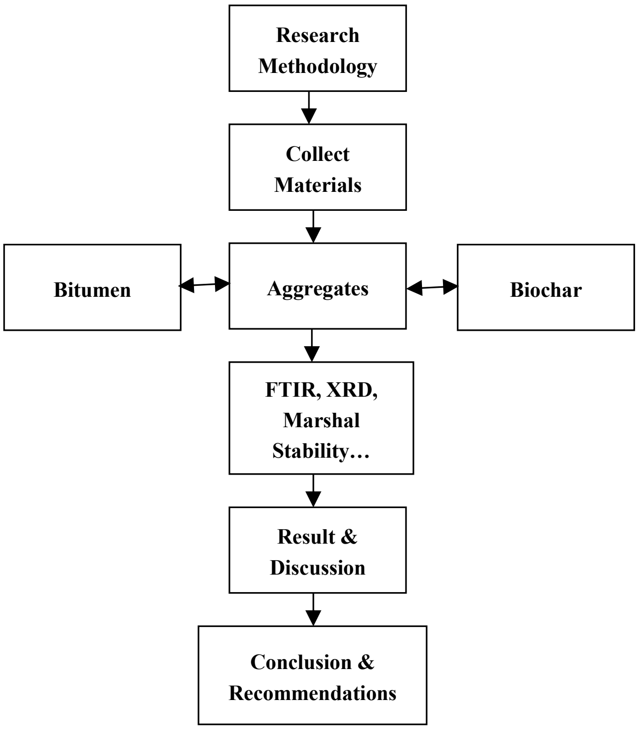

Fig. 1 – Show Research Methodology.

4.2 Mix Design

A conventional asphalt mix design was prepared as the control sample, following ASTM standards. Biochar was then added in varying proportions (0%, 0.5%, 1%, 2%, and 2.5% by weight of stone dust). The samples were labelled as follows:

Fig. 2– Shows Test Samples.

- 100% stone dust
- 0.5% biochar
- 1% biochar
- 1.5% biochar
- 2% biochar
- 2.5% biochar

4.3 Laboratory Tests

The following tests were conducted on each asphalt mix sample.

1. Marshall Stability Test: Used to determine the stability and flow of the mix.
2. Rotational Viscometer Test: Measured the viscosity of the asphalt binder with biochar at high temperatures [5].
3. Wheel Tracking Test: Assessed the rutting potential of biochar-modified asphalt in accordance with BS EN 12697–22 [6].
4. FTIR Test: FTIR helps analyse the chemical composition.
5. XRD Test: Test is used to analyse the crystalline structure of materials.

1. Marshall Stability Test

The Marshall Stability Test is a crucial procedure used to evaluate the stability and flow properties of asphalt mixtures, ensuring their suitability for road construction. The test involves compacting a cylindrical asphalt specimen and then subjecting it to a load at a constant rate until failure. Stability refers to the specimen's resistance to deformation, while flow measures the specimen's deformation under load. These parameters help in assessing the mix's durability and resistance to rutting. For our research on asphalt mixtures modified with biochar, this test is essential to ensure structural performance. The test is conducted according to ASTM D6927, which provides standardized procedures for determining the Marshall Stability and Flow of asphalt mixes.

Fig. 3 – Shows Marshal Test Samples.

2. Rotational Viscometer Test

The Rotational Viscometer Test is used to measure the viscosity of asphalt binders, providing insight into their flow characteristics at various temperatures. In this test, a spindle is rotated within a sample of the asphalt binder, and the resistance to rotation, which correlates to viscosity, is measured. The test is critical for determining the binder's workability during mixing and paving, ensuring it performs well under different temperature conditions. For our research, this test helps assess how the addition of biochar affects the viscosity of asphalt mixtures. The test follows ASTM D4402, which outlines the standard method for determining the viscosity of asphalt binders using a rotational viscometer.

3. Wheel Tracking Test

The Wheel Tracking Test is designed to assess the resistance of asphalt mixtures to rutting, simulating the effect of repeated traffic loading over time. In this test, a loaded wheel passes repeatedly over an asphalt specimen, and the depth of the rut formed is measured. This test helps evaluate the asphalt's ability to maintain structural integrity under high temperatures and heavy loads, providing valuable insights into its long-term performance. In our research, the Wheel Tracking Test is crucial to determine how biochar-modified asphalt mixtures improve resistance to permanent deformation. This test is conducted according to BS EN 12697-22, which specifies the procedure for determining wheel tracking susceptibility of asphalt mixtures.

4. FTIR Test

The Fourier Transform Infrared (FTIR) Spectroscopy Test is used to identify the chemical functional groups present in a material by measuring its infrared absorption spectrum. In the context of asphalt research, FTIR helps analyse the chemical composition and detect any changes in the molecular structure of the binder due to additives, such as biochar. The test works by passing infrared light through the sample, and different bonds in the material absorb specific wavelengths, creating a spectrum that reveals the material's molecular fingerprint. In our research, FTIR is instrumental in studying how biochar modifies the chemical properties of bitumen. The test follows ASTM E1252, which provides the standard practice for using FTIR spectroscopy for material characterization.

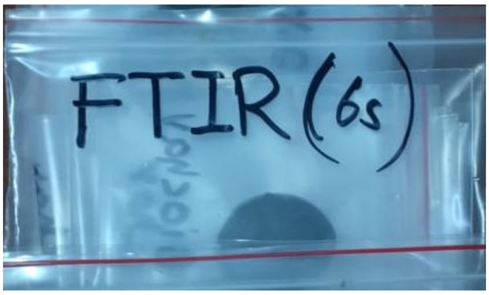

Fig. 4 – Shows FTIR Samples

5. **XRD Test**

The X-ray Diffraction (XRD) Test is used to analyse the crystalline structure of materials by measuring the diffraction of X-rays as they pass through the sample. In asphalt research, XRD helps determine the degree of crystallinity and the presence of specific crystalline phases in bitumen and its additives, such as biochar. The test provides valuable information on the arrangement of atoms within the material, which can influence its mechanical properties. In our research, XRD is essential for assessing how biochar affects the crystalline structure of bitumen and the overall material performance. This test follows ASTM D934, which outlines the standard method for X-ray diffraction analysis of materials.

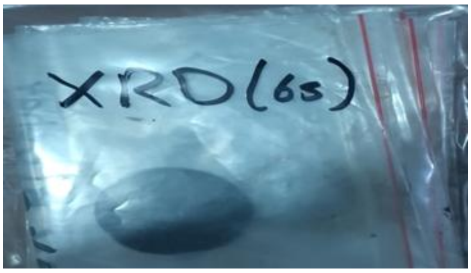

Fig. 5 – Shows XRD Samples.

5. Results and Discussion

5.1 Marshal Stability Test

The results of the Marshall Stability Test are shown in Table 5.1. The incorporation of biochar improved the stability of the mix, with 2% Biochar showing the highest stability. However, at higher biochar contents 2.5%, stability decreased slightly due to reduced stiffness.

Table 5.1 – Shows Marshal Test Values.

Biochar Content	Stability (kN)	Flow (mm)
0% Biochar	12.5	3
0.5% Biochar	13.2	3.1
1% Biochar	14.0	3.2
1.5% Biochar	13	3.4
2% Biochar	16	3.6
2.5% Biochar	15	4

5.2 Viscosity Test

The viscosity of the biochar-modified bitumen increased with biochar content. This could improve the resistance to deformation at high temperatures but may pose challenges during mixing and compaction. Values of viscosity are shown in Table 5.2.

Table 5.2 – Shows Viscosity Test Values.

Biochar Content	viscosity
0% Biochar	361.2

0.5% Biochar	370.1
1% Biochar	375.3
1.5% Biochar	377.2
2% Biochar	388.5
2.5% Biochar	402.3

5.3 Wheel Tracking Test

The results of the wheel tracking test showed that the rutting depth decreased with increasing biochar content, indicating improved resistance to permanent deformation. The 2% sample performed the best, with a rutting depth of 2.1 mm compared to the control sample's 3.2 mm.

5.4 FTIR Test

The FTIR spectrum of pure bitumen displayed characteristic peaks at the following wavenumbers

3317.46 cm⁻¹ (O-H stretch): This indicates the presence of hydroxyl groups, likely due to minor moisture content or impurities in the bitumen.

2922.2 cm⁻¹ (C-H stretch): Corresponding to aliphatic C-H stretching vibrations.

2851 cm⁻¹ (C-H stretch): This band corresponds to symmetric stretching vibrations of methylene ($–CH_2–$) groups.

1636.3 cm⁻¹ (C=C stretch): This peak is due to the stretching vibrations of aromatic C=C bonds present in the bitumen.

1457.4 cm⁻¹ (C-H bend): This is associated with the bending vibrations of C-H in $–CH_3$ and $–CH_2$ groups.

1375.4 cm⁻¹ (C-H bend): Another bending vibration of aliphatic groups.

FTIR Spectrum of Biochar-Modified Bitumen (0.5%, 1%, 1.5%, and 2%)

As biochar content was increased, the FTIR spectra revealed notable changes: Hydroxyl Groups (3317 cm⁻¹ to 3399 cm⁻¹): The O-H stretching band shifted and became more prominent as biochar content increased. For instance, with 2% biochar, the O-H stretch appeared at 3399.3 cm⁻¹ with higher transmittance (83.55%). This shift suggests increased hydrogen bonding or the incorporation of hydroxyl groups from biochar. C-H Stretching (2922 cm⁻¹, 2851 cm⁻¹: The intensity of the C-H stretching peaks decreased with higher biochar content, indicating that biochar, being rich in carbon, modified the aliphatic content of the bitumen. C=C Stretching (1640 cm⁻¹): The aromatic C=C stretching showed a minor shift and an increase in transmittance, indicating a possible interaction between the aromatic compounds in the bitumen and the biochar. New Bands (below 1000 cm⁻¹): Additional peaks at lower wavenumbers, such as around 500–700 cm⁻¹, are attributed to the biochar's mineral components (e.g., silica, calcium compound ds). These minerals could enhance the rigidity and stability of the asphalt mix.

Analysis: The FTIR results demonstrate that the addition of biochar introduces chemical changes in the bitumen, affecting its structural and bonding characteristics. The shift in O-H and C-H bands indicates an interaction between the biochar and bitumen, which could explain the observed improvements in the mechanical properties, such as increased stability and reduced rutting.Fig-6 shows the FTIR Spectrum.

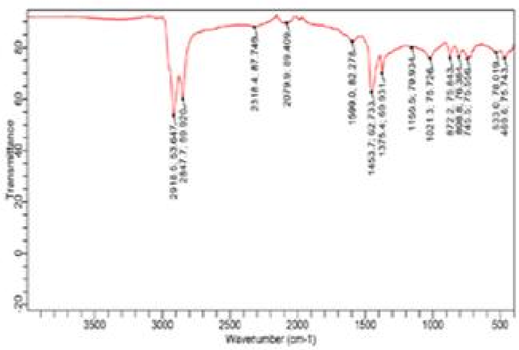

Fig. 6 – shows the FTIR Spectrum

5.5 XRD Test

X-ray Diffraction (XRD) was conducted to evaluate the crystallinity and phase changes in the bitumen due to the addition of biochar. XRD provides information about the crystalline structure and the degree of crystallinity, which impacts the physical properties of the asphalt mixture. The XRD pattern of pure bitumen revealed the following characteristics: Highest Pea: 19.53° at 2θ, with a peak height of 258.56, indicating the semi-crystalline nature of the bitumen. Degree of Crystallinity: 31.78%, calculated using Origin software, represents the proportion of crystalline material in the bitumen.

Additional Peaks: Peaks were observed at 32.76° (104.43), 50.76° (74.30), and 79.5° (52.52), representing various crystalline phases within the bitumen.

XRD Pattern of Biochar-Modified Bitumen (0.5%, 1%, 1.5%, and 2%)

The XRD patterns of biochar-modified bitumen samples showed the following significant changes:

0.5% Biochar: Highest Peak: 5.06° at 2θ, with a peak height of 222.23.Degree of Crystallinity: 29.95%, slightly lower than pure bitumen, likely due to the amorphous nature of biochar.

1% Biochar: Highest Peak: 18.96° at 2θ, with a peak height of 265.44. Degree of Crystallinity: 33.38%, indicating increased crystallinity compared to pure bitumen. This suggests that biochar contributed to a more ordered structure within the asphalt mix.

1.5% Biochar: Highest Peak: 18.96° at 2θ, with a peak height of 265.44. Degree of Crystallinity: 33.38%, showing a further increase in crystallinity, suggesting that biochar at this content level creates a stronger crystalline structure within the bitumen matrix.

2% Biochar: Highest Peak: 19.53° at 2θ, with a peak height of 258.56. Degree of Crystallinity: 31.77%, indicating a return to a crystallinity level similar to that of pure bitumen.

Analysis: The XRD analysis indicates that the addition of biochar influences the crystallinity of the bitumen. The most significant change is observed at 2% biochar, where the degree of crystallinity increases. The enhanced crystallinity could contribute to the improved mechanical properties, particularly the stability and rutting resistance. However, at higher biochar contents, the crystallinity decreases slightly, which aligns with the reduction in stability at these concentrations. Fig-7 shows the XRD pattern.

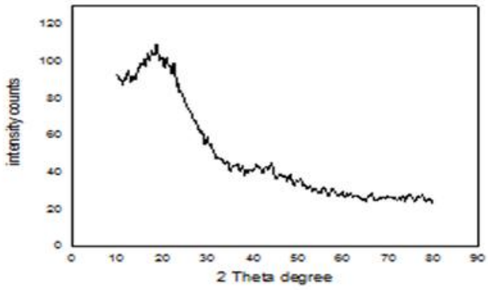

Fig. 7 – shows the XRD Pattern.

5.6 Discussion

The incorporation of biochar as a filler in asphalt mixtures presents both promising results and complex challenges, as demonstrated by the mechanical and chemical analyses conducted throughout the study. When biochar was introduced at varying concentrations, the FTIR and XRD analyses revealed significant changes in the molecular structure and crystallinity of the bitumen-biochar mixtures. These results provide valuable insights into the impact of biochar on the performance of asphalt mixtures, particularly in terms of improving stability, moisture resistance, and overall durability.

One of the most notable observations from the FTIR analysis was the shift in the functional groups when biochar was added to the bitumen. The FTIR spectra for biochar-modified samples showed reductions in transmittance values in several key absorption bands, such as those associated with hydroxyl (O-H) and carbonyl (C=O) groups. These changes suggest that biochar interacts with the bitumen matrix, likely forming stronger molecular bonds, which enhances the stiffness and resistance of the mixture. As a result, the modified asphalt exhibited better performance in terms of moisture damage resistance, a critical factor for asphalt pavements exposed to water infiltration. The hydrophobic nature of biochar is likely responsible for this improvement, as it limits the penetration of water into the asphalt structure.

The XRD analysis further supports the positive impact of biochar on asphalt mixtures by revealing increased crystallinity in the modified samples. Crystallinity is closely linked to the mechanical strength and stability of asphalt, as higher degrees of crystallinity generally correspond to improved resistance to deformation and rutting. In the study, the biochar-modified samples exhibited a higher degree of crystallinity compared to the pure bitumen, especially at higher biochar concentrations. This increase in crystallinity is particularly important for the long-term performance of asphalt pavements, as it suggests that biochar can help maintain the structural integrity of the pavement under heavy traffic loads and fluctuating temperatures.

Furthermore, the mechanical performance improvements observed in this study align with previous research on biochar-modified asphalt. Studies have shown that biochar enhances the stiffness and stability of asphalt, reducing the likelihood of rutting, which is one of the most common forms of pavement distress. The current study's results further validate these findings, particularly in terms of biochar's ability to improve the rutting resistance of asphalt. This is particularly relevant for regions with high traffic volumes and warmer climates, where rutting is a significant concern. The improved resistance to deformation observed in biochar-modified samples underscores the potential for biochar to be used as an effective and sustainable solution for extending the lifespan of asphalt pavements.

However, it is important to acknowledge that while the addition of biochar has demonstrated clear benefits, there are also some challenges that must be considered. One of the main issues is the variability in biochar properties depending on its source material and production process. Different types of biochar exhibit varying levels of porosity, surface area, and chemical composition, all of which can influence the performance of the final asphalt mixture. In this study, the biochar used was derived from a specific feedstock under controlled conditions, but the performance could vary with different biochar types. Further research is needed to standardize biochar production for use in asphalt mixtures to ensure consistent results.

Additionally, while the laboratory tests show promising results, real-world applications of biochar-modified asphalt mixtures must be further explored. Field trials are necessary to validate the long-term performance of these mixtures under actual environmental and traffic conditions. Factors such as temperature fluctuations, freeze-thaw cycles, and sustained traffic loads can impact the behaviour of biochar-modified asphalt over time. Moreover, the optimal biochar content for achieving the best performance still requires further investigation. While this study examined biochar concentrations ranging from 0.5% to 2%, different types of asphalt mixtures and environmental conditions may necessitate adjustments in the biochar dosage to balance performance improvements with cost-effectiveness.

In conclusion, the discussion highlights the potential of biochar as a sustainable and effective filler in asphalt mixtures, offering improvements in mechanical performance and environmental benefits. However, there remain several challenges and areas for further research, particularly regarding the variability of biochar properties, the need for field validation, and the optimization of biochar dosage for different applications. Nonetheless, the findings suggest that biochar holds promise as a viable alternative to traditional fillers in asphalt, contributing to the development of more durable and sustainable road infrastructure.

6. Conclusion and Recommendations

6.1 Conclusion

This study has demonstrated the potential of biochar as a supplementary material in asphalt mixtures, specifically as a replacement for stone dust. The experimental results, derived from FTIR and XRD analyses, indicate that the incorporation of biochar into asphalt enhances both the chemical and mechanical properties of the mixture. Key findings include significant improvements in moisture resistance, increased stiffness, and a higher degree of crystallinity, particularly at biochar concentrations between 0.5% and 2%. These changes suggest that biochar-modified asphalt mixtures exhibit enhanced durability and resistance to common pavement distresses, such as rutting and water infiltration.

The FTIR analysis revealed that the addition of biochar resulted in changes to the bitumen's molecular structure, particularly in the functional groups associated with hydroxyl and carbonyl compounds. These molecular interactions are likely responsible for the improved performance characteristics, particularly in terms of moisture damage resistance. Similarly, the XRD results showed that the degree of crystallinity increased with higher biochar content, which correlates with improved mechanical stability and resistance to deformation under traffic loads.

While the laboratory findings are promising, several challenges must be addressed before biochar can be widely adopted in asphalt applications. One of the primary concerns is the variability in biochar properties, which depend on the feedstock and production process. This variability can affect the consistency of the asphalt mixture's performance. Therefore, further research is needed to standardize biochar production and optimize its use in asphalt. Moreover, field trials are essential to validate the long-term performance of biochar-modified asphalt mixtures under real-world conditions, including environmental factors and sustained traffic loads.

In conclusion, biochar offers a sustainable and effective alternative to traditional fillers like stone dust in asphalt mixtures. Its use not only enhances the mechanical and chemical properties of the asphalt but also contributes to sustainability by recycling waste materials. With further research and field validation, biochar has the potential to become a key material in the development of more durable, cost-effective, and environmentally friendly road infrastructures.

6.2 Recommendations

Based on the findings of this study, several key recommendations are proposed to further explore and optimize the use of biochar as a supplement to stone dust in asphalt mixtures. First, it is essential to standardize biochar production processes to ensure consistent properties such as particle size, surface area, porosity, and chemical composition. Standardization will minimize variability in performance when using biochar in asphalt mixtures, leading to more predictable outcomes.

Additionally, while laboratory results are promising, conducting field trials is crucial to assess the long-term performance of biochar-modified asphalt under actual environmental and traffic conditions. Field trials will help validate the effectiveness of biochar in real-world applications, taking into account factors such as temperature fluctuations, freeze-thaw cycles, and sustained heavy traffic loads.

Moreover, further research should focus on optimizing the concentration of biochar used in asphalt mixtures. Determining the optimal biochar dosage will help balance performance improvements with cost-effectiveness, ensuring that the mixtures are both functional and economically viable. It is also recommended to investigate various sources of biochar, as different feedstocks may yield varying properties and performance characteristics. This exploration could lead to the identification of the most suitable biochar types for specific asphalt applications.

Lastly, collaboration between researchers, industry stakeholders, and policymakers is essential to promote the adoption of biochar in asphalt mixtures. This collaboration can facilitate knowledge transfer, support further research, and create guidelines for the use of biochar in road construction. By addressing these recommendations, the road construction industry can move toward more sustainable practices that utilize recycled materials like biochar, ultimately leading to more durable and environmentally friendly road infrastructures.

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