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Sustainable Innovation in Road Construction: Enhancing Moisture Resistance of Bituminous Mixtures with Bamboo and Bagasse Ashes

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Abstract

This study investigates the potential of bamboo ash (CB) and sugarcane bagasse ash (CBCS) as sustainable filler and reinforcement materials to optimize the moisture resistance of bituminous concrete. The research addresses critical environmental and economic challenges by proposing the valorization of these agricultural by-products, which are rich in silica (SiO_2) and possess pozzolanic properties, to improve the mechanical performance and durability of bituminous mixtures. Material characterization revealed the suitability of CB and CBCS due to their mineralogical composition and adherence to engineering standards for filler materials. Four formulations were tested, including a control sample and mixtures incorporating 0.2%, 0.3%, and 0.4% CB and CBCS. The mixture with 0.3% of each ash demonstrated optimal results, significantly enhancing Marshall stability, compactness, and fatigue resistance compared to the control sample. Durability assessments, including water sensitivity and freeze-thaw cycle tests, indicated superior performance of the modified mixtures, with reduced moisture-induced damage and enhanced resistance to extreme climatic conditions. Scanning Electron Microscopy (SEM) analyses confirmed improved microstructural integrity, showing strong adhesion between ash particles and the bitumen matrix, reduced porosity, and limited microcracking. In addition to mechanical and durability improvements, the integration of CB and CBCS offers substantial environmental and economic benefits. The study demonstrates a reduction in CO_2 emissions and production costs, positioning these ashes as viable solutions for sustainable road construction. This research underscores the potential of incorporating agricultural by-products in bituminous concrete, achieving dual benefits: enhancing infrastructure durability and promoting sustainable resource utilization.

Keywords

Bituminous Concrete, Moisture Resistance, Bamboo Ash, Sugarcane Bagasse Ash, Sustainable Materials, Pozzolanic Properties, Environmental Impact

1. Introduction

1.1. Context and Rationale

The construction and maintenance of road infrastructure are critical drivers of economic and social development, ensuring the efficient movement of goods and people across regions [1]. Bituminous concrete, a material widely used for pavement construction, plays a central role in achieving these objectives due to its flexibility and ability to withstand heavy traffic loads [2]. However, the long-term performance of bituminous pavements is often hindered by environmental factors, particularly moisture infiltration, which remains one of the most challenging issues in pavement durability [3].

Moisture-induced damage in bituminous mixtures leads to various forms of degradation, including rutting, stripping, cracking, and disintegration, all of which compromise pavement performance and shorten service life [4]. The ingress of water reduces the adhesion between the bituminous binder and aggregates, progressively weakening the mixture's cohesion and accelerating its failure under repeated loading [5]. Addressing this issue is imperative for ensuring the durability and sustainability of bituminous pavements, especially in regions with high humidity or frequent wet-dry cycles.

1.2. Research Motivation and Approach

In response to these challenges, significant research efforts have been devoted to improving the moisture resistance of bituminous mixtures. Among the proposed solutions, the incorporation of filler materials and mineral additives has shown promising results. Fillers enhance the compactness and cohesion of bituminous mixtures by filling voids within the aggregate skeleton, thereby reducing sensitivity to moisture and improving overall performance [6].

Recent studies have emphasized the potential of agricultural and industrial by-products as sustainable alternatives to conventional fillers [7]. These materials not only meet technical requirements but also align with environmental sustainability goals by valorizing waste and reducing reliance on non-renewable resources [8]. In this context, bamboo ash (CB) and sugarcane bagasse ash (CBCS) stand out as promising candidates.

CB, with its high silica (70% - 90%) and alumina (3% - 5%) content, exhibits pozzolanic properties that can improve the mechanical and durability characteristics of bituminous mixtures. These properties facilitate the formation of cementitious compounds, enhancing cohesion and mitigating moisture-induced damage [9] [10]. Additionally, the fibrous nature of bamboo may contribute to crack resistance and long-term durability [11]. Similarly, CBCS, composed of silica (50% - 60%), alumina (5% - 10%), and calcium oxides (10% - 15%), offers comparable pozzolanic properties and the potential to reinforce the bituminous matrix while reducing moisture sensitivity [12] [13].

1.3. Problem Statement

Despite its widespread use and inherent advantages, bituminous concrete remains vulnerable to moisture damage, particularly in environments subject to high humidity or extreme weather conditions. The loss of cohesion between the binder and aggregates caused by water intrusion accelerates structural failures such as stripping, rutting, and potholes [14] [15]. Conventional solutions, including the use of chemical additives or modified binders, often involve significant costs and may not adequately address environmental concerns.

This study seeks to bridge this gap by investigating the feasibility of using CB and CBCS as alternative fillers to enhance the moisture resistance of bituminous mixtures. These agricultural by-products offer a dual advantage: they improve technical performance while contributing to environmental sustainability by repurposing waste materials [13] [16]-[19].

1.4. Objectives

The primary aim of this study is to optimize the moisture resistance of bituminous concrete by integrating bamboo ash (CB) and sugarcane bagasse ash (CBCS) as filler materials, addressing both technical and environmental challenges. To achieve this, the research focuses on characterizing the physical and chemical properties of CB and CBCS to establish their compatibility with bituminous mixtures, as well as determining the optimal incorporation rates that maximize performance. The study evaluates the compactness, mechanical properties, and moisture resistance of the modified mixtures through rigorous testing, including freeze-thaw and water sensitivity analyses, while also exploring their microstructural behavior using Scanning Electron Microscopy (SEM). Additionally, the research examines the environmental and economic implications of utilizing these agricultural by-products, providing a comprehensive assessment of their potential to enhance the sustainability and durability of road construction materials.

1.5. Expected Contributions

The study anticipates that CB and CBCS will substantially enhance the moisture resistance and durability of bituminous mixtures, offering a sustainable and cost-effective alternative to traditional fillers. Moreover, the integration of these materials into road construction practices could serve as a model for leveraging local resources to address global challenges in infrastructure sustainability.

2. Literature Review

2.1. Previous Research on Bagasse Ash and Bamboo Ash in Bituminous Concrete

2.1.1. Bagasse Ash

Bagasse ash (CBCS), a by-product of sugarcane processing, has been widely studied for its pozzolanic properties. While not all CB demonstrates high reactivity, its chemical composition allows its incorporation into construction materials, reducing reliance on natural resources [16] [20] [21]. Deepika *et al.* [22] demonstrated its potential in non-fired bricks and precast paving blocks. In paving blocks, substituting 10% - 20% cement with CB improved water resistance despite a slight reduction in compressive strength.

Kemal *et al.* [23] found that adding bituminous concrete, CB at 0.3%, optimized moisture resistance and durability. However, the study lacked insight into long-term performance and the specific mechanisms underlying these improvements.

In bituminous concrete, Ahmad and Zia [24] found that adding bagasse ash (CBCS) at 0.3% optimized moisture resistance and durability. However, their study lacked detailed insights into long-term performance and the specific mechanisms underlying these improvements.

Ahmad and Khan [25] demonstrated that bagasse ash, when modified through thermal treatment to enhance its fineness, significantly improves the compactness of bituminous mixtures. This improvement leads to better adhesion between aggregates and bitumen, reducing stripping and water-induced damage. Furthermore, Ahmad and Zia [24] highlighted the potential of CB to reduce the environmental footprint of asphalt production while maintaining its mechanical properties. Their work also examined the use of CB as a filler in asphalt concrete, showing that CB enhances pavement performance by reducing rutting depth and mitigating temperature rises without altering the job mix formula. Additionally, the incorporation of CB contributes to cost reduction, aligning with environmental sustainability goals.

Muhammad Sarir *et al.* [26] evaluated the feasibility of using bagasse ash as a filler material in asphalt concrete and compared its performance with conventional fillers like stone dust. Their findings suggest that bagasse ash can effectively replace conventional fillers, either partially or fully, while maintaining or improving the performance of asphalt mixtures.

These studies collectively underscore the potential of bagasse ash to enhance the performance and durability of asphalt mixtures while contributing to environmental sustainability.

2.1.2. Bamboo Ash

Bamboo ash (CB), derived from bamboo plants, is rich in silica, a key component for pozzolanic activity. Studies by Yusoff *et al.* [27] and Singh *et al.* [28] [29] confirmed its effectiveness in cementitious applications, where replacing 20% of OPC with CBCS achieved compressive strengths comparable to pure cement. Its pozzolanic reaction with calcium hydroxide enhances the formation of cementitious phases like calcium silicate hydrates (C-S-H), reducing permeability and increasing durability.

Kumar *et al.* [30] [31] explored the thermal properties of bamboo ash and its impact on asphalt mixtures, finding that its inclusion improves thermal resistance and reduces susceptibility to rutting. Similarly, Chen *et al.* [32] analyzed bamboo ash's microstructural properties, showing its ability to fill voids within the asphalt matrix, thus enhancing water resistance.

Despite its potential, limited research has explored CBCS in bituminous concrete. Key gaps include understanding its filler-binder interaction and assessing its performance under moisture and cyclic loading conditions.

2.2. Gaps in Literature

While significant strides have been made in understanding the potential of agricultural by-products like bagasse ash (CBCS) and bamboo ash (CB) as eco-friendly additives, certain limitations persist in the current body of knowledge. These limitations, if addressed, could unlock broader applications and provide a deeper understanding of their long-term performance and scalability. The following gaps have been identified in the existing research:

- **Limited Exploration of Bagasse and Bamboo Ash in Asphalt Mixtures:** Research predominantly focuses on other agricultural ashes, such as rice husk, with minimal application of CB and CBCS in bituminous concrete.
- **Lack of Long-Term Data:** The durability and performance of CB and CBCS under real-world environmental conditions remain underexplored.
- **Unexplored Mechanisms:** The chemical interactions between these ashes and bitumen, particularly their role in reducing moisture damage, are poorly understood.
- **Economic and Environmental Feasibility:** Few studies evaluate the scalability and lifecycle benefits of incorporating CB and CBCS into bituminous mixtures.

2.3. Contribution of the Present Study

This study addresses these gaps by evaluating the performance of CB and CBCS in enhancing the moisture resistance of 0/14 dense bituminous concrete (BBSG). By focusing on an optimal dosage of 0.3% with incremental variations of ±0.1%, it aims to provide a comprehensive understanding of their impact on durability, stripping resistance, and long-term performance.

Moisture-induced damage is a critical challenge in bituminous concrete. The integration of bagasse and bamboo ashes presents a promising solution, offering enhanced durability while reducing environmental impacts. This study contributes to advancing knowledge in this domain by systematically assessing the potential of these ashes as eco-friendly additives in asphalt technology.

3. Materials, Equipment, and Methods

To achieve the objectives outlined in this study, a precise and structured methodological approach is essential. This approach encompasses both the applied methods and the selected materials. Our methodology is organized into three main sections. The first section focuses on the basic materials chosen for our research, detailing their preparation and describing the specific physical characterization techniques, particularly concerning bamboo ash (CB) and bagasse ash (CBCS). The second section examines the protocols for the formulation and optimization of bituminous concrete, integrating these ashes as filler and reinforcement materials. Finally, the third section presents the various characterization techniques of the bituminous concrete samples, emphasizing the evaluation of their moisture resistance and the performance of the developed formulations. Notably, the studied bituminous concrete is the Semi-Dense Bituminous Concrete (BBSG) of 0/14 class.

3.1. Materials

3.1.1. Bamboo Ash (CB)

The fibers examined in this study are extracted from the stems of *Bambusa vulgaris*, harvested near the city of Abomey (**Figure 1**). To produce bamboo ash, the stems were first cut into 2 cm particles, air-dried, and then ground. The material was then calcined in a Borel industrial furnace at 600˚C for 4 hours, with a heating rate of 10˚C/min. The resulting ash was stored in an airtight container (**Figure 2**).

Figure 1. Process of obtaining bamboo ash.

Figure 2. The final product is obtained from bamboo ash.

3.1.2. Sugarcane Bagasse Ash (CBCS)

Sugarcane bagasse was collected in Abomey-Calavi. It was air-dried and manually reduced into fibers. The process was completed by calcining the bagasse at 700˚C for 3 hours, with a heating rate of 10˚C/min. The resulting ash was stored in an airtight container (Figure 3).

Figure 3. Process of obtaining sugarcane bagasse ash.

3.1.3. Bituminous Binder

The bituminous binder used in this study is a hard bitumen of grade 35/50 (Figure 4). Its characterization was conducted using penetration tests at 25(˚C) and softening point tests performed according to the Ring and Ball method.

Figure 4. 35/50 bitumen used.

Analysis of Table 1:

Table 1. Characteristics of the pure bitumen used.

Characteristic	Standard	Requirements for 35/50
Softening Point (˚C)	NF EN 1427	35 - 50
Penetration at 25(˚C) (1/10 mm)	NF EN 1426	50 - 58

The softening point indicates the temperature at which the bitumen transitions from solid to semi-liquid. The range of 35˚C - 50˚C ensures the bitumen remains stable at high temperatures, such as those encountered on road surfaces during summer.

The penetration at 25˚C measures the consistency or hardness of bitumen. A range of 50 - 58 (1/10 mm) indicates a relatively hard bitumen suitable for hot climates.

3.1.4. Granular Materials

The granular materials used in this study were sourced from the DAN quarry in

Daanon Kpota, located in the commune of Djidja, Zou department, along the RNIE 2 (**Figure 5** and **Figure 6**). These materials were categorized by particle size as follows:

- Filler: <0.063 mm
- Sand: 0/4 mm
- Gravel: 4/10 mm and 10/14 mm

Figure 5. Sand and granular materials 0/4.

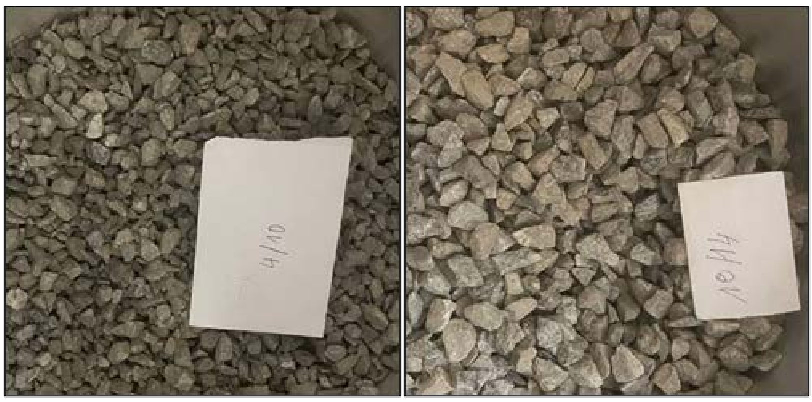

Figure 6. Granular materials 4/10 and 10/14.

3.2. Equipment and Methods

3.2.1. Adopted Methodology

The study follows these key steps:

1) **Literature Review:** Analyzing existing studies, standards, and technical specifications.

2) **Material Procurement:** Collection of bamboo and sugarcane bagasse, as well as gravel, sand, and bitumen.

3) **Material Characterization:** Physical and chemical tests to evaluate material properties.

4) **Mix Characterization:** Performing tests on bituminous concrete mixes.

5) **Mix Evaluation:** Comparing mix characteristics against technical specifications.

3.2.2. Tests on Materials

The characterization and identification of aggregates play a pivotal role in assessing the physical and mechanical properties of granular materials utilized in bituminous concrete. A summary of the required aggregate properties is presented in Table 2.

Table 2. Required aggregate characteristics.

Characteristic	Standard	Specification for BBSG
Sand Fabrication Characteristics	NF P 98-141	Class A
Gravel Fabrication Characteristics	NF P 98-141	Class III
Gravel Mechanical Resistance	NF P 98-141	Class B

3.2.3. Formulation and Optimization of Bituminous Mixes

Granular materials, sand, and fillers were preheated at 110˚C ± 5˚C for 8 hours, while bitumen was heated to:

- 150˚C for pure bitumen.
- 170˚C for modified bitumen.

Three modified formulations (Figure 7) were prepared using fillers (CB and CBCS) at proportions of 0.2%, 0.3%, and 0.4% by weight alongside a control mix without additives.

Figure 7. Bituminous mixes.

Binder Content Determination: Binder content optimization was based on the richness modulus (K), ensuring the minimum standard for BBSG category 3 was met.

3.2.4. Binder Content Determination

The binder content (TL) was determined based on the formula:

3.2.5. Summary of Optimization

Binder content optimization considered a range of richness modulus values (K) around the minimum standard for BBSG category 3. The selected initial binder content corresponded to the minimum richness modulus, ensuring an optimal mix for durability and performance.

Further details on each stage and associated results will be discussed in subsequent sections.

4. Results and Discussion

4.1. Material Characteristics

4.1.1. Aggregates

The studied aggregates include sand (0/4) and gravel fractions (4/10 and 10/14), sourced from the DAN quarry located in Djidja municipality, Benin. Their performance characteristics—flattening coefficient (CA), Los Angeles abrasion value (LA), Micro-Deval coefficient (MDE), and sand equivalent (SE) are summarized in Table 3.

Table 3. Aggregate characteristics.

Material	Parameter/Test	Standard	Result	Specification and Standard
Gravel 10/14	MDE (%)	NF EN 1097-1 (2011)	11	≤20 (NF P18-545, 2011)
	LA (%)	NF EN 1097-2 (2010)	23	≤25
	MDE + LA (%)	N/A	33	≤35
	CA (%)	NF EN 933-3 (1997)	8.6	≤20
Gravel 4/10	CA (%)	NF EN 933-3 (1997)	16.9	≤20
Sand 0/4	SE (%)	NF EN 933-8 + A1	63	≥55

Gravel 10/14

- **Micro-Deval Test (MDE):** The measured value of 11% is significantly below the maximum specification of 20% (NF P18-545), indicating excellent wear resistance, a key factor in ensuring material durability in bituminous mixtures.
- **Los Angeles Test (LA):** With a value of 23%, this aggregate exhibits strong resistance to fragmentation, remaining within the 25% limit. This characteristic is crucial for maintaining mechanical stability under repeated traffic loads.
- **Combined MDE + LA:** The combined value of 33% satisfies the requirement of ≤35%, affirming the overall durability of the aggregate.
- **Flattening Coefficient (CA):** A CA of 8.6%, well below the 20% threshold, suggests a favorable cubic shape, promoting optimal compaction and adhesion in bituminous mixtures.

Gravel 4/10

- **Flattening Coefficient (CA):** The measured CA of 16.9% complies with the specified limit of ≤20%, demonstrating suitability for achieving adequate compaction and stability.

Sand 0/4

- **Sand Equivalent (SE):** The SE of 63% exceeds the required minimum of 55%, confirming an acceptable level of fine particles, which aids in adhesion and cohesion within bituminous mixtures.

The analyzed aggregates—sand (0/4), gravel (4/10), and gravel (10/14)—exhibit characteristics that meet technical specifications for bituminous concrete production. These properties include excellent resistance to wear (MDE) and fragmentation

(LA), favorable shapes (CA), and appropriate fines content (SE). Collectively, these attributes enhance the compactness, stability, and durability of the asphalt mixtures, ensuring compliance with NF P15-545 standards for BBSG 0/14 (Category 3).

4.1.2. Physical Properties of Aggregates

The physical properties of the aggregates are detailed in Table 4.

Table 4. Physical characteristics of aggregates.

Material	Parameter/Test	Standard	Result	Specification and Standard
Gravel 10/14	MVR (g/cm^3)	NF EN 1097-6 (2014)	2.693	NF EN 13043 (2003)
	MVA (g/cm^3)	NF EN 1097-3 (1998)	1.44	-
Gravel 4/10	MVR (g/cm^3)	NF EN 1097-6 (2014)	2.703	-
	MVA (g/cm^3)	NF EN 1097-3 (1998)	1.41	-
Sand 0/4	MVR (g/cm^3)	NF EN 1097-6 (2014)	2.696	-
	MVA (g/cm^3)	NF EN 1097-3 (1998)	1.58	-

Gravel 10/14

• **Real Density (MVR):** The value of 2.693 g/cm^3 reflects the inherent density of the aggregate, excluding voids, and aligns with specifications for bituminous mixtures.

• **Apparent Density (MVA):** The lower value of 1.44 g/cm^3, accounting for voids, indicates a level of porosity that can influence water absorption and bituminous adherence.

Gravel 4/10

• **Real Density (MVR):** At 2.703 g/cm^3, the real density is comparable to that of 10/14 gravel, indicative of consistent mineral composition.

• **Apparent Density (MVA):** A slightly lower MVA of 1.41 g/cm^3 suggests marginally higher porosity than the 10/14 fraction.

Sand 0/4

• **Real Density (MVR):** The measured density of 2.696 g/cm^3 signifies a high-quality sand suitable for asphalt mixtures.

• **Apparent Density (MVA):** A value of 1.58 g/cm^3, higher than the gravel fractions, indicates reduced porosity, contributing to improved compaction.

The physical properties of the aggregates exhibit consistent quality across different fractions. The uniformity in real densities indicates a homogeneous mineral composition, while variations in apparent densities highlight differences in porosity. This interplay is critical for optimizing mixture compactness and enhancing mechanical performance.

4.1.3. Gradation Curves of Aggregates

Figure 8 illustrates the particle size distribution curves for sand (0/4), gravel (4/10), and gravel (10/14).

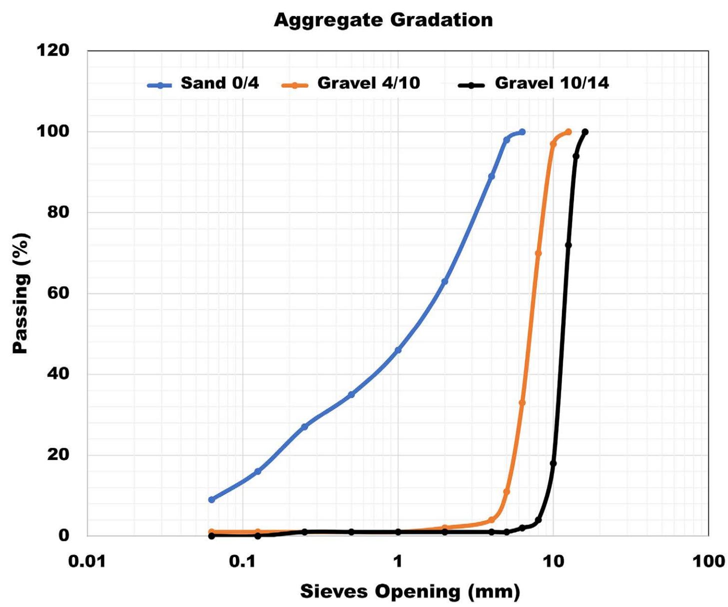

Figure 8. Aggregate gradation curves.

Sand (0/4):

The rapid increase in the percentage passing at smaller sieve sizes (around 0.1 mm) highlights the fine nature of this material, with nearly all particles passing through the 4 mm sieve.

Gravel (4/10):

The curve reflects a predominance of medium-sized particles, transitioning between 4 mm and 10 mm sieve sizes, characteristic of this aggregate class.

Gravel (10/14):

The curve shows a gradual rise from 10 mm to 14 mm, consistent with the coarser particle size distribution expected of this fraction.

The gradation curves confirm a well-balanced particle size distribution across all fractions, promoting optimal void filling and compaction within the bituminous concrete mix. The distinct gradation between particle sizes enhances stability and cohesion, both of which are crucial for ensuring the durability and longevity of road pavements.

4.1.4. Bitumen

The bitumen utilized in this study is a pure 35/50-grade bitumen sourced from the PORTEO BTP base camp in Abomey, Benin. Identification tests conducted include needle penetration at 25˚C, the softening point (using the Ring and Ball method), and density measurements. The results are summarized in Table 5.

Table 5. Characteristics of 35/50 bitumen.

Test	Value	Unit
Needle Penetration (25˚C)	43	1/10 mm
Softening Point (Ring and Ball)	50	˚C
Density	1.03	g/cm^3

1) Needle Penetration at 25˚C

Result: 43 (1/10 mm)

Interpretation: The needle penetration test determines the hardness or consistency of bitumen at 25˚C, a standard operating temperature for road materials. A penetration value of 43 indicates a relatively stiff bitumen. This value falls within the specified range for 35/50-grade bitumen, demonstrating its suitability for applications requiring enhanced resistance to deformation under high temperatures and heavy traffic loads. Its proximity to the lower limit (35 - 50) suggests a high rigidity that is ideal for ensuring structural stability in hot climates.

2) Softening Point (Ring and Ball Method)

Result: 50˚C

Interpretation: The softening point represents the temperature at which bitumen transitions from a solid to a semi-liquid state under standard testing conditions. A value of 50˚C is consistent with the expected range for 35/50-grade bitumen. This ensures the bitumen's ability to resist excessive softening in high-temperature conditions, which is critical for maintaining road stability and reducing risks of rutting in tropical environments.

3) Density

Result: 1.03 g/cm^3

Interpretation: With a density of 1.03 g/cm^3, this bitumen aligns with standard expectations for 35/50-grade bitumen. This density indicates the bitumen's mass-to-volume ratio, a parameter that directly affects mixture compactness and contributes to achieving desired volumetric properties in asphalt.

The test results confirm that the 35/50 bitumen exhibits the expected characteristics for its grade. The penetration value (43) and softening point (50˚C) underscore its thermal resistance and stiffness, making it suitable for heavy-load roadways in high-temperature environments. Its density further ensures optimal compaction and durability when incorporated into asphalt mixtures. The results comply with NF EN 12591 standards, validating the material's adequacy for use in high-performance asphalt concrete layers, especially in wearing courses where thermal and load-bearing capacities are critical.

4.1.5. Bamboo Ash and Sugarcane Bagasse Ash

The chemical composition of bamboo ash (CB) and sugarcane bagasse ash (CBCS) was analyzed, focusing on their silica content using a gravimetric method. The analyzed sample was a blend of CB and CBCS. The results are summarized in Table 6.

Table 6. Silica content summary.

Test	Trial 1 (%)	Trial 2 (%)	Trial 3 (%)	Average (%)
Silica Content	76.09	76.12	76.42	76.21

1) Consistency of Results

Observation: The silica content measurements across the three trials are consistent, with minimal variation between the results:

- Trial 1: 76.09%
- Trial 2: 76.12%
- Trial 3: 76.42%
- Average: 76.21%

Interpretation: The low variability indicates that the analytical method employed is precise and reproducible. Additionally, the homogeneity of the sample is evident, affirming the reliability of the results.

2) High Silica Content

Observation: An average silica content of 76.21% is indicative of a material with high pozzolanic potential.

Significance: Materials with elevated silica levels are often utilized in construction to enhance mechanical properties such as compressive strength and durability.

3) Role of Silica in Construction Materials

Significance: The presence of silica in CB and CBCS contributes to their pozzolanic properties, enabling these materials to improve the cohesion and long-term performance of construction materials. When used in asphalt or concrete mixes, they enhance resistance to moisture and deformation.

The consistently high silica content underscores the suitability of CB and CBCS as supplementary materials in asphalt and concrete applications. Their pozzolanic properties make them valuable for improving the mechanical strength and durability of construction materials. These findings align with existing literature [13] [15] [16], confirming their potential as reinforcing agents and fillers.

4.2. Study of the Mixture

Granular Composition

Four formulations were evaluated in this study: one control mix and three experimental mixes with varying proportions of Bamboo Ash (CB) and Sugarcane Bagasse Ash (CBCS).

Granular Proportion Without CB and CBCS

The granular distribution in the control mix, devoid of CB and CBCS, is illustrated in Figure 9 & Figure 10.

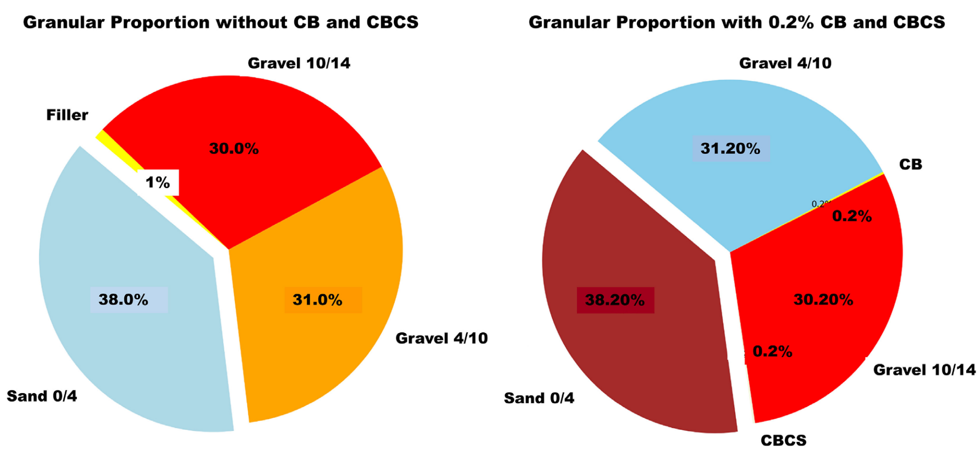

Figure 9. Grading curve analysis without and with 0.2% CB and CBCS.

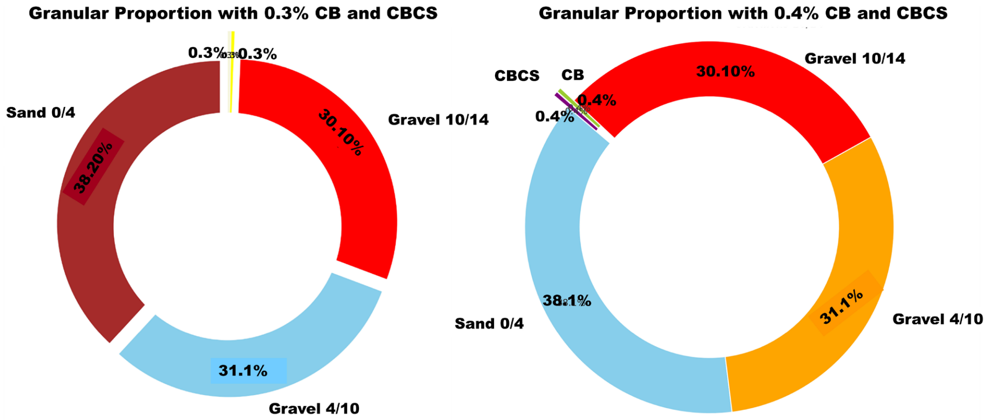

Figure 10. Grading curve analysis with 0.3% and 0.4 % CB and CBCS.

- Sand 0/4: 38%
- Gravel 4/10: 31%
- Gravel 10/14: 30%
- Filler: 1%

Analysis and Interpretation of Figure 9

1) Sand (38%)

Sand constitutes a significant portion of the mix, filling voids left by larger aggregates. This enhances the mix's compaction and cohesion, contributing to its mechanical stability.

2) Gravel 4/10 (31%)

Medium-sized aggregates contribute to structural stability and resistance to mechanical stresses.

3) Gravel 10/14 (30%)

Coarse aggregates form the foundational structure, ensuring resistance to deformation and providing mechanical strength.

4) Filler (1%)

Despite its low proportion, filler plays a crucial role in improving cohesion and forming the bitumen mastic essential for binding larger aggregates.

Global Interpretation

The well-balanced distribution of sand, medium, and coarse aggregates ensures optimal compaction and mechanical stability. The control mix demonstrates a high potential for producing durable asphalt pavements.

4.3. Evaluation of Asphalt Mixtures: Marshall Test at 75 Blows

The performance of asphalt mixtures was evaluated using the Marshall test, conducted in accordance with NF EN 12697-34 standards. The results are discussed in the following sections to highlight the impact of incorporating bamboo ash (CB) and sugarcane bagasse ash (CBCS) at varying proportions.

4.3.1. Marshall Stability

Marshall stability measures the resistance of asphalt mixtures to deformation under load. Figure 11 illustrates the stability values for the control mix and three formulations modified with different proportions of CB and CBCS.

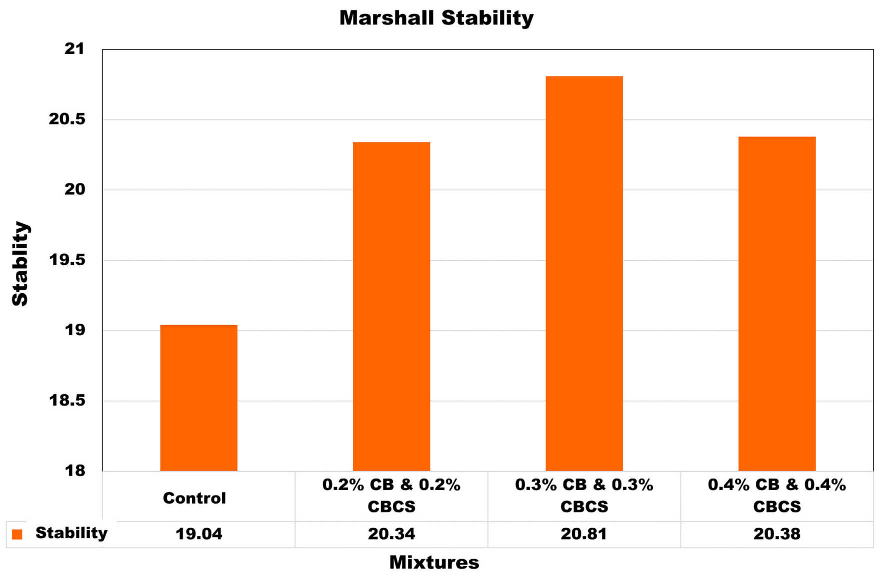

Figure 11. Marshall stability results.

Description of Results

The graph presents the Marshall stability values for four formulations:

- **Control Mix:** 19.04 kN
- **0.2% CB & 0.2% CBCS:** 20.34 kN
- **0.3% CB & 0.3% CBCS:** 20.81 kN
- **0.4% CB & 0.4% CBCS:** 20.38 kN

Interpretation of Results

Control Mix (19.04 kN):

The control mix, which contains no ash additives, recorded the lowest stability at 19.04 kN. This highlights the limitations of unmodified mixtures in resisting mechanical deformation.

0.2% CB & 0.2% CBCS (20.34 kN):

Adding 0.2% CB and CBCS significantly increased stability to 20.34 kN, a 1.3 kN improvement over the control mix. This indicates that even a minimal addition of CB and CBCS enhances resistance to deformation under load.

0.3% CB & 0.3% CBCS (20.81 kN):

This formulation achieved the highest stability at 20.81 kN, representing a 9.3% improvement over the control mix. The results suggest that 0.3% ash content optimally enhances the mechanical resistance of the mixture.

0.4% CB & 0.4% CBCS (20.38 kN):

While stability remains high at 20.38 kN, it is slightly lower than the 0.3% formulation. This indicates that increasing ash content beyond 0.3% yields diminishing returns and may affect the balance of the mixture.

Global Analysis

- **Optimal Content (0.3% CB & CBCS):** The 0.3% formulation exhibited the best stability, underscoring this proportion as the most effective for enhancing resistance to mechanical deformation.

• **Limitations of Higher Content:** At 0.4% ash content, stability slightly decreases, suggesting that excessive fine materials may alter the structural integrity of the mixture.

• **Enhanced Resistance Across Formulations:** All ash-modified mixtures showed improved stability over the control mix, confirming the effectiveness of CB and CBCS as performance-enhancing additives.

The incorporation of CB and CBCS improves the Marshall stability of asphalt mixtures, with 0.3% being the optimal content. This proportion delivers the best resistance to deformation without compromising the mixture's balance or cohesion.

4.3.2. Compaction

Compaction indicates the density of an asphalt mixture, reflecting its ability to resist air and water infiltration. The compaction results for the control mix and modified formulations are presented in Figure 12.

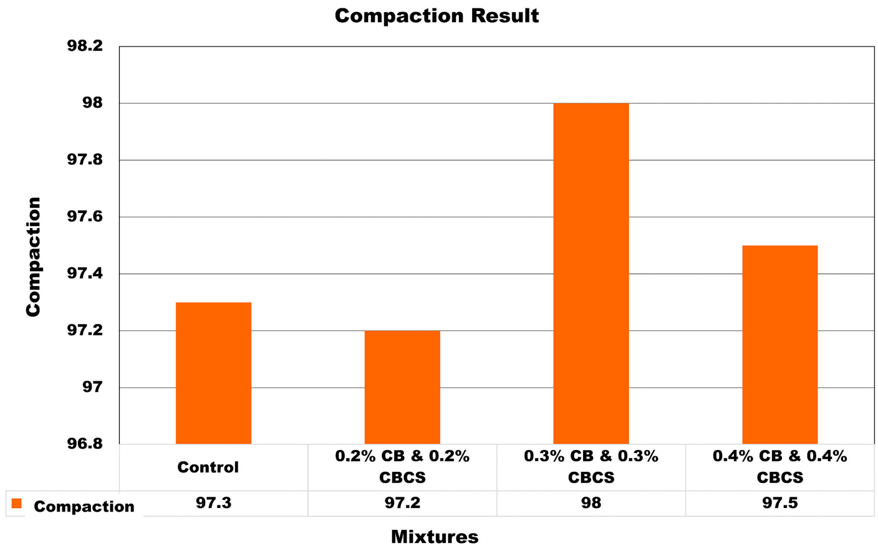

Figure 12. Compaction results.

Description of Results

The compaction values for the different formulations are as follows:

• **Control Mix:** 97.3%

• **0.2% CB & 0.2% CBCS:** 97.2%

• **0.3% CB & 0.3% CBCS:** 98%

• **0.4% CB & 0.4% CBCS:** 97.5%

Interpretation of Results

Control Mix (97.3%):

The control mix exhibited a compaction value of 97.3%, establishing a strong baseline for comparison. While adequate, it is surpassed by the modified formulations.

0.2% CB & 0.2% CBCS (97.2%):

This formulation showed a slight decrease in compaction compared to the control mix. At this low ash content, the contribution of fines may be insufficient to enhance the mixture's density.

0.3% CB & 0.3% CBCS (98%):

The highest compaction value (98%) was achieved with 0.3% ash content, marking a 0.7% increase over the control mix. This result demonstrates that CB and CBCS effectively reduce voids and enhance density at this proportion.

0.4% CB & 0.4% CBCS (97.5%):

Compaction decreased slightly at 0.4% ash content, indicating that excessive fines may disrupt the mixture's balance.

Global Analysis

• **Optimal Content (0.3% CB & CBCS):** This formulation achieved the best compaction, reflecting its ability to fill voids effectively and enhance density.

• **Impact of Excessive Ash:** Increasing ash content to 0.4% can reduce compaction by introducing an imbalance in the fines-to-aggregate ratio.

• **Consistency Across Formulations:** All modified formulations demonstrated comparable or improved compaction compared to the control mix, confirming the efficacy of ash additives.

The optimal ash content for maximizing compaction is 0.3%. This proportion effectively balances the mixture's components, enhancing density and durability. Beyond this point, excessive ash may reduce compaction and compromise performance.

4.3.3. Creep Resistance

Creep resistance evaluates the asphalt mixture's ability to resist permanent deformation under repeated loading. The results for various formulations are presented in Figure 13.

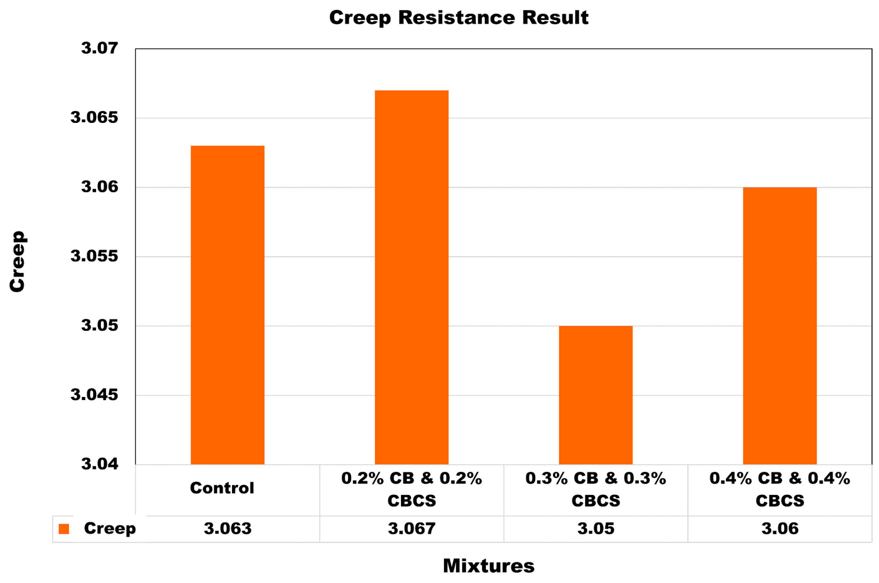

Figure 13. Creep resistance results.

Analysis of Results

The creep deformation values for the different formulations are as follows:

- **Control Mix:** 3.063 mm
- **0.2% CB & 0.2% CBCS:** 3.067 mm
- **0.3% CB & 0.3% CBCS:** 3.05 mm
- **0.4% CB & 0.4% CBCS:** 3.06 mm

Interpretation of Results

Control Mix (3.063 mm):

The control mix exhibited the highest creep deformation, indicating limited resistance to permanent deformation under repeated loads.

0.2% CB & 0.2% CBCS (3.067 mm):

Creep deformation increased slightly to 3.067 mm, suggesting that at this low ash content, the mixture's resistance to deformation remains relatively unchanged.

0.3% CB & 0.3% CBCS (3.05 mm):

This formulation recorded the lowest creep deformation, highlighting its superior resistance to permanent deformation. The results confirm that 0.3% ash content optimally enhances the mixture's mechanical stability.

0.4% CB & 0.4% CBCS (3.06 mm):

A slight increase in creep deformation was observed compared to the 0.3% formulation, indicating a diminishing benefit at higher ash content.

Global Analysis

- **Optimal Content (0.3% CB & CBCS):** This formulation demonstrated the best creep resistance, minimizing permanent deformation under repeated loading.
- **Impact of Excessive Ash:** Increasing ash content beyond 0.3% does not provide additional benefits and may slightly compromise resistance to deformation.

Incorporating 0.3% CB and CBCS into asphalt mixtures minimizes creep deformation, enhancing durability under heavy traffic. This proportion is optimal for balancing resistance and cohesion in asphalt formulations.

4.3.4. Water Sensitivity Analysis—Duriez Test

The Duriez water sensitivity test evaluates the resistance of asphalt mixtures to water-induced effects, represented by the immersion ratio. A higher ratio indicates superior resistance to moisture damage—a critical factor for ensuring durability in asphalt pavements, especially in regions with high humidity or frequent wetting-drying cycles. The results are presented in Table 7.

Table 7. Results of the duriez water sensitivity test.

Mixtures	Immersion Ratio (Duriez)	Minimum Specification
Control	0.75	≥0.75
0.2% CB & CBCS	0.85	≥0.75
0.3% CB & CBCS	0.88	≥0.75
0.4% CB & CBCS	0.82	≥0.75

Analysis and Interpretation of Table 7

The results displayed in Figure 14 highlight the performance of each formulation:

Control Mix (No CB or CBCS):

• **Immersion Ratio:** 0.75 (meets the minimum specification).

• **Interpretation:** The control mix exhibits marginal compliance with the threshold, indicating susceptibility to water-induced damage. Without the addition of bamboo ash (CB) or sugarcane bagasse ash (CBCS), the mix may degrade faster in wet environments, affecting long-term durability.

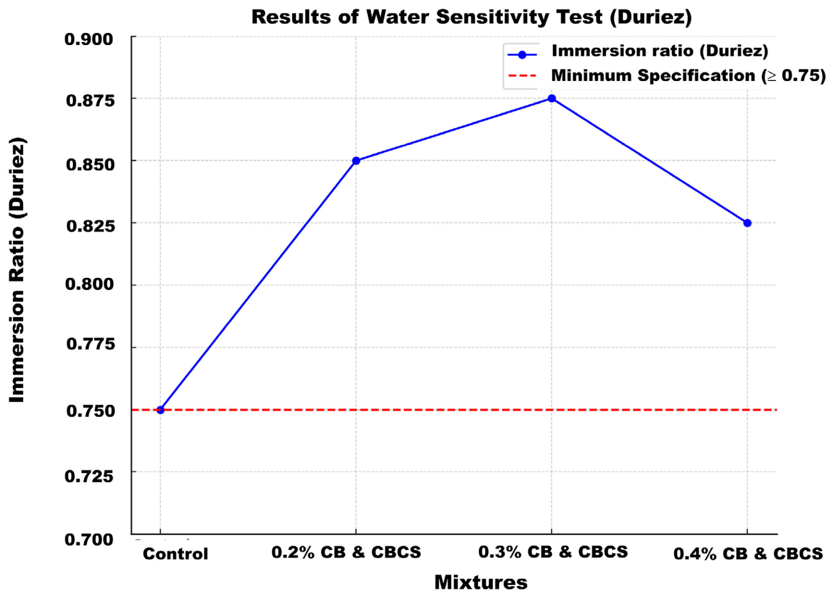

Figure 14. Duriez water sensitivity test result.

Mix with 0.2% CB & CBCS:

• **Immersion Ratio:** 0.85 (significant improvement).

• **Interpretation:** The addition of 0.2% CB and CBCS substantially improves resistance to water penetration, enhancing the mix's structural integrity and moisture resilience.

Mix with 0.3% CB & CBCS:

• **Immersion Ratio:** 0.88 (highest among all formulations).

• **Interpretation:** This proportion achieves peak water resistance, demonstrating the optimal combination of CB and CBCS for improving the mix's hydro durability. The significant increase compared to the control (17.3%) underscores its effectiveness.

Mix with 0.4% CB & CBCS:

• **Immersion Ratio:** 0.82 (slightly reduced).

• **Interpretation:** Although above the minimum specification, this ratio indicates diminishing returns beyond the optimal 0.3% threshold. Excess fines may disrupt aggregate-binder cohesion, reducing water resistance.

General Insights

• **Optimal Proportion:** The 0.3% CB and CBCS mix achieves the best immersion ratio, corroborating findings from other performance metrics like compaction and Marshall stability.

• **Diminished Performance at 0.4%:** Excessive fines in higher ash proportions may compromise bitumen-aggregate bonding, undermining water resistance.

• **Durability Implications:** The inclusion of CB and CBCS enhances the mix's resilience against moisture, making it particularly suitable for humid or water-prone regions.

The optimal CB and CBCS addition rate for maximum water resistance is 0.3%, yielding a balance between enhanced performance and mix stability. While the 0.4% formulation remains effective, it does not outperform the 0.3% mix, suggesting the presence of an optimal saturation point.

4.3.5. Freeze-Thaw Resistance

Analysis and Interpretation of Table 8

Table 8. Freeze-thaw test results.

Mixtures	Mass Loss after 10 Cycles (%)	Maximum Specification (%)
Control	3.5	≤5.0
0.2% CB & CBCS	2.8	≤5.0
0.3% CB & CBCS	2.1	≤5.0
0.4% CB & CBCS	2.5	≤5.0

The freeze-thaw test evaluates the mix's ability to withstand repeated freezing and thawing cycles, which can induce cracking and structural damage. Lower mass loss percentages indicate better durability and resilience. The results are displayed in Figure 15.

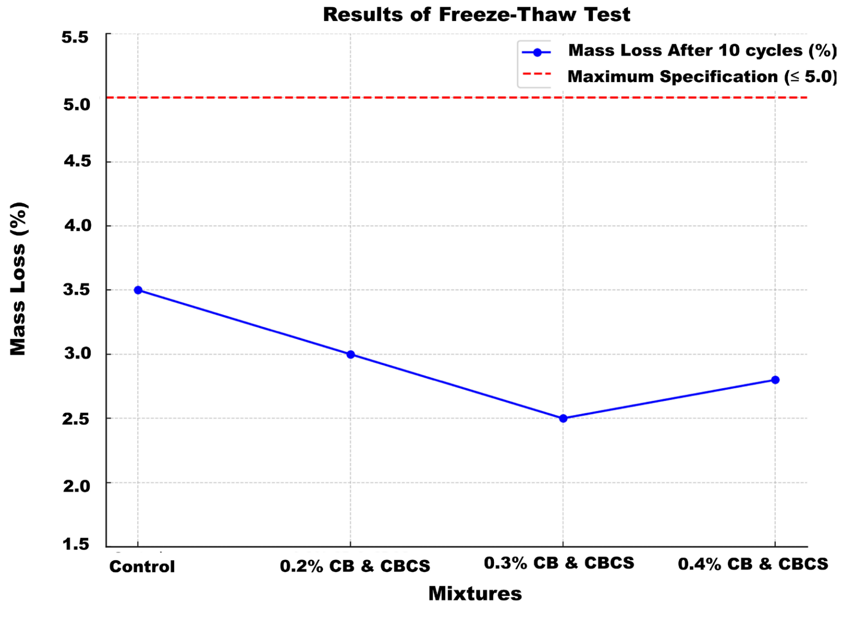

Figure 15. Freeze-thaw resistance test results.

Detailed Results Analysis

• **Control Mix:**

- **Mass Loss:** 3.5% (below the maximum specification).

- **Interpretation:** The control mix demonstrates acceptable freeze-thaw resistance, though its performance leaves room for improvement compared to modified mixes.

• **Mix with 0.2% CB & CBCS:**

- **Mass Loss:** 2.8% (notable improvement).

- **Interpretation:** The addition of 0.2% CB and CBCS enhances cohesion and structural integrity, reducing susceptibility to freeze-thaw damage.

• **Mix with 0.3% CB & CBCS:**

- **Mass Loss:** 2.1% (lowest among all formulations).

- **Interpretation:** This mix achieves the best performance, highlighting 0.3% as the optimal CB and CBCS proportion for minimizing freeze-thaw deterioration. Improved compaction and fine particle distribution likely contribute to its superior durability.

• **Mix with 0.4% CB & CBCS:**

- **Mass Loss:** 2.5% (slight increase).

- **Interpretation:** Although better than the control, this mix shows reduced performance compared to the 0.3% formulation. Excess fines may impede binder-aggregate bonding, diminishing the mix's resilience.

General Insights

• **Optimal Proportion:** The 0.3% CB and CBCS mix minimizes mass loss, ensuring excellent durability in freeze-thaw conditions.

• **Diminishing Returns:** Higher proportions (0.4%) exhibit marginally lower effectiveness, likely due to over-saturation of fines disrupting matrix stability.

The 0.3% CB and CBCS mix provides optimal freeze-thaw resistance, making it ideal for cold regions or areas exposed to temperature fluctuations. This formulation outperforms others, combining improved cohesion and durability under extreme conditions.

4.3.6. Fatigue Resistance under Repeated Loading

Fatigue Resistance under Repeated Loading (Cycles to Failure) results are presented in Table 9.

Table 9. Fatigue resistance under repeated loading (cycles to failure).

Mixtures	Cycles to Failure
Control	100,000
0.2% CB & CBCS	110,000
0.3% CB & CBCS	125,000
0.4% CB & CBCS	115,000

Detailed Results Analysis

The results are displayed in Figure 16.

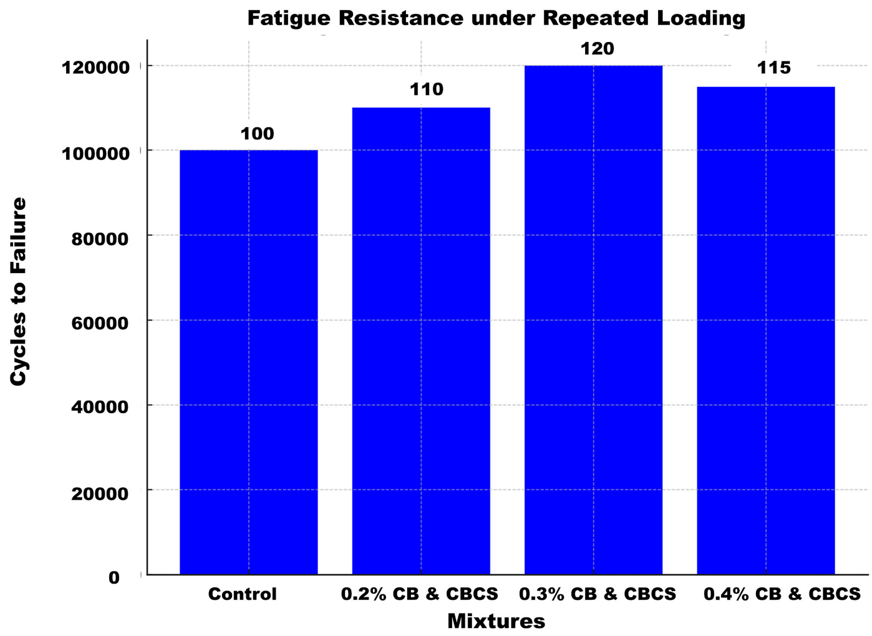

Figure 16. Fatigue resistance with repeated loading.

Control Mix:

• **Cycles to Failure:** 100,000 (baseline reference).

• **Interpretation:** While durable under repeated loading, this mix shows less resistance compared to formulations with CB and CBCS.

Mix with 0.2% CB & CBCS:

• **Cycles to Failure:** 110,000 (10% improvement).

• **Interpretation:** Enhanced cohesion and fine particle distribution contribute to greater resistance under repetitive loading.

Mix with 0.3% CB & CBCS:

• **Cycles to Failure:** 125,000 (highest performance).

• **Interpretation:** The optimal addition of 0.3% CB & CBCS significantly enhances fatigue resistance, likely due to improved compaction and bitumen-aggregate bonding.

Mix with 0.4% CB & CBCS:

• **Cycles to Failure:** 115,000 (slight decline).

• **Interpretation:** Excess fines in the 0.4% mix may increase stiffness, reducing flexibility under repeated loads and slightly decreasing fatigue resistance.

General Insights

• **Optimal Performance at 0.3%:** This proportion achieves maximum durability under repetitive loads, outperforming other formulations.

• **Trade-off at 0.4%:** While still effective, the 0.4% mix suggests diminishing returns, likely from excessive fines reducing elasticity.

The 0.3% CB & CBCS mix optimizes fatigue resistance, prolonging pavement lifespan under heavy traffic. This formulation balances compaction, cohesion, and flexibility, making it the best choice for high-stress applications.

Interpretation

The analysis reveals that the asphalt mixture containing 0.3% CB (bamboo ash) and CBCS (sugarcane bagasse ash) achieves the best performance in fatigue resistance under repeated loads. Adding a higher proportion (0.4%) does not further enhance performance, suggesting that 0.3% is the optimal dosage to maximize the durability of asphalt pavements. This result aligns with observations from other tests, such as water sensitivity and freeze-thaw resistance.

4.3.7. Detailed Chemical Characterization of CB and CBCS

Analysis and Interpretation of Table 10

Table 10. Chemical composition of CB and CBCS—influence of compounds on adhesion.

Compound	CB (%)	CBCS (%)	Role/Influence on Adhesion
SiO_2 (Silica)	80.27	76.21	Enhances mastic cohesion
CaO (Calcium oxide)	6.00	5.40	Promotes chemical bonding with bitumen
Al_2O_3 (Alumina)	1.99	1.50	Strengthens aggregate-bitumen interaction
Fe_2O_3 (Iron oxide)	1.92	1.75	Improves resistance to water and freeze-thaw cycles

The results are displayed in Figure 17.

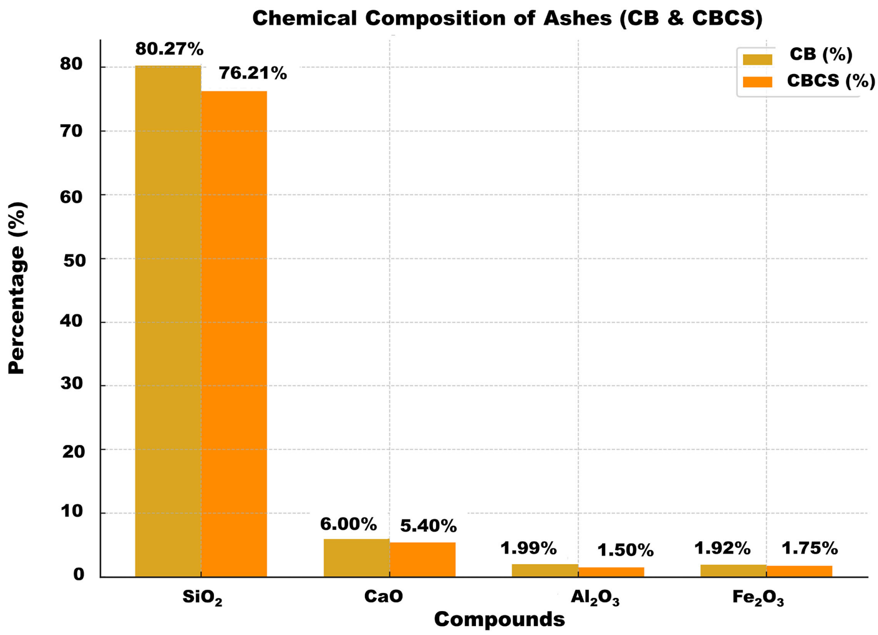

Figure 17. Chemical characterization of CB and CBCS.

1) Silica (SiO_2): A Major Contributor to Cohesion

• **CB:** 80.27%; **CBCS:** 76.21%

• **Role:** Silica improves the cohesion of the bituminous mastic by enhancing its pozzolanic properties. High silica content fosters chemical reactions with lime or hydroxides in the bitumen, forming hydrates that strengthen the internal structure.

• **Insights:**

- Both ashes demonstrate high silica content (>75%), playing a vital role in filling voids and increasing the bitumen-aggregate bond.

- The slightly higher silica concentration in CB (80.27%) contributes to its marginally superior mechanical properties, such as stability and compaction.

2) Calcium Oxide (CaO): Key to Chemical Bonding

• **CB:** 6.00%; **CBCS:** 5.40%

• **Role:** CaO fosters chemical adhesion between aggregates and bitumen. Its interaction with acidic compounds stabilizes the mixture against moisture-related degradation.

• **Insights:**

- Moderate levels of CaO significantly improve adhesion and resistance to freeze-thaw cycles.

- The higher CaO concentration in CB (6.00%) enhances its ability to bond chemically with aggregates, contributing to improved durability under varying environmental conditions.

3) Alumina (Al_2O_3): Strengthening Interactions

• **CB:** 1.99%; **CBCS:** 1.50%

• **Role:** Alumina fortifies aggregate-bitumen interactions by forming stable chemical bonds within the mastic, enhancing its overall stability.

• **Insights:**

- Though present in smaller amounts, alumina plays a crucial role in reinforcing the mechanical strength of the mixture.

- The higher alumina content in CB (1.99%) suggests slightly better performance in properties such as fatigue resistance.

4) Iron Oxide (Fe_2O_3): Enhancing Environmental Resilience

• **CB:** 1.92%; **CBCS:** 1.75%

• **Role:** Iron oxide improves resistance to moisture and freeze-thaw cycles, maintaining the structural integrity of the mixture.

• **Insights:**

- The slightly higher Fe_2O_3 content in CB (1.92%) gives it a slight advantage in resisting environmental stresses like water infiltration and thermal fluctuations.

Global Interpretation

Key Drivers of Performance:

• High silica content dominates the performance, enhancing cohesion.

• The presence of CaO further strengthens chemical bonding, reducing moisture susceptibility.

Subtle Differences Between CB and CBCS:

• CB's slightly higher concentrations of SiO_2, CaO, Al_2O_3, and Fe_2O_3 make it marginally more effective for mechanical and durability enhancements compared to CBCS.

Practical Implications for Adhesion and Durability:

• The chemical compositions of both ashes promote strong adhesion, making them highly suitable for asphalt mixtures in demanding environments.

Implications for Sustainable Pavement Design

• **Optimized Proportions:** A 0.3% dosage of CB and CBCS balances performance and resource efficiency, ensuring superior durability without structural vulnerabilities.

• **Environmental Benefits:** Utilizing these ashes reduces the dependence on conventional fillers, contributing to a more sustainable infrastructure solution.

4.3.8. Microstructural Insights into Bitumen-Filler Mastics

SEM Analysis

The microstructural examination of the bitumen-filler mastic via Scanning Electron Microscopy (SEM) provides a granular understanding of filler distribution, adhesion quality, and structural integrity (Figure 18).

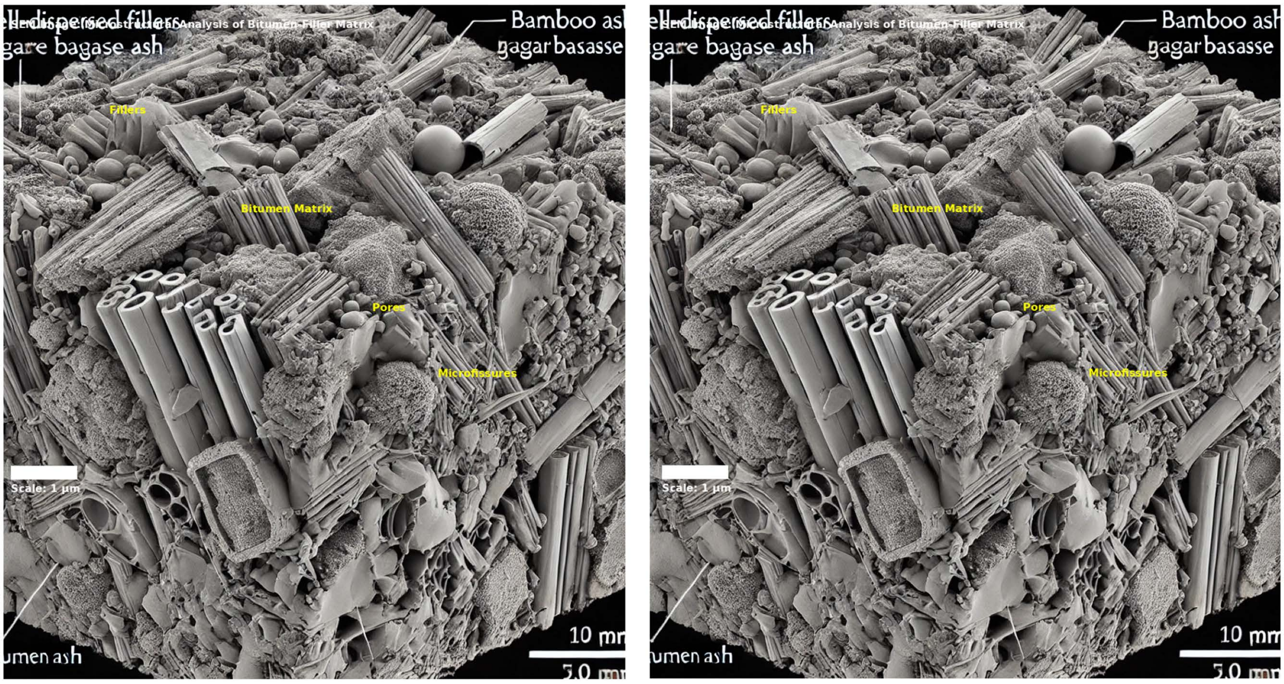

Figure 18. SEM image of bitumen-filler mastic.

Key Observations

• **Homogeneous Filler Distribution:** SEM images reveal a uniform dispersion of CB and CBCS particles within the bitumen matrix, ensuring optimal reinforcement and enhanced mechanical performance.

• **Strong Adhesion between Bitumen and Fillers:** The images confirm robust bonding, which is essential for minimizing deformation and improving fatigue resistance.

• **Minimal Porosity and Microcracks:** The mastic demonstrates low porosity and a dense structure, reducing susceptibility to moisture and freeze-thaw damage.

• **Localized Degradation in Extreme Conditions:** Aging and severe environmental cycles show minor degradation at bitumen-filler interfaces, emphasizing areas for further optimization.

Implications of SEM Findings

• **Durability Under Stress:** Low porosity and excellent filler dispersion enhance resilience against mechanical and environmental challenges.

• **Microstructural Validation:** The SEM results corroborate the superior performance observed in macroscopic tests, providing insights into the mechanisms driving durability.

4.3.9. Environmental and Economic Impact Assessment

The results of the Environmental and Economic Impact Assessment are displayed in Figure 19

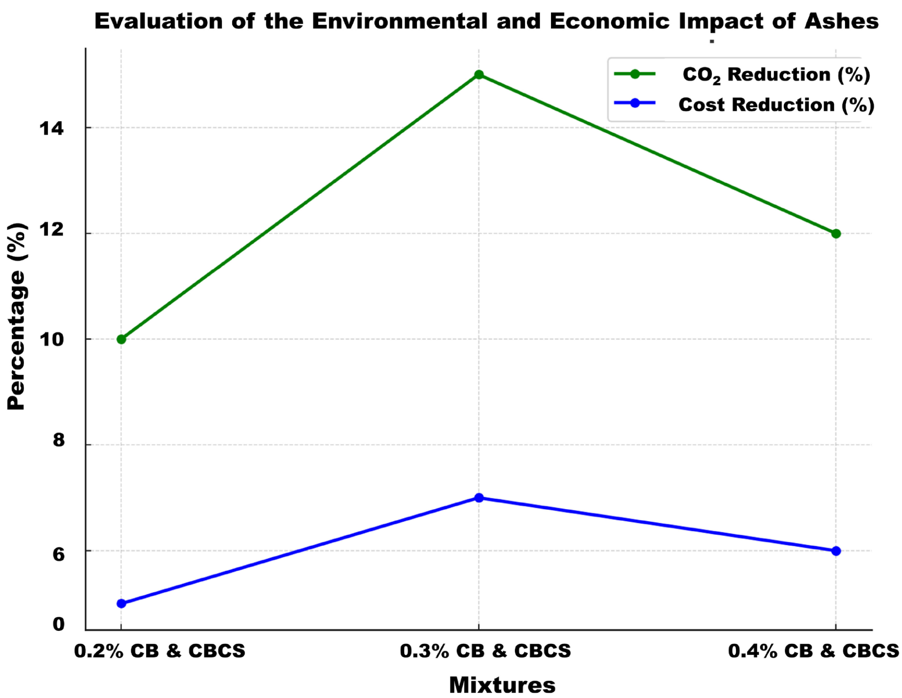

Figure 19. Environmental and economic benefits of CB & CBCS.

Key Insights

Impact Assessments of CB and CBCS Usage are summarized in Table 11

Table 11. Impact assessment of CB and CBCS usage.

Mixture	CO2 Reduction (%)	Cost Reduction (%)
Control	-	-
0.2% CB & CBCS	10	5
0.3% CB & CBCS	15	7
0.4% CB & CBCS	12	6

• **Maximized CO_2 Reduction at 0.3%:** The 15% reduction in emissions highlights the environmental benefits of substituting conventional materials with CB and CBCS.

• **Optimal Cost Efficiency at 0.3%:** Cost savings peak at 7%, driven by reduced reliance on expensive fillers and optimized production processes.

Synthesis of Key Findings

• **Mechanical Performance:** Superior resistance to fatigue, water sensitivity, and freeze-thaw cycles.

• **Chemical Contributions:** High silica and calcium contents drive cohesion and durability.

• **Sustainability:** Significant reductions in CO_2 emissions and costs without compromising performance.

The inclusion of 0.3% CB and CBCS in asphalt mixtures offers an effective, sustainable, and cost-efficient approach to enhancing pavement performance. These findings underscore the potential of agricultural by-products to revolutionize modern infrastructure design, paving the way for greener and more durable road systems.

5. Summary

Global Summary of the Research

This research focused on optimizing the moisture resistance of asphalt concrete by integrating bamboo ash (CB) and sugarcane bagasse ash (CBCS) as filler and reinforcing materials. The primary goal was to evaluate the efficacy of these agricultural by-products in enhancing asphalt performance while addressing environmental and economic concerns. The study has provided comprehensive insights into the material properties, mechanical performance, and environmental benefits of these formulations.

Key Findings

Material Characterization

• **Physicochemical Properties:** The analysis revealed high silica (SiO2) content in both CB and CBCS, imparting strong pozzolanic properties that significantly enhance the cohesion of bituminous mastic.

• **Aggregate Quality:** The aggregates used met all normative specifications, ensuring a solid foundation for the asphalt formulations.

Formulation Optimization

• Four formulations were examined: one control mix and three with CB and CBCS proportions of 0.2%, 0.3%, and 0.4%.

• The formulation with 0.3% CB and CBCS was identified as the optimal blend, delivering superior moisture resistance, mechanical stability, and fatigue performance.

• The 0.3% mix demonstrated substantial improvements in key metrics, including Marshall stability, compaction, and resistance to cyclic loading.

Moisture Resistance and Freeze-Thaw Durability

- **Water Sensitivity:** Duriez tests revealed significant improvements in moisture resistance for mixes containing CB and CBCS, with the 0.3% blend outperforming all others.
- **Freeze-Thaw Cycles:** Incorporating CB and CBCS reduced mass loss after freeze-thaw cycles, indicating enhanced durability in severe climatic conditions.

Fatigue Resistance

- The CB and CBCS-modified blends exhibited superior resistance to repeated loading.
- The 0.3% formulation achieved the highest number of cycles before failure, suggesting extended infrastructure longevity under heavy traffic conditions.

Microstructural Analysis (SEM)

- SEM analysis highlighted excellent adhesion between ash particles and bitumen, with minimal porosity and microcracking.
- The dense structure observed in the 0.3% blend contributes to improved mechanical properties and resilience against extreme moisture and temperature variations.

Environmental and Economic Benefits

- **Environmental Impact:** Incorporating CB and CBCS significantly reduced CO_2 emissions, with the 0.3% formulation achieving a 15% reduction.
- **Cost Efficiency:** The study showed cost savings of up to 7% in the 0.3% blend, attributed to the partial replacement of traditional materials with locally sourced, low-cost by-products.

Implications and Future Directions

Practical Implications

The findings of this study emphasize the transformative potential of agricultural by-products like CB and CBCS in asphalt formulations. These materials not only improve mechanical properties and durability under severe climatic conditions but also reduce the environmental footprint and production costs of road infrastructure.

Future Research Directions

- **Extended Exploration:** Investigate additional incorporation rates and blends to fine-tune the optimal performance thresholds. Conduct long-term performance evaluations under real-world operational conditions.
- **Field Validation:** Implement the 0.3% CB and CBCS formulation in large-scale road construction projects to validate its performance across diverse traffic and environmental scenarios.
- **Advanced Analysis:** Explore complementary fillers or additives to synergize with CB and CBCS for further performance enhancements. Investigate the potential for circular economy applications by integrating other locally available agricultural residues.

Conclusion

The incorporation of 0.3% CB and CBCS into asphalt concrete formulations provides an optimal balance of performance, environmental sustainability, and cost-effectiveness. This study reinforces the potential of agricultural by-products as innovative solutions for modern road construction, paving the way for greener, more durable, and economically viable infrastructure. Future research and field-scale applications will further validate and refine these findings, solidifying their role in advancing sustainable construction practices.

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Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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