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Research Article

# Development of High Performance Bituminous Mixtures incorporating Sugarcane Bagasse Ash

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## Abstract

This study investigates the potential of sugarcane bagasse ash as an additive in bituminous mixtures to enhance mechanical properties while promoting sustainability through agricultural waste utilization. Sugarcane bagasse ash was incorporated into 60/70 bitumen at varying contents of 0%, 3%, 5%, and 7%, and its impact on physical, chemical, and mechanical properties was evaluated. The characterization of sugarcane bagasse ash using X-ray fluorescence (XRF) and scanning electron microscopy (SEM) revealed a high silica content (78.34%) and favorable filler properties, contributing to improved performance. The modified binders demonstrated reduced penetration and increased softening points at 3% and 5% sugarcane bagasse ash, indicating enhanced resistance to deformation at high temperatures. The mechanical evaluation showed significant improvements in Marshall stability, stiffness, and indirect tensile strength at 3% and 5% sugarcane bagasse ash, with peak stability (9.965 kN) and indirect tensile strength (753.612 kPa) achieved at 5% and 3% sugarcane bagasse ash, respectively. However, higher sugarcane bagasse ash content (7%) resulted in reduced stability, stiffness, and tensile strength due to excessive voids and weakened cohesion. The correlation analysis revealed strong relationships between stability, density, and abrasion loss, with the optimal performance observed at moderate sugarcane bagasse ash levels. The study concludes that sugarcane bagasse ash is a viable additive for bituminous mixtures, providing improved mechanical performance and sustainability benefits when used at optimal levels of 3%-5%. This research highlights the dual benefits of enhancing bitumen performance and managing agricultural waste, contributing to sustainable construction practices.

**Keywords:** Sugarcane Bagasse Ash, Stability, Indirect Tensile Strength, Abrasion Loss

## Introduction

The integration of waste materials into bitumen mixtures has gained momentum, prompting the need to investigate the performance of bituminous mixtures modified with waste materials [1, 2]. Numerous studies have explored the feasibility of reusing waste in bitumen production to enhance mixture properties and promote sustainability. In an effort to promote conservation, waste is increasingly being employed as a substitute for paving materials. The quantity of agricultural and biomass waste is on the rise, and many developed nations have acknowledged the significance of recycling and reusing to address this swiftly growing problem [3, 4]. As a result, the utilization of agro-waste is gaining popularity due to its several advantages in the construction industry, including reduced construction costs, enhanced sustainability, and increased pavement design life [5, 6]. Malaysia produces approximately 168 million tonnes of biomass, including palm oil waste, rice husks, coconut debris, sugar cane waste, urban waste, and forestry waste [7].

The incorporation of sugarcane bagasse ash (SCBA) into bitumen modification has gained attention as a sustainable alternative to traditional fillers in bitumen mixtures, showing promising potential to enhance mechanical performance, particularly in terms of rutting resistance, moisture damage, and durability. Sam et al. [8] investigated calcined sugarcane bagasse ash (CSCBA) as a filler in bitumen emulsion mixtures for stabilizing lateritic clay soils used in gravel road bases. Their findings highlighted the ability of CSCBA to improve the plasticity index and mechanical properties, achieving notable indirect tensile strength values of 183.9 kPa (dry) and 132 kPa (wet). Similarly, Muhammad [9] demonstrated that bagasse ash (BA) could enhance the stability and flexibility of bitumen mixtures by increasing friction and viscosity due to its rough surface texture, positioning BA as a viable replacement for traditional fillers like stone dust. However, while both studies establish the benefits of SCBA or BA in improving bitumen's mechanical performance, they primarily focus on laboratory evaluations without exploring long-term field performance or durability under varying environmental conditions. Additionally, the interaction mechanisms between SCBA and bitumen at the microstructural level remain insufficiently addressed, highlighting a gap in understanding how SCBA influences binder-aggregate adhesion and fatigue resistance in real-world applications.

Khandelwal et al. [10], Arkhash et al. [11], and Sarir et al. [12] have collectively highlighted the potential of sugarcane bagasse ash (SCBA) as a sustainable additive in bitumen modification, particularly for enhancing the performance of bitumen mixtures. Khandelwal et al. [10] demonstrated that SCBA improves the viscosity and reduces the temperature susceptibility of bitumen, leading to enhanced durability and suitability for highway construction, while also showing promise in improving subgrade properties. Akarsh et al. [11] extended this research by focusing on the mechanical behavior of Stone Mastic Bitumen (SMA) modified with SCBA, observing significant improvements in durability and mechanical performance, reinforcing the material's value as a performance-enhancing modifier. Similarly, Sarir et al. [12] evaluated the use of SCBA as a filler in bitumen concrete and found that it outperformed traditional fillers like stone dust by reducing rut depth and increasing dynamic stiffness. While all three studies consistently demonstrate the benefits of SCBA in enhancing bitumen performance, the research remains limited to controlled laboratory environments. A critical gap exists in understanding the long-term field performance of SCBA-modified bitumen under diverse traffic and climatic conditions, as well as in exploring its compatibility with different binder types and gradations to optimize its application.

Mendoca et al. [13] and Yadav et al. [14] explored the use of sugarcane industry by-products bagasse fibers and bagasse ash, respectively in enhancing bitumen and bitumen performance, offering both mechanical and environmental benefits. Mendoca et al. [13] incorporated sugarcane bagasse fibers into bitumen mixtures using the Superpave method, reporting improved mechanical strength and environmental sustainability by repurposing sugar industry waste. On the other hand, Yadav et al. [14] focused on sugarcane bagasse ash, rich in silica, as a partial replacement in bitumen, finding optimal performance at 40% replacement. This proportion significantly enhanced bitumen properties, making it suitable for low-volume traffic roads while maintaining cost-effectiveness and ease of maintenance. Both studies emphasize the sustainability of using sugarcane by-products; however, Mendoca et al. [13] concentrated on fiber's structural contributions, while Yadav et al. [14] emphasized ash's chemical properties. A critical gap in both works lies in the limited exploration of these materials' long-term field performance under varying traffic loads and climates, which is essential for scaling their application in diverse road construction projects.

Despite extensive research into the use of sugarcane bagasse ash in bitumen modification and bitumen mixtures, several critical gaps and limitations remain. Existing studies have primarily focused on the mechanical performance improvements, such as enhanced stability [15], stiffness [16], and rutting resistance [17], but have largely overlooked the long-term durability, aging behavior, and moisture susceptibility under diverse environmental and traffic conditions.

Extensive research has shown that the percentage of optimal percentages of sugarcane bagasse ash (SCBA) for modifying bitumen vary across studies, reflecting its potential as a sustainable filler in asphalt mixtures. Sam et al. [8] found that 4% CSCBA was effective for stabilizing lateritic clay soils in bitumen emulsion mixtures, while Muhammad [9] and Sarir et al. [12] findings that 4%, 5.5%, and 6.5% as a filler, with partial replacements of stone dust at 10% and 20% showing promising results for hot mix asphalt. This paper attempts to find the optimal percentage of SCBA between 0% to 7% and that the strong justification for the chosen percentage.

Furthermore, the optimal proportions of sugarcane bagasse ash for balanced mechanical and durability properties are not yet well-established, particularly for varying bitumen mixture types and construction scenarios. Many of these investigations are limited to laboratory settings, lacking validation through extensive field trials that can demonstrate the practical applicability and performance of sugarcane bagasse ash modified mixtures on a larger scale.

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Additionally, the interaction between sugarcane bagasse ash and other bitumen components, as well as its influence on workability and compaction properties, remains underexplored. These limitations underscore the need for a more comprehensive approach to fully understand and utilize sugarcane bagasse ash as a sustainable alternative in bitumen mixture design. This study aims to bridge these gaps by systematically evaluating the mechanical and physical properties of sugarcane bagasse ash modified bitumen mixtures, optimizing its content for enhanced performance while addressing sustainability in pavement engineering.

## Materials and Methods

### Sugarcane Bagasse Ash

Sugarcane bagasse, a byproduct of sugar production, consists of the fibrous residue left after juice extraction from sugarcane stalks. This material, commonly found in large quantities in markets, was collected from a market located in Jaya Gading, Pahang, Malaysia and processed to develop sugarcane bagasse ash for application in bituminous mixtures. Next the sugarcane bagasse was cut into 15cm lengths. Subsequently, the sugarcane bagasse was sun-dried directly for a day to reduce moisture content. Initially, raw sugarcane bagasse underwent a drying process to reduce its moisture content and facilitate handling. The dried material was then subjected to an incineration process in a controlled environment at 600°C [18]. This process (Figure 1) was designed to ensure complete combustion, eliminating organic matter and leaving behind the ash residue. The resultant sugarcane bagasse ash exhibited a fine texture, with color ranging from light gray to dark gray, depending on the incineration conditions and residual carbon content.

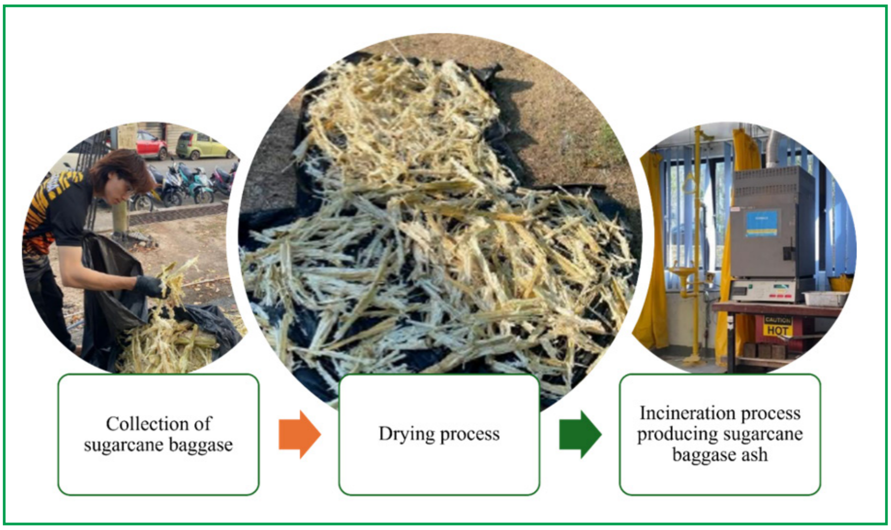


**Figure 1.** Preparation of sugarcane baggase ash

### Bitumen and Aggregate

The bitumen binder used in this research was bitumen with a 60/70 degree of penetration (PEN 60/70), supplied by Kemaman Bitumen Company, located in the city of Terengganu, Malaysia. The study used granitic aggregates, 12.5 mm, 9.5 mm, and river bed sand with particle sizes fractions passing 4.25 mm and retained on 0.075 mm BS sieves (Figure 2), all from the Bekelah Quarry, Pahang, Malaysia.

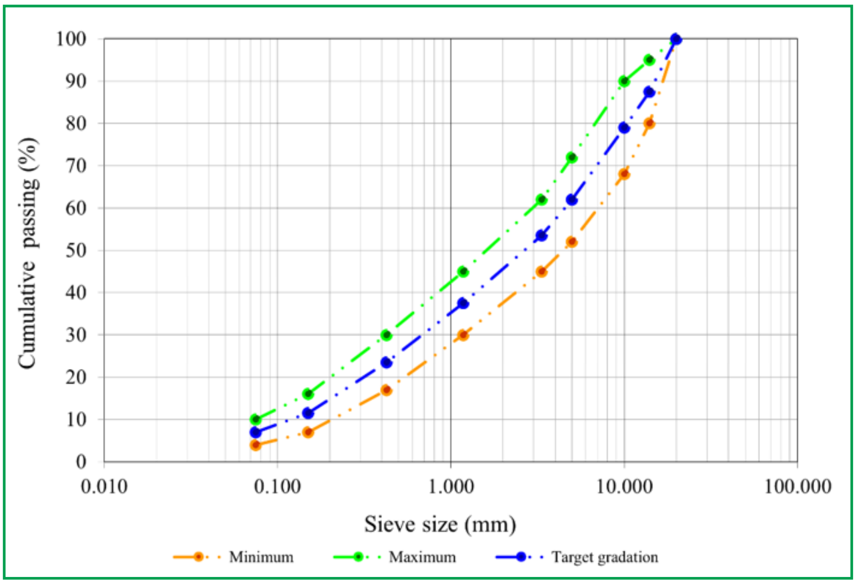


**Figure 2.** Particle size distribution of ACW 14

## Experimental

### Sugarcane Bagasse Ash Preparations

The preparation and characterization of sugarcane bagasse ash involve incinerating sugarcane bagasse at 600°C for 2 hours to produce ash, which is then sieved through a 0.075mm sieve, milled, and further sieved through a 75µm sieve. The bagasse ash is characterized for its chemical and physical properties and incorporated into the bituminous mixtures in increments of 0%, 3%, 5%, and 7%. Figure 3 presents the flowchart of this study. Bituminous mixtures are prepared in line with the Malaysia Standard Specification for Road Works [19], ensuring consistency and homogeneity. This comprehensive methodology ensures a thorough evaluation of the performance of high-performance bituminous mixtures incorporating sugarcane bagasse ash, providing valuable insights into its potential use in road construction and demonstrating the feasibility and benefits of using sugarcane bagasse ash as an additive in bitumen mixtures.

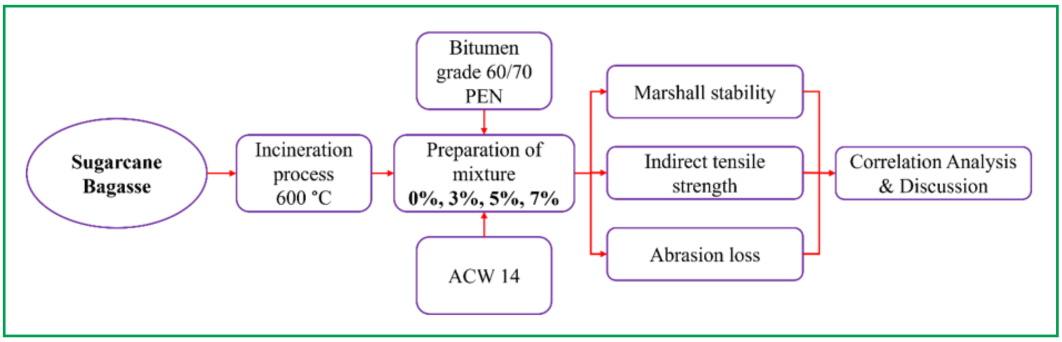


**Figure 3.** Flowchart of this study

### *Bitumen Mixtures Preparations*

In this study, the wet mixing method was employed for incorporating sugarcane bagasse ash into the bituminous binder. The sugarcane bagasse ash was blended with the binder using a high-shear mixer operating at 1500 rpm for 60 minutes to ensure homogeneity and proper dispersion of the additive. The optimum bitumen content (OBC) for the control sample was determined to be 5%. The sugarcane bagasse ash was introduced at varying percentages (0%, 3%, 5%, and 7%) by weight of the binder. This methodology ensures consistent mixing and preparation of SCBA-modified asphalt mixtures for subsequent testing.

### *Chemical Test*

The chemical composition of sugarcane bagasse ash was determined using X-ray Fluorescence (XRF) using PANalytical AXIOS XRF spectrometer. The surface morphology and particle structure of sugarcane bagasse ash were analyzed using scanning emission microscope (SEM), performed under standard procedures using equipment Zeiss MERLIN Field Emission SEM. The combined chemical and morphological data [20, 21] ensured a thorough evaluation of sugarcane bagasse ash ‘s suitability for asphalt modification.

### *Test on Bitumen*

The penetration and softening point tests were conducted to evaluate the consistency and thermal susceptibility of the bitumen binder modified with sugarcane bagasse ash. The penetration test followed ASTM D5 [22] standards, where a standard needle was allowed to penetrate the bitumen under a load of 100 g for 5 seconds at a temperature of 25°C. The softening point was determined using the ring-and-ball method in accordance with ASTM D36 [23], measuring the temperature at which the bitumen softened enough to allow a steel ball to fall a specified distance. These tests provided insights into the effects of sugarcane bagasse ash content on the physical properties and performance of the binder under varying conditions.

### *Test of Aggregate*

The aggregate testing was conducted to determine its mechanical properties using the Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests, following JKR standards. For the AIV test, aggregates passing through a 14 mm sieve and retained on a 10 mm sieve were subjected to 15 blows of a standard hammer in a cylindrical steel mold. The percentage of fines generated was calculated to assess the aggregate's resistance to impact. For the ACV test, aggregates of the same size range were placed in a compression testing machine and subjected to a load of 400 kN over 10 minutes. The percentage of crushed fines was determined to evaluate the aggregate's resistance to crushing. Both tests were performed under standard conditions, and the results were compared against JKR specifications, where acceptable limits are 20%-30% for AIV and <25% for ACV. The percentage of fines in the AIV and ACV can be determined using the equation provided below and Table 1 provides the categorization of the AIV according to JKR/SPJ/2008.

$$Percentage\ fines = \frac{Weight\ loss\ (M_1)}{Initial\ weight\ (M_1)}\ x\ 100\%$$

**Table 1.** Classification of AIV values [19]

| % Passing by Weight | Results |
|---|---|
| < 20 % | < 20 % |
| 10 – 20 % | 10 – 20 % |
| 20 – 30 % | 20 – 30 % |
| > 35 % | > 35 % |

### *Marshall Stability Test*

The Marshall stability test was conducted to evaluate the mechanical properties of bitumen mixtures, including stability, flow, bulk density, and stiffness, following ASTM D6927 [24] and JKR/SPJ/2008 standards [19]. Bitumen mixtures with sugarcane bagasse ash contents of 0%, 3%, 5%, and 7% were prepared using 60/70 PEN bitumen and ACW14 aggregate gradation with the optimum bitumen content (OBC) of 5%. Each mixture was compacted into cylindrical specimens (101.6 mm diameter and 63.5 mm height) using a Marshall compactor with 75 blows on each face. The specimens were conditioned at 60°C for 30–40 minutes before testing.

The stability was determined as the maximum load the specimen could withstand before failure, measured using a Marshall stability machine. Flow values were recorded as the vertical deformation at maximum load. Bulk density was calculated based on the specimen's mass, volume, and specific gravity. Stiffness was derived by dividing the stability by the flow. The results were analyzed to determine the influence of sugarcane bagasse ash on the mechanical performance of the mixtures, adhering to standard requirements for stability (minimum 8 kN), flow (2–4 mm), and density (2.3–2.5 g/cm$^3$).

### *Indirect Tensile Strength Test*

The Indirect Tensile Strength test was performed to evaluate the tensile properties of bitumen mixtures, following ASTM D6931 [25] and JKR/SPJ/2008 standards [19]. Cylindrical specimens with a diameter of 101.6 mm and a height of 63.5 mm were prepared using ACW14 aggregate gradation and 60/70 PEN bitumen modified with sugarcane bagasse ash at 0%, 3%, 5%, and 7% contents. The specimens were compacted using a Marshall compactor with 75 blows on each face to achieve uniform density. The test specimens were conditioned at 25°C for at least 4 hours before testing. Each specimen was placed horizontally between two steel loading strips in the indirect tensile testing machine. A compressive load was applied along the vertical diametrical plane at a constant rate of 50 mm/min until failure occurred. The indirect tensile strength value was calculated using the formula:

$$Indirect\ Tensile\ Strength\ = \frac{2P}{\pi t d}$$

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Where $P$ is the maximum load at failure (N), $t$ is the specimen thickness (mm), and $d$ is the specimen diameter (mm). The indirect tensile strength results were analyzed to assess the tensile strength and cracking resistance of the mixtures, with standard requirements of minimum 200 kPa specified by JKR for dense-graded mixtures.

### *Abrasion Loss Test*

The abrasion loss test was conducted to evaluate the durability and wear resistance of aggregates using the Los Angeles abrasion machine, following ASTM standard [26] and JKR/SPJ/2008 standards [19]. Aggregates passing the 12.5 mm sieve and retained on the 10 mm sieve were used for testing. A sample weighing approximately 5,000 g was placed in the Los Angeles abrasion drum, along with a specified number of steel spheres. The drum was rotated at a speed of 30–33 rpm for 500 revolutions. After the test, the material was sieved through a 1.7 mm sieve to separate the fines generated during the process. The percentage of abrasion loss was calculated using the formula:

$$Abrasion\ loss\ (\%) = \frac{(Initial\ weight - Final\ weight)}{Initial\ weight}\ x\ 100$$

This test evaluates the aggregate's ability to resist surface wear due to friction and impact. According to JKR standards, the acceptable abrasion loss value is less than 30% for aggregates used in road construction. The results were analyzed to determine the effect of sugarcane bagasse ash on the abrasion resistance of the modified mixtures.

## *Results*

### *Characteristic of Physical and Chemical Composition of Sugarcane Bagasse Ash*

The physical properties (Table 2) of sugarcane bagasse ash highlight its potential for use as a supplementary material in bituminous mixtures. The surface area of sugarcane bagasse ash is notably high at 5140 $cm^2/g$, which enhances its reactivity and ability to bond with other materials, such as bitumen, through improved interfacial interactions. The density of 2.52 $g/cm^3$ aligns with typical values for mineral additives, ensuring compatibility in bitumen mixtures without causing significant changes in overall mixture density. The particle size of sugarcane bagasse ash is 28.90 µm, indicating fine particles that can fill voids within the aggregate structure and improve the packing density of the mixture. Additionally, the reddish-grey color of the ash reflects its chemical composition, likely influenced by the presence of iron oxides and other mineral elements formed during incineration. These physical attributes make sugarcane bagasse ash a viable candidate for enhancing the mechanical and durability properties of bitumen mixtures.

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**Table 2.** Physical properties of sugarcane bagasse ash

| Physical Properties | Value |
|---|---|
| Surface area | 5140 $cm^2/g$ |
| Density | 2.52 $g/cm^3$ |
| Particle size | 28.90 µm |
| Colour | Reddish grey |

The chemical composition of sugarcane bagasse ash highlights its potential as a mineral additive in bituminous mixtures. Table 3 summarizes its main chemical properties, showcasing a high content of Silica oxide ($SiO_2$) at 78.34%, which enhances pozzolanic activity. Additionally, the presence of calcium oxide (CaO) at 2.15% supports hydration reactions, improving the mechanical properties of mixtures. The ash also contains aluminum oxide ($Al_2O_3$), ferum oxide ($Fe_2O_3$), and potassium oxide ($K_2O$), which contribute to its filler effect and improved interfacial bonding. With a loss on ignition (LOI) value of 1.84%, the material demonstrates a moderate level of unburned carbon, indicating efficient combustion.

**Table 3.** Sugarcane bagasse ash's chemical properties [20]

| Chemical Properties | Composition (%) |
|---|---|
| $SiO_2$ | 78.34 |
| $Al_2O_3$ | 8.55 |
| $Fe_2O_3$ | 3.61 |
| CaO | 2.15 |
| MgO | 1.65 |
| $K_2O$ | 3.46 |
| $Na_2O$ | 0.12 |
| $SO_3$ | 0.18 |
| MnO | 0.10 |
| LOI | 1.84 |

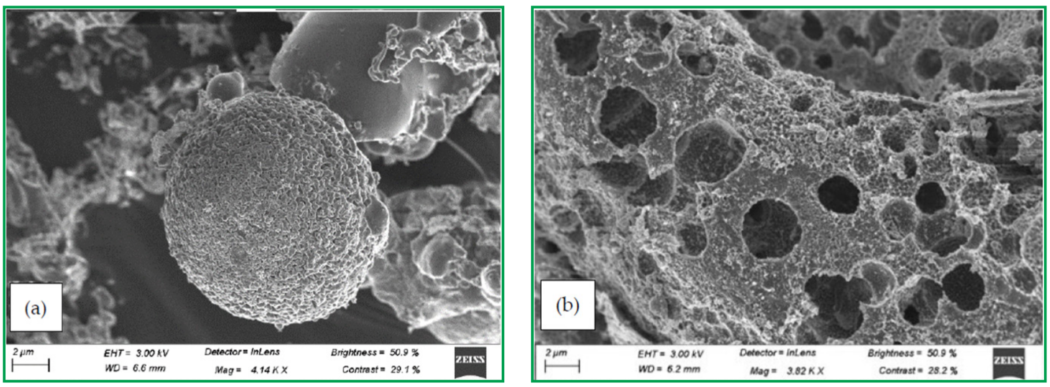


**Figure 4.** SEM images of (a) raw and (b) sugarcane bagasse ash [21]

The Scanning electron microscope (SEM) images illustrate the structural transformation of sugarcane bagasse before and after incineration into ash [21]. In Figure 4(a), the raw sugarcane bagasse exhibits a smooth, spherical

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morphology with an organized and dense surface structure, characteristic of its lignocellulosic composition, which includes cellulose, hemicellulose, and lignin. This structure provides mechanical strength and resilience to the raw material. In contrast, Figure 4(b) demonstrates the microstructural changes after thermal treatment at 600°C, resulting in sugarcane bagasse ash. The ash shows a porous and irregular surface with visible voids and collapsed structures, indicating the decomposition of organic components and the release of volatile matter during incineration. The ash's rough texture and porous nature enhance its surface area, making it potentially reactive and suitable as a supplementary material in bituminous mixtures. These microstructural modifications are critical in influencing the ash's performance when incorporated into bitumen binder and mixtures.

### Characteristic of Aggregate

The aggregate used in this study was evaluated for its suitability in bitumen mixtures through the Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests. The AIV of the aggregate was found to be 25.5%, which falls within the standard acceptable range of 20–30% specified for aggregates used in road construction (Table 4). This indicates that the aggregate possesses sufficient resistance to sudden impacts and shocks, making it suitable for bitumen mixtures subjected to dynamic traffic loads. The ACV of the aggregate was recorded at 10.6%, which is well below the maximum standard limit of 25%, demonstrating excellent resistance to crushing under gradually applied compressive loads. The low ACV signifies the aggregate's durability and strength, which are critical for maintaining the structural integrity of the bitumen pavement. Overall, the results suggest that the aggregate used meets the required standards for use in bituminous mixtures, ensuring long-term performance under traffic and environmental stresses. However, the AIV being on the higher end of the acceptable range warrants consideration, particularly for heavy traffic conditions, as higher impact values may reduce the pavement's resistance to aggregate degradation.

**Table 4.** Aggregate impact value and aggregate crushing value results

| Properties | Outcomes (%) | Standards (%) |
|---|---|---|
| AIV | 25.5 | 20-30 |
| ACV | 10.6 | < 25 |

### Characterization of Sugarcane Bagasse Ash Modified Bitumen Binder

Figure 5 shows the softening point of the bitumen binder increases with the addition of sugarcane bagasse ash. The unmodified binder (0% sugarcane bagasse ash) recorded a softening point of 50.5°C. However, with 3% sugarcane bagasse ash, a decrease to 3°C was observed, likely due to the incomplete dispersion or dilution of the binder matrix at low sugarcane bagasse ash content [11]. Beyond this, at 5% and 7% sugarcane bagasse ash, the softening points rose to 53.2°C and 54°C, respectively, indicating the stiffening effect of sugarcane bagasse ash at higher concentrations. This trend aligns with the pozzolanic properties of sugarcane bagasse ash, which contribute to enhancing the thermal resistance of the binder. The increasing softening point with higher sugarcane bagasse ash content demonstrates improved thermal stability, meeting the minimum requirement for tropical climates, as specified in ASTM D36 [23], where a softening point between 49 to 56°C is preferred for bitumen binders.

The penetration values decrease with the addition of sugarcane bagasse ash, indicating a progressive stiffening effect on the binder. The control binder exhibited a penetration value of 67.3 dmm, which decreased to 65.2 dmm, 64 dmm, and 57.8 dmm for 3%, 5%, and 7% sugarcane bagasse ash, respectively (Figure 6). This reduction suggests that the addition of sugarcane bagasse ash reduces the binder's susceptibility to deformation under applied loads. The stiffening behavior can be attributed to the fine sugarcane bagasse ash particles filling voids and interacting with the bitumen matrix, resulting in a denser and less penetrable structure. The penetration values for all modified binders remain within the acceptable range specified by JKR and ASTM D5 [22] for 60/70 penetration-grade bitumen, ensuring adequate workability and performance.

The penetration index (PI) is a measure of the temperature susceptibility (A) of bitumen binders. It can be calculated using the formula:

$$PI = \frac{20\,(1 - 25A)}{1 + 50A}$$

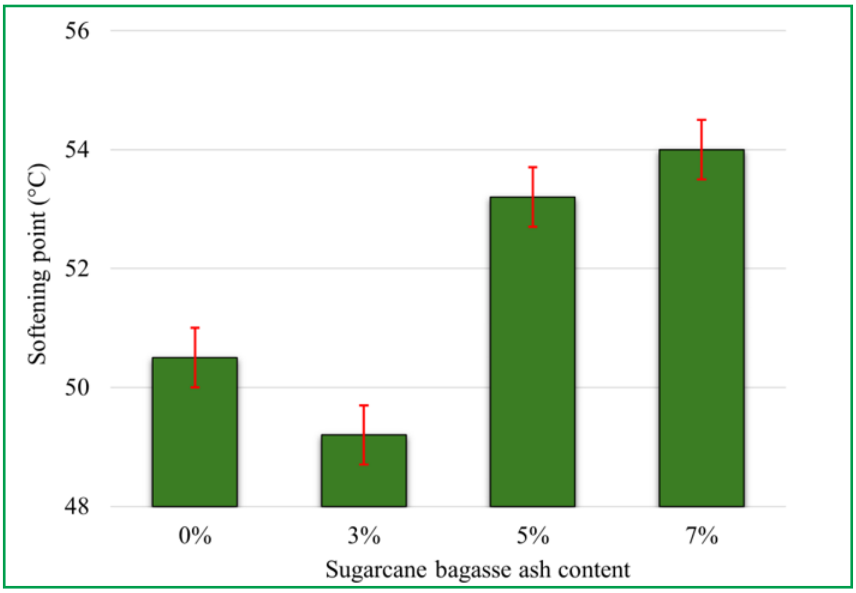


**Figure 5.** Softening point results at different percentage of sugarcane bagasse ash

The penetration index for all samples is negative, which is typical for bitumen binders, indicating moderate temperature susceptibility. However, the PI becomes less negative as sugarcane bagasse ash content increases, suggesting reduced temperature susceptibility with higher sugarcane bagasse ash levels. This improvement is attributed to the stiffening effect and enhanced thermal stability imparted by sugarcane bagasse ash. According to standards, a PI close to -1 is acceptable for tropical climates, where binders need to resist both high temperatures and rutting while maintaining flexibility at lower temperatures.

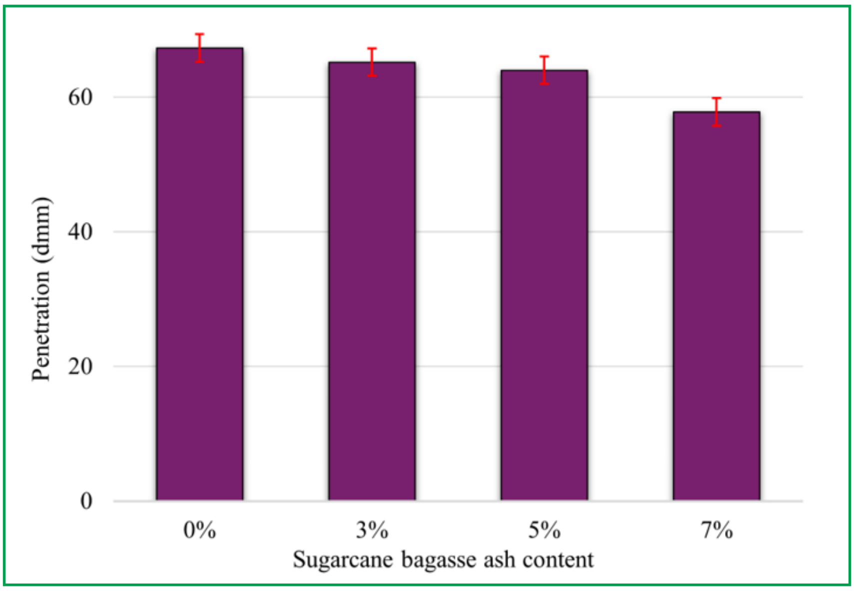


**Figure 6.** Penetration results at different percentage of sugarcane bagasse ash

### *Characteristic of Sugarcane Bagasse Ash Modified Bitumen Mixture*

#### *Marshall stability*

The Marshall stability of the sugarcane bagasse ash modified bitumen mixtures shows significant improvement with the addition of sugarcane bagasse ash compared to the control mixture (0%). The stability value increases from 8.464 kN for the control mixture to 9.619 kN and peaks at 9.965 kN for 3% and 5% sugarcane bagasse ash content, respectively (Figure 7). However, a slight decrease to 9.111 kN is observed at 7% sugarcane bagasse ash. The improved stability at 3% and 5% sugarcane bagasse ash can be attributed to enhanced particle-binder interaction and the pozzolanic effect of sugarcane bagasse ash, which contributes to a stiffer mix. The reduction at 7% may be due to excessive ash content leading to reduced workability and poor dispersion. According to JKR specifications, the minimum stability requirement for bitumen mixtures is 8 kN, indicating that all sugarcane bagasse ash modified mixtures satisfy the standard, with 5% sugarcane bagasse ash demonstrating the highest stability and optimal performance.

#### *Flow*

Figure 8 depicts the flow values of the sugarcane bagasse ash modified mixtures exhibit a decreasing trend with the incorporation of sugarcane bagasse ash up to 5%, followed by a slight increase at 7%. The control mixture (0% sugarcane bagasse ash) shows the highest flow value of 3.789 mm, which decreases to 3.57 mm and 3.105 mm for 3% and 5% sugarcane bagasse ash, respectively, and rises slightly to 3.832 mm at 7%. The reduction in flow values at 3% and 5% sugarcane

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bagasse ash indicates enhanced resistance to deformation under loading, attributed to improved particle-binder interaction and the stiffening effect of sugarcane bagasse ash. The slight increase at 7% sugarcane bagasse ash may be due to excessive ash content, leading to reduced workability and increased void content, which compromises resistance to deformation. According to JKR and ASTM D6927 [24], the acceptable range for flow values in bitumen mixtures is 2–4 mm. Mixtures with 3% and 5% sugarcane bagasse ash satisfy the standard, with 5% sugarcane bagasse ash achieving the optimal flow value of 3.105 mm, reflecting an ideal balance between stiffness and flexibility.

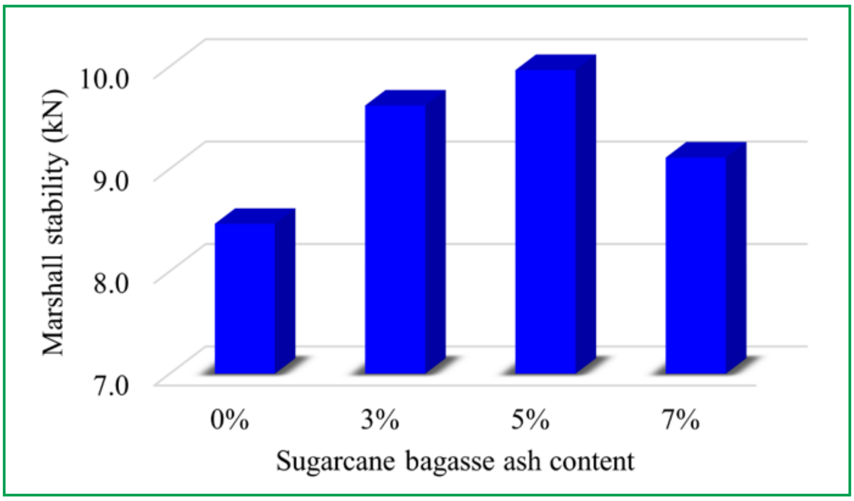


**Figure 7.** Marshall stability at different percentage of sugarcane bagasse ash

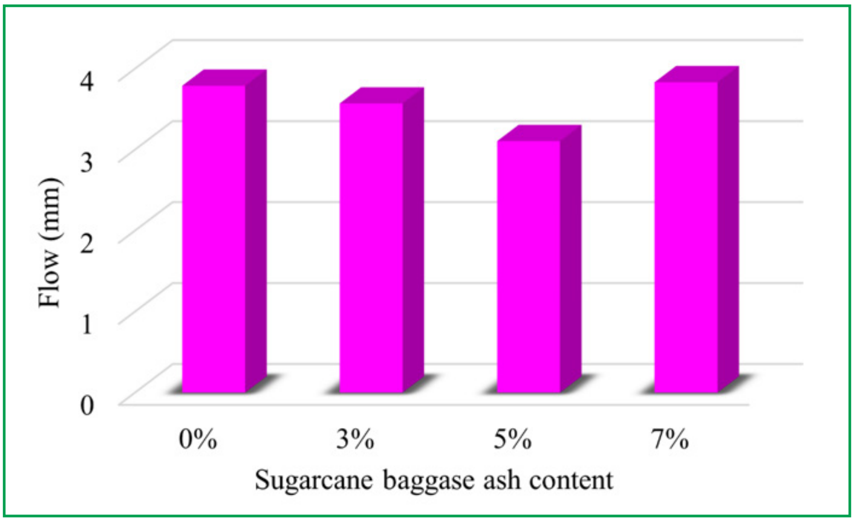


**Figure 8.** Flow at different percentage of sugarcane bagasse ash

### *Density*

The bulk density of the mixtures decreases progressively with increasing sugarcane bagasse ash content. The control mixture records the highest density of 2.244 g/cm³, which declines to 1.746 g/cm³, 1.62 g/cm³, and 1.598 g/cm³ for 3%, 5%, and 7% sugarcane bagasse ash, respectively (Figure 9). This reduction in density can be attributed to the lower specific gravity of sugarcane bagasse ash compared to traditional mineral fillers, resulting in a lighter mix. While a lower density promotes sustainability by reducing the overall weight of the pavement, it may affect compacted strength and structural integrity. The reduction in density beyond 5% sugarcane bagasse ash indicates the potential onset of excessive void content, which can lead to permeability issues and reduced durability. Standards such as JKR recommend a dense bitumen mixture to ensure structural stability, suggesting that 3% and 5% sugarcane bagasse ash are the most favorable for balancing density with performance.

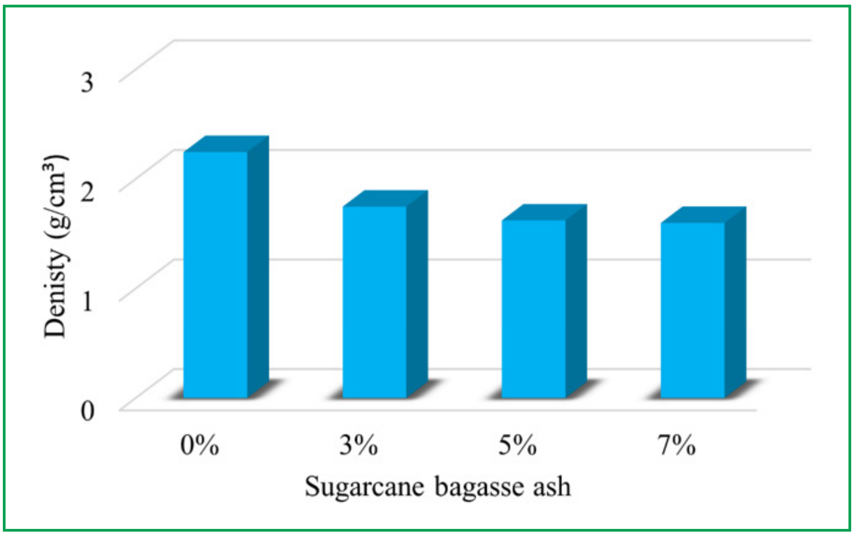


**Figure 9.** Density at different percentage of sugarcane bagasse ash

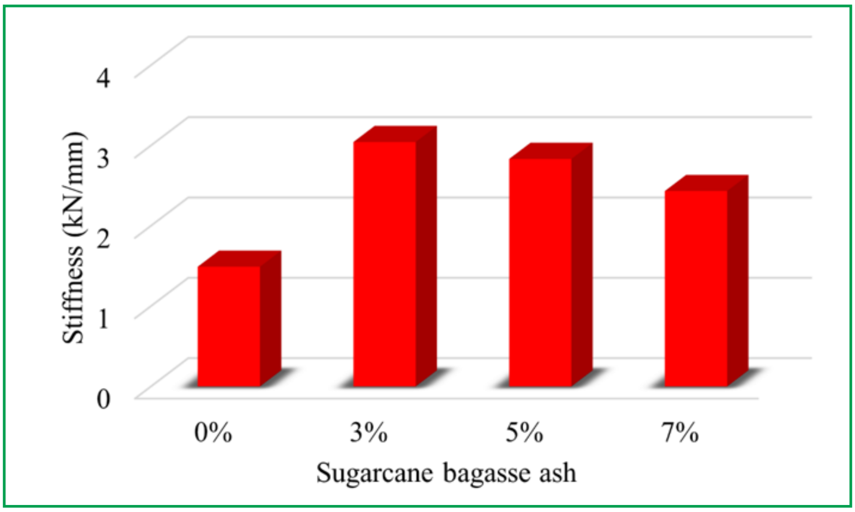


**Figure 10.** Stiffness at different percentage of sugarcane bagasse ash

### *Stiffness*

Figure 10 presents the stiffness of the mixtures, which measures resistance to deformation under load, peaks at 3% sugarcane bagasse ash and then decreases slightly at higher sugarcane bagasse ash contents. The stiffness value increases from 1.49 kN/mm for the control mixture to 3.043 kN/mm at 3% sugarcane bagasse ash, then slightly drops to 2.832 kN/mm at 5% sugarcane bagasse ash and further declines to 2.433 kN/mm at 7% sugarcane bagasse ash. The increased stiffness at 3% and 5% sugarcane bagasse ash is attributed to improved particle interlocking and the pozzolanic reaction of sugarcane bagasse ash, which enhances the binder's rigidity. However, at 7% sugarcane bagasse ash, the decline in stiffness may result from excessive ash leading to poor dispersion and reduced cohesiveness within the mixture. According to JKR standards, higher stiffness is desirable to resist rutting and deformation under heavy traffic loads, particularly in tropical climates. Therefore, 3% sugarcane bagasse ash demonstrates the optimal stiffness performance, making it suitable for high-performance bitumen applications.

### *Indirect Tensile Strength*

The Indirect Tensile Strength values of the sugarcane bagasse ash modified mixtures reveal significant improvement compared to the control mixture, peaking at 3% sugarcane bagasse ash before slightly declining with further addition (Figure 11). The control mixture (0% sugarcane bagasse ash) records a tensile strength value of 375.710 kPa, which increases markedly to 753.612 kPa at 3% sugarcane bagasse ash. However, the tensile strength values decrease to 684.769 kPa and 638.288 kPa at 5% and 7% sugarcane bagasse ash, respectively. The enhancement at 3% sugarcane bagasse ash is attributed to improved adhesion between the binder and aggregates, as well as the filler effect of sugarcane bagasse ash, which improves the cohesion and tensile strength of the mixture. The decline at higher sugarcane bagasse ash contents (5% and 7%) may be due to poor dispersion of the ash or excessive voids, reducing the mixture's tensile resistance. According to JKR specifications, the minimum indirect tensile strength value for bitumen mixtures is 200 kPa, indicating that all sugarcane bagasse ash modified mixtures meet the standard. The highest tensile strength value at 3% sugarcane bagasse ash demonstrates superior tensile strength and cracking resistance, making it the most suitable content for enhancing bitumen performance. However, the declining trend beyond 3% suggests the need for careful optimization to balance sugarcane bagasse ash content and performance.

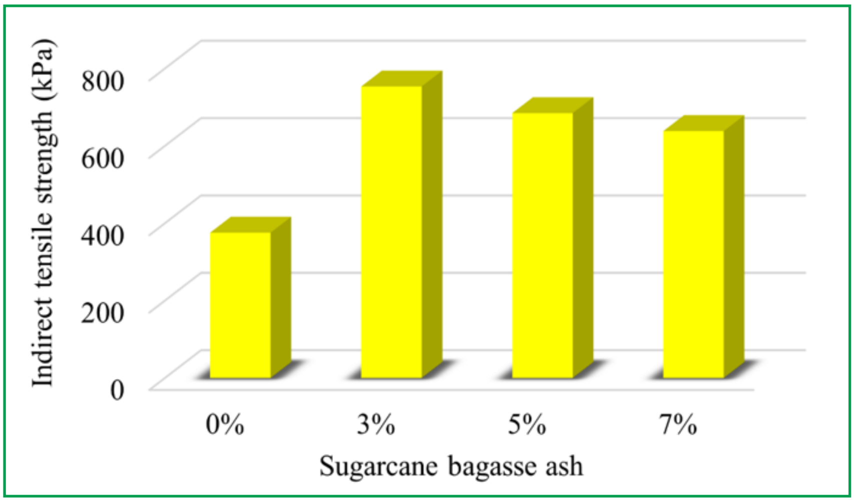


**Figure 11.** Indirect tensile strength at different percentage of sugarcane bagasse ash

https://doi.org/10.70028/sgm.v1i2.20

### Abrasion Loss

The performance of the mixtures shows a distinct trend as the percentage of sugarcane bagasse ash increases. For the control sample with 0% sugarcane bagasse ash, the abrasion loss was found to be 2.77%. This relatively low value indicates a high resistance to abrasion, which is expected from a standard bituminous mixture without any additives. When 3% sugarcane bagasse ash was introduced into the mixture, the abrasion loss increased significantly to 27.01%. This substantial increase suggests that the inclusion of sugarcane bagasse ash at this percentage level begins to negatively affect the durability of the mixture. As the percentage of sugarcane bagasse ash increased to 5%, the abrasion loss further escalated to 48.02%. This indicates a continued trend of reduced resistance to abrasion with higher sugarcane bagasse ash content. The most dramatic change was observed at 7% sugarcane bagasse ash, where the abrasion loss skyrocketed to 92.49%. This very high value clearly shows that at this level, the bituminous mixture becomes highly susceptible to abrasion, making it unsuitable for practical use in road construction or other applications where durability is critical.

### Stability and Density

The correlation between stability and density (Figure 12) exhibits a quadratic relationship, described by the equation $y = -0.084x^2 + 0.6935x + 8.4325$ with a high coefficient of determination ($R^2 = 0.9602$). This indicates a strong relationship where stability initially increases with a decrease in density at lower sugarcane bagasse ash contents but starts to decline as density further reduces at higher sugarcane bagasse ash contents. The peak stability at 5% sugarcane bagasse ash corresponds to the optimal balance between binder and ash content, enhancing the internal cohesion and aggregate bonding. However, the further reduction in density at 7% sugarcane bagasse ash suggests excessive voids and filler material, leading to reduced compactness and a subsequent decline in stability. This behavior highlights the critical need to balance density and sugarcane bagasse ash content for optimal mechanical performance.

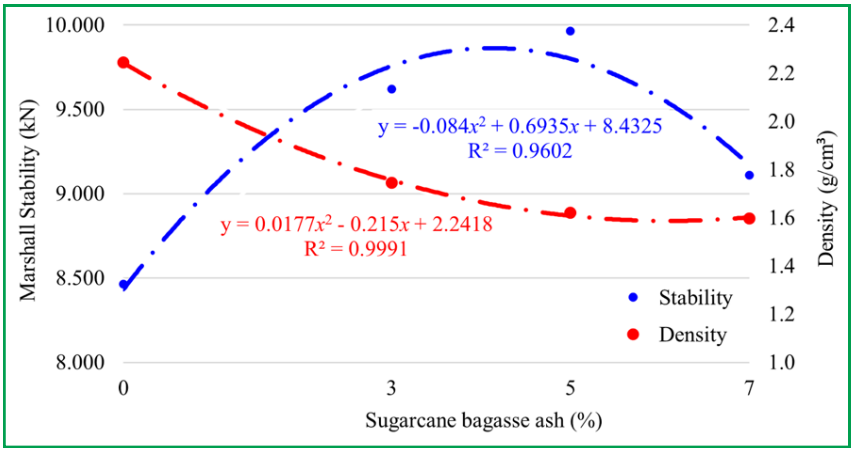


**Figure 12.** Stability and density at different percentage of sugarcane bagasse ash

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### LOSS AND STABILITY

The relationship between stability and abrasion loss is strongly quadratic, represented by the equation $y = 1.4317x^2 + 2.5005x + 3.4868$, with an exceptionally high $R^2 = 0.9939$. This demonstrates that as the abrasion loss increases with higher sugarcane bagasse ash content, the stability first improves, peaking at 5% sugarcane bagasse ash, before declining (Figure 13). The increase in abrasion loss indicates reduced wear resistance at higher sugarcane bagasse ash contents, potentially due to weaker bonding caused by excessive ash. Stability's initial rise with increasing abrasion loss suggests that moderate ash incorporation strengthens the mixture by enhancing filler-binder interaction. However, excessive ash compromises the durability and stability, as observed at 7% sugarcane bagasse ash, underscoring the necessity to optimize sugarcane bagasse ash levels to minimize abrasion loss while maintaining high stability.

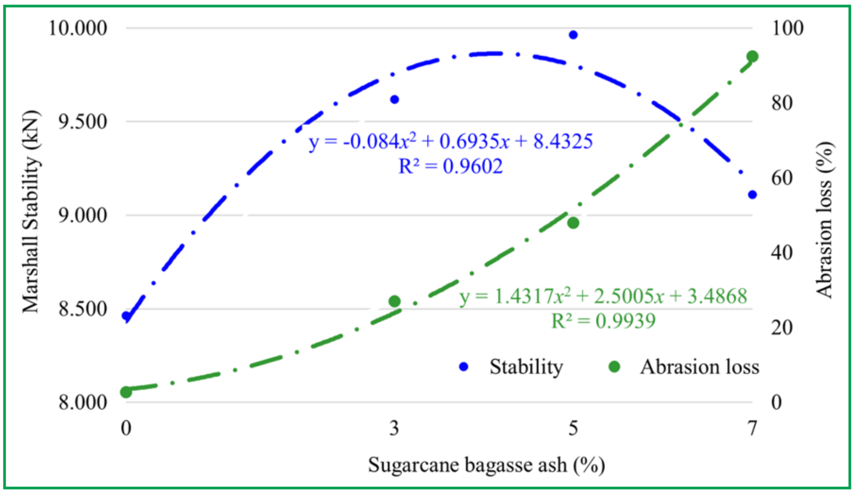


**Figure 13.** Stability and abrasion loss at different percentage of sugarcane bagasse ash

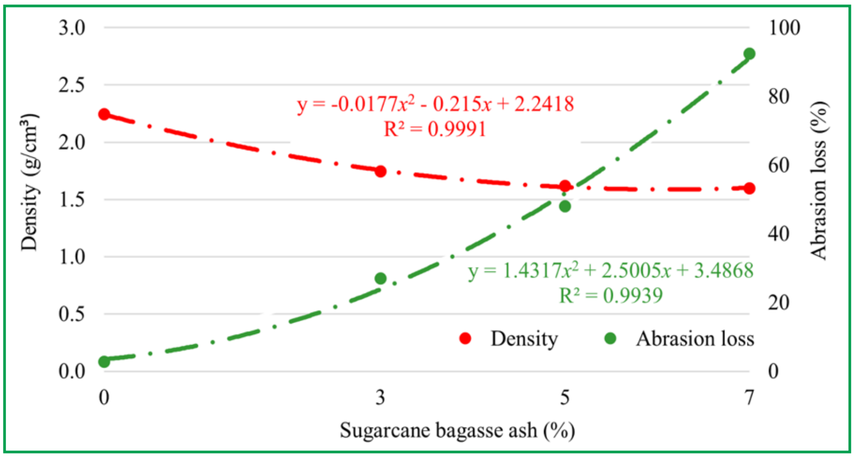


**Figure 14.** Density and abrasion loss at different percentage of sugarcane bagasse ash

### LOSS AND DENSITY

The correlation between abrasion loss and density (Figure 14) also shows a quadratic trend, described by $y = 0.0177x^2 - 0.215x + 2.2418$, with an $R^2 = 0.9991$. As density decreases, abrasion loss increases significantly, reflecting reduced compactness and cohesiveness of the bitumen mixture at higher sugarcane bagasse ash contents. The lower density at higher ash levels creates more voids and weakens the interfacial bonding, leading to higher susceptibility to abrasion. While lower density may contribute to sustainability by reducing the mixture's weight, excessive reduction in density compromises durability, as evidenced by the high abrasion loss at 7% sugarcane bagasse ash. This highlights the importance of maintaining a balance between density and sugarcane bagasse ash content to achieve optimal wear resistance and durability.

### Correlation Analysis for Stability, Density and Abrasion Loss

The correlation analysis demonstrates strong relationships between stability, density, and abrasion loss, as reflected by the high $R^2$ values. Both Marshall stability and density exhibit $R^2 = 0.9602$ and $R^2 = 0.9991$, respectively, indicating a significant relationship with sugarcane bagasse ash content (Table 5). Stability peaks at an optimal ash percentage before declining, while density decreases consistently with increasing sugarcane bagasse ash, attributed to the lower density of sugarcane bagasse ash compared to conventional aggregates. Abrasion loss shows an almost perfect correlation ($R^2 = 0.9939$), with a sharp increase at higher ash contents due to the porous and brittle nature of sugarcane bagasse ash particles. This highlights a critical trade-off, where increased sugarcane bagasse ash improves stability up to an optimum level but compromises density and abrasion resistance at higher contents. These findings underline the need to balance sugarcane bagasse ash content to achieve desired mechanical and durability properties in bitumen mixtures.

**Table 5.** Correlation analysis of stability, density and abrasion loss

| Component | Correlation Equation and $R^2$ |
|---|---|
| Marshall stability | $y = -0.084x^2 + 0.6935x + 8.4325$ <br> $R^2 = 0.9602$ |
| Density | $y = 0.0177x^2 - 0.215x + 2.2418$ <br> $R^2 = 0.9991$ |
| Abrasion loss | $y = 1.4317x^2 + 2.5005x + 3.4868$ <br> $R^2 = 0.9939$ |

## Conclusions

The results demonstrate that sugarcane bagasse ash has the potential to enhance the performance of bitumen binders and mixtures when incorporated at an optimal content. The analysis shows that sugarcane bagasse ash improves critical mechanical properties such as stability, tensile strength, and stiffness, particularly at 3% and 5% content. The reduction in penetration and increase in softening point indicate improved binder resistance to high-temperature deformation, making sugarcane bagasse ash a viable additive for use in regions with extreme climatic conditions. However, at 7% sugarcane bagasse ash, a decline in stability, stiffness, and tensile strength is observed, accompanied by a significant increase in flow and abrasion loss, which highlights the detrimental effects of excessive ash content. These results underline the necessity of careful optimization to maximize the benefits of sugarcane bagasse ash while minimizing its negative impacts. Sugarcane bagasse ash is effective as an additive when used within the recommended range of 3% to 5%, but higher content compromises the durability and mechanical performance of the bitumen mixture.

Sugarcane bagasse ash exhibits desirable characteristics as a partial replacement for conventional fillers in bitumen mixtures, contributing to sustainability by utilizing agricultural waste. The quadratic relationship between stability and density, along with the improved indirect tensile strength and reduced penetration, suggests enhanced binder-aggregate interaction at moderate sugarcane bagasse ash contents (3% to 5%). However, the increase in abrasion loss and reduction in density and stiffness at higher sugarcane bagasse ash levels (7%) reflect the trade-offs associated with excessive filler content. While sugarcane bagasse ash can enhance the performance of bituminous mixtures in terms of stability and resistance to cracking and rutting, its adverse effects at higher contents necessitate careful control of the mix design. Based on the findings, sugarcane bagasse ash is feasible as an additive in bitumen binders and mixtures, particularly for applications requiring enhanced mechanical properties and sustainability, but its usage should be limited to optimal levels (3%-5%) to avoid performance deterioration.

Future research should focus on extended field trials to assess sugarcane bagasse ash -modified mixtures under diverse traffic loads and climatic conditions. Investigations into sugarcane bagasse ash's interactions with different binders and aggregates, as well as its influence on long-term aging and moisture resistance, are essential for broader adoption. Additionally, optimizing sugarcane bagasse ash processing methods to ensure consistent quality will enhance its applicability in various construction scenarios. This study uniquely highlights the use of sugarcane bagasse ash as an innovative additive in bituminous mixtures, offering insights into its potential for improving mechanical properties while supporting sustainable practices. Unlike previous research, this work emphasized specific combinations and optimal content levels of sugarcane bagasse ash, providing a foundation for advancing the use of agricultural waste in modern pavement engineering.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

**Wan Noor Hin Mior Sani:** conceptualization, methodology, writing-reviewing and editing **Ungku Hilmy Daniel Ungku Mohd Arif:** data curation, writing - original draft preparation. **Manizawati Zainal Abidin:** visualization, investigation. **Abdullahi Ali Mohamed:** supervision, validation. **Mohd Hazree Hashim:** funding.

## Data Availability Statement

The data used to support the findings of this study are included within the article.

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