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Research Article

Effect of Sugarcane Bagasse as a Filler on the Performance of Asphalt Mixtures

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Abstract

Sugarcane (Saccharum officinarum) is a major tropical crop widely cultivated due to its high sugar yield and extensive industrial applications. As the primary source of sucrose, it plays a vital role in the global production of sugar and related by-products such as ethanol, molasses, and jaggery, contributing significantly to the agricultural economies of countries including Brazil, India, Thailand, and Malaysia. However, sugarcane processing generates substantial quantities of bagasse the dry, fibrous residue remaining after juice extraction which is often underutilized or improperly disposed of through open burning or landfilling, leading to environmental concerns such as air pollution and waste accumulation. In Malaysia, one ton of processed sugarcane can produce approximately 280 kg of bagasse, highlighting the urgency of sustainable waste management strategies. This study investigates the potential use of sugarcane bagasse as a filler material in asphalt mixtures, focusing on its effects on the physical and mechanical properties of asphalt performance. The research further aims to determine the optimum percentage of bagasse filler for enhancing asphalt mixture performance. Modified asphalt mixtures were evaluated using the Marshall Stability test and the Indirect Tensile Strength (ITS) test to assess strength, stability, and overall performance characteristics. The findings indicate that incorporating sugarcane bagasse in proportions ranging from 4% to 8% by filler weight can significantly improve stability, tensile strength, and moisture resistance. These results demonstrate the feasibility of utilizing sugarcane bagasse as a sustainable alternative filler, supporting eco-friendly pavement construction and contributing to the circular reuse of agricultural waste.

Keywords: Strength, Stability, Sugarcane, Bagasse, Asphalt

Introduction

The growing emphasis on sustainable infrastructure has intensified research into alternative materials for asphalt pavement construction [1]. Conventional asphalt mixtures rely heavily on virgin mineral fillers such as limestone powder to enhance stiffness, stability, and durability [2]. However, the continuous extraction of these materials contributes to environmental degradation, resource depletion, and rising construction costs [3]. As a result, the incorporation of waste-derived materials has emerged as a promising strategy to improve pavement performance while supporting environmental sustainability [4].

Fillers, defined as finely divided materials passing the 0.075 mm sieve, play a critical role in asphalt mixture behavior despite constituting a small proportion of the total mix [5]. They interact with bitumen to form asphalt mastic, which governs key performance characteristics including stiffness, resistance to permanent deformation, moisture susceptibility, and durability [6]. Traditional fillers such as limestone dust are favored for their compatibility with bitumen, alkaline nature, and ability to improve aggregate–binder adhesion [6]. Limestone filler enhances mixture densification, reduces air voids [7], and improves Marshall stability, making it one of the most widely used fillers in asphalt pavements [8].

Nevertheless, limestone filler production involves quarrying, crushing, and grinding processes that consume significant energy and generate environmental impacts [9]. This has driven increasing interest in alternative fillers derived from agricultural and industrial wastes [10]. Agricultural waste ashes, in particular, have shown potential due to their fine particle size, silica-rich composition, and pozzolanic characteristics [11]. These properties allow waste-based fillers to function not only as void-filling agents but also as active components that influence binder rheology and mixture performance [12].

Several studies have demonstrated the feasibility of using agricultural waste materials as partial or full replacements for mineral fillers in asphalt mixtures [10]. Corn cob ash (CCA), groundnut shell ash (GSA), and egg shell powder (ESP) have been reported to improve Marshall stability, volumetric properties, and stiffness when incorporated at optimal replacement levels [13-15]. However, excessive dosages often lead to reduced ductility and workability, highlighting the importance of dosage optimization [11]. These findings collectively indicate that agricultural waste fillers can perform comparably to conventional fillers when properly processed and proportioned [10].

Among agricultural wastes, sugarcane bagasse ash (SBA) has gained attention due to the large volume of bagasse generated by the sugar industry, particularly in tropical countries [16]. SBA is produced through the controlled combustion of sugarcane bagasse, resulting in a fine ash rich in silica and other oxides [16]. Compared to limestone filler, SBA exhibits lower specific gravity but higher surface area and silica content, which enhances its interaction with asphalt binder [17]. The porous and irregular particle morphology of SBA promotes better mastic formation and mechanical interlocking within the asphalt matrix [18].

In contrast, limestone filler is predominantly calcium-based and chemically inert, contributing primarily to physical densification and adhesion improvement through its alkaline nature [19]. SBA, on the other hand, provides both physical and chemical contributions. Its high silica content enhances binder stiffening and improves moisture resistance by strengthening the aggregate–binder

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interface [16]. Studies have shown that asphalt mixtures containing SBA exhibit comparable or higher Marshall stability and indirect tensile strength than those incorporating limestone filler, particularly at moderate replacement levels [16].

Furthermore, SBA has demonstrated improved resistance to permanent deformation under high-temperature conditions, a critical advantage in tropical climates [20]. The fine particle size of SBA enables efficient void filling, resulting in denser mixtures with reduced air voids and improved durability [20]. Limestone filler, while effective in improving initial stiffness, does not contribute to pozzolanic or reactive interactions within the mixture, limiting its performance enhancement to physical mechanisms alone [18].

From an environmental perspective, the utilization of SBA offers significant advantages over limestone filler [21]. SBA valorizes agricultural waste that would otherwise be disposed of through open burning or landfilling, contributing to air pollution and waste accumulation [16]. Replacing limestone filler with SBA reduces the demand for non-renewable mineral resources and lowers the overall carbon footprint of asphalt pavement construction [21]. These sustainability benefits align with global initiatives promoting circular economy and low-impact infrastructure development [21].

Despite the demonstrated potential of SBA, existing studies remain limited in scope, particularly with respect to tropical pavement conditions [16]. Many investigations have focused on cementitious applications, while research on asphalt mixtures has been relatively sparse and fragmented [24]. Moreover, direct comparative evaluations between SBA and conventional limestone filler under standardized testing conditions are still insufficient, especially in terms of mechanical performance indicators such as Marshall stability and indirect tensile strength [16].

Based on the reviewed literature, it is evident that sugarcane bagasse ash has the potential to function as an effective alternative filler to limestone in asphalt mixtures [16]. Its favorable physicochemical properties, coupled with environmental benefits, make SBA a promising material for sustainable pavement applications [16]. However, further experimental investigations are required to establish optimal SBA content [18] and to systematically compare its performance with conventional fillers under tropical climatic conditions [11].

Therefore, this study aims to address these research gaps by evaluating the mechanical and performance characteristics of asphalt mixtures incorporating sugarcane bagasse ash as a filler, with direct comparison to limestone filler [16]. The findings are expected to contribute to the development of eco-friendly asphalt pavements and support the broader adoption of agricultural waste materials in road construction [16].

Materials and Methods

Materials

Sugarcane bagasse ash (SBA), penetration-grade bitumen 60/70, and AC14 aggregates were used in this study. Raw sugarcane bagasse was collected from local vendors and air-dried to remove residual moisture prior to combustion. Figure 1 shows the physical appearance of raw sugarcane bagasse, while Figure 2 illustrates the ash generated from the burning process. The dried bagasse was incinerated under controlled conditions at temperatures between 500 °C and 700 °C using a combustion furnace to obtain ash, as illustrated in Figure 3. The resulting sugarcane bagasse ash was cooled, crushed, and sieved to obtain particles smaller than 30 µm, ensuring consistency and suitability as a filler material.

Figure 1. Preparation stage of sugarcane bagasse prior to ash production

Figure 2. Sugarcane Bagasse Ash (SBA)

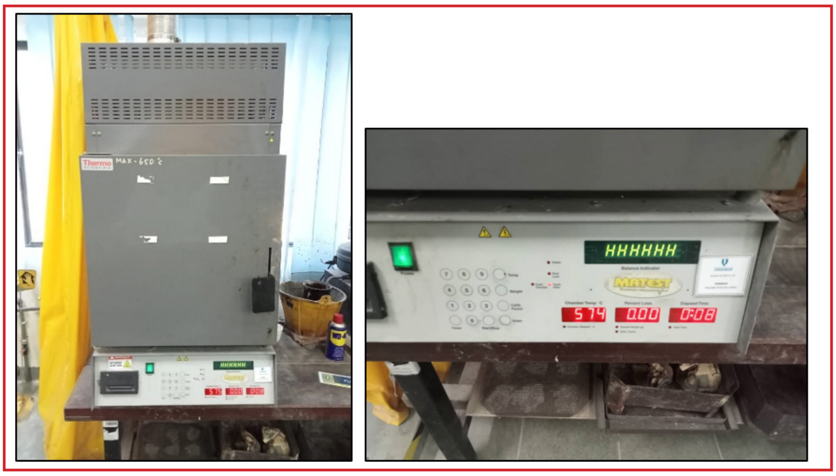

Figure 3. Combustion process of sugarcane bagasse in furnace

Penetration-grade 60/70 bitumen, commonly used in flexible pavement applications in tropical regions, was selected as the binder. The bitumen properties were verified using the standard penetration test [23] and softening point test [24] to ensure compliance with pavement specifications. AC14 aggregates were employed as the coarse and fine aggregate components. Aggregate quality and gradation were confirmed through sieve analysis [25], Aggregate Crushing Value (ACV) test [26], and Aggregate Impact Value (AIV) test [27]. The penetration-grade bitumen 60/70 and AC14 aggregates utilized in this investigation are shown in Figure 4. Figure 5 also shows the study's entire experimental flowchart, which includes steps for material preparation, processing, and testing.

Figure 4. Bitumen 60/70 and AC14 aggregates

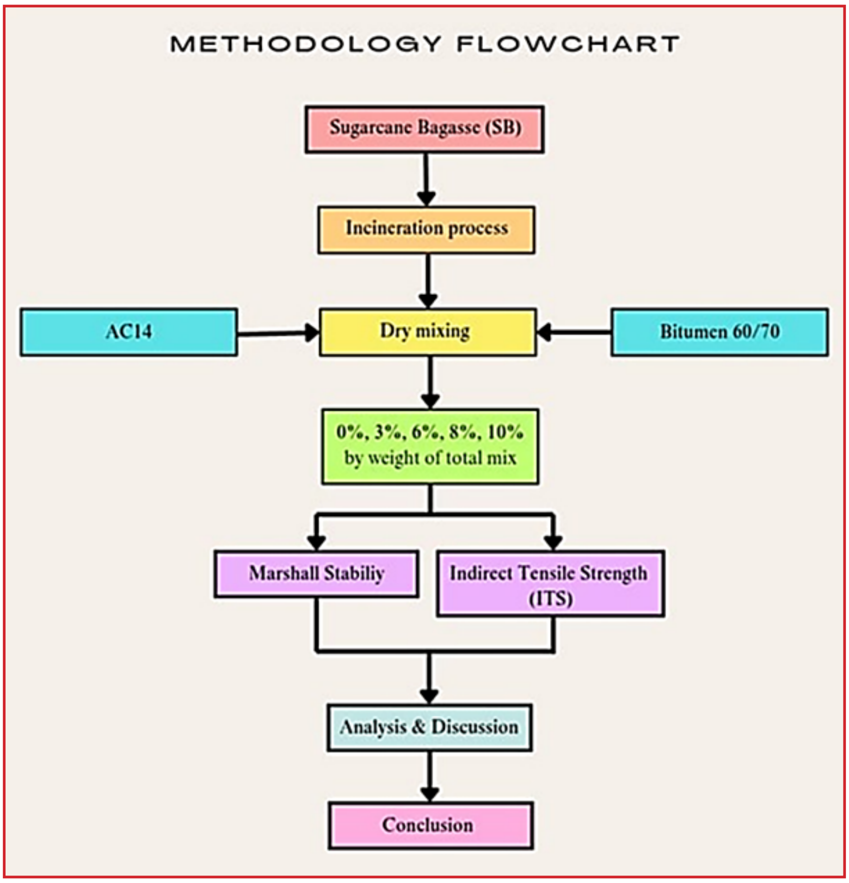

Figure 5. Flowchart of the experimental methodology

Asphalt Mixture Design

The Marshall mix design method was adopted to prepare asphalt mixtures incorporating SBA as a partial replacement for conventional mineral filler. The control mixture utilized limestone filler, while modified mixtures incorporated SBA at replacement levels of 0%, 3%, 6%, 8%, and 10% by total filler weight. Table 1 summarizes the number of asphalt mixture specimens prepared for each replacement level, and Table 2 presents the detailed mix design parameters for all mixtures. The quantities of aggregate, bitumen, and filler are provided in grams, following standard Marshall mix design procedures. All mixtures were designed using a nominal aggregate gradation of AC14 and a target bitumen content of approximately 5% by total mix weight. Aggregates were oven-dried and heated prior to mixing. Bitumen was heated to approximately 160 °C to achieve the required viscosity. SBA and conventional filler were dry-mixed with the heated aggregates before adding bitumen to ensure uniform distribution. The prepared mixtures were compacted in standard Marshall molds using 75 blows per face to simulate heavy traffic conditions. Figure 6 and Figure 7 depicts the preparation and compaction process for Marshall specimens.

Table 1. Summary of specimens for mechanical testing of asphalt mixtures

SBA (%)	Number of Samples		Total Number of Samples
	Marshall Stability	ITS	
0	3	3	6
3	3	3	6
6	3	3	6
8	3	3	6
10	3	3	6
Total Samples	15	15	30

Table 2. Mix proportions of asphalt mixtures with different SBA contents

(SBA %)	SBA Content (g)	Bitumen Content (g)	Aggregate Content (g)
M1 (0%)	0	63.16	1200
M2 (3%)	39.09	63.16	1200
M3 (6%)	80.68	63.16	1200
M4 (8%)	109.91	63.16	1200
M5 (10%)	140.44	63.16	1200

Figure 6. Incorporation of sugarcane bagasse ash (SBA) into the asphalt mixture through manual mixing to ensure homogeneity

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Figure 7. Marshall specimen preparation prior to testing, including mold filling, air void removal, and standard compaction

Sample Preparation and Conditioning

Cylindrical Marshall specimens were prepared for each filler replacement level. After compaction, specimens were allowed to cool at room temperature and subsequently conditioned according to the requirements of each test method. For Marshall Stability testing, specimens were immersed in a water bath at 60 °C for 30–45 minutes prior to testing. Figure 8 displays the Marshall sample placed in the water bath prior to testing, along with the specimen after being immersed in the bathtub. Figure 9 presents the Marshall specimens that are prepared for testing. For Indirect Tensile Strength (ITS) testing, specimens were conditioned at 25 °C to represent typical service temperature conditions.

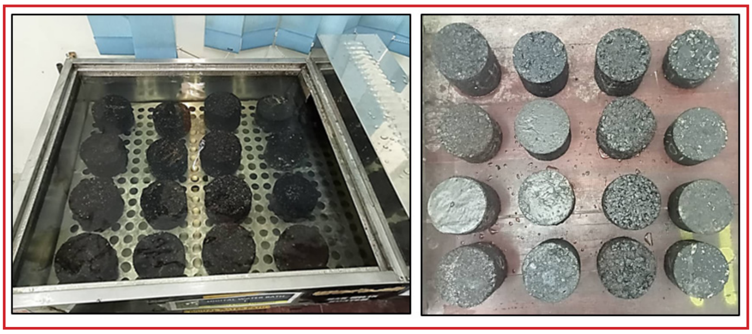

Figure 8. Marshall specimens during, and after water bath conditioning

Figure 9. Marshall specimens after compaction, ready for testing

Mechanical Testing

The mechanical performance of the asphalt mixtures was evaluated using the Marshall Stability test and the Indirect Tensile Strength (ITS) test. Marshall Stability and flow values were determined in accordance with [28] by applying a compressive load at a constant deformation rate of 50 mm/min until failure. The maximum load sustained by the specimen was recorded as the Marshall stability, providing an indication of load-bearing capacity and resistance to plastic deformation. Figure 10 shows the Marshall stability testing of an asphalt mixture with Sugarcane Bagasse Ash (SBA) as filler.

Figure 10. Marshall stability testing of asphalt mixture containing Sugarcane Bagasse Ash

Figure 11. Indirect Tensile Strength testing of asphalt mixture containing Sugarcane Bagasse Ash

The ITS test was conducted in accordance with [29] to evaluate tensile strength and cracking resistance. Specimens were positioned horizontally between loading strips and subjected to diametral compressive loading at a constant rate

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of 50 mm/min until failure. The maximum load at failure was recorded and used to calculate the indirect tensile strength. This test was employed to assess the influence of SBA on the tensile behavior and crack resistance of the asphalt mixtures. Figure 11 shows the Indirect Tensile Strength testing of an asphalt mixture with Sugarcane Bagasse Ash (SBA) as filler.

Experimental Framework and Data Analysis

All test results were compared against the control mixture containing limestone filler to evaluate the effectiveness of sugarcane bagasse ash as an alternative filler. The influence of SBA content on Marshall stability and indirect tensile strength was analyzed to identify the optimal replacement level. The experimental framework enabled a direct performance comparison between SBA-modified and conventional asphalt mixtures under standardized laboratory conditions.

Table 3. Softening point test result (1)

Timer Reading (Minutes)	Temperature (°C)	
	Ball 1	Ball 2
0	26.5	26.5
1	26.5	26.5
2	26.6	26.6
3	27.6	27.6
4	27.9	27.9
5	28.1	28.1
6	28.3	28.3
7	29.2	29.2
8	29.8	29.8
9	30.1	30.1
10	30.2	30.2
11	31.7	31.7
12	32.2	32.2
13	32.4	32.4
14	33.3	33.3
15	34.1	34.1
16	35.1	35.1
17	36.2	36.2
18	37.3	37.3
19	38.4	38.4
20	39.4	39.4
21	40.1	40.1
22	41.4	41.4
23	42.0	42.0
24	43.5	43.5
25	44.3	44.3
26	45.6	45.6
27	46.8	46.8
28	47.7	47.7
29		48.7
30		49.5

Results and Discussions

Binder and Aggregate Characterization

The penetration grade 60/70 bitumen used in this study exhibited an average softening point of 48.6 °C and a mean penetration value of 66 dmm, confirming its suitability for flexible pavement applications in tropical climates. These values indicate adequate resistance to temperature-induced softening while

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maintaining sufficient flexibility. The outcomes of the softening point test are detailed in Table 3 and Table 4. Figure 12 displays a bar chart that compares the temperatures of Ball 1 and Ball 2, while Figure 13 shows the softening points of these balls. Table 5 summarizes the penetration values for the bitumen samples, and the penetration test apparatus is depicted in Figures 14 and Figure 15, which include a bar chart of the penetration values for the bitumen samples.

Table 4. Softening point test result (2)

Test	1	2	Average
Softening Point (°C)	47.7	49.5	48.6

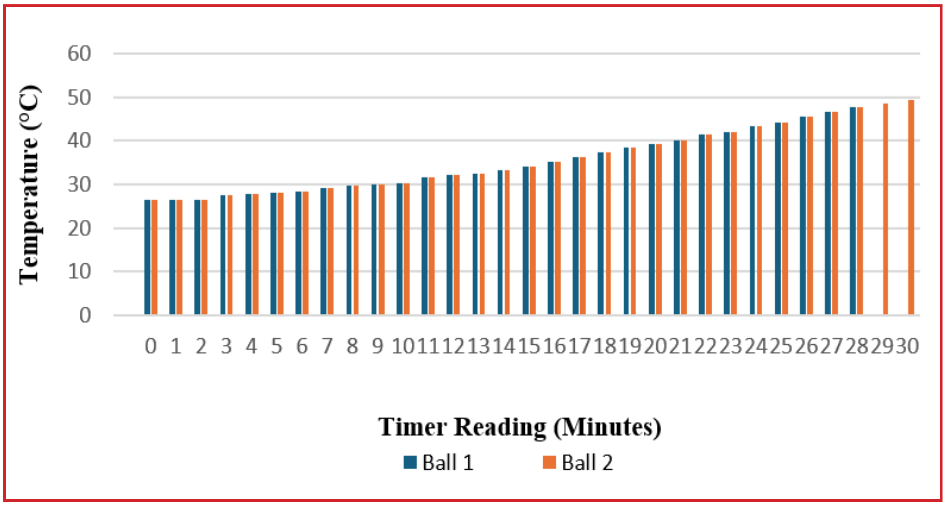

Figure 12. Ball 1 and Ball 2's softening point temperatures

Figure 13. Ball 1 reached the softening point and dropped, while Ball 2 was approaching it

Table 5. Standard penetration test result

No. of Penetration	Penetration (mm)			Average
1	54.7	66.7	78.1	66.50
2	72.7	64.5	71.0	69.40
3	56.3	63.2	67.3	62.27
AVERAGE				**66.06**

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Figure 14. Penetration test apparatus during testing

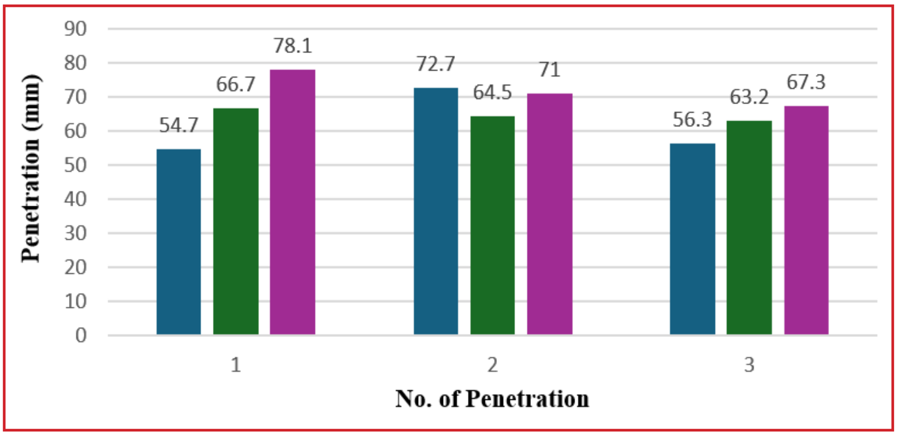

Figure 15. Penetration values of bitumen samples

Aggregate quality assessment revealed an Aggregate Impact Value (AIV) of 18% (Table 6) and an Aggregate Crushing Value (ACV) of 9.39% (Table 7), demonstrating high resistance to impact and compressive stresses. These properties ensured that aggregate-related variability did not govern mixture performance, allowing the effect of Sugarcane Bagasse Ash (SBA) to be clearly evaluated.

Table 6. Aggregate impact value test result

Sample	Aggregate size (mm)	Weight of Aggregate (g)			Loss (%)
		Before test (M_1)	Retain at 2.36mm sieve (M_2)	Passing at 2.36mm (Loss) (M_3)	
A	14 - 10	312.49	244.29	58.38	18

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Table 7. Aggregate crushing value test result

Sample	A
Total mass of surface – dry sample M1 (g)	2573.14
Mass of the fraction passing the 2.36mm test sieve M3 (g)	241.50
Percentage fines (y) $\frac{M_3}{M_1} \times 100$	9.39
Mean percentage fines (Y) %	9.39
Maximum force recorded (kN)	126
Mean maximum force recorded (X) (kN)	63
Force required to produce 10% fines $\frac{(14X)}{(Y+4)} \times 100$	66

Marshall Stability and Volumetric Performance

Marshall stability results showed a clear dependency on SBA content (Table 8). The control mixture containing limestone filler exhibited stable load-bearing performance; however, the incorporation of SBA at low replacement levels significantly enhanced stability. The highest corrected Marshall stability, approximately 14.7 kN, was achieved at 3% SBA, indicating improved aggregate interlock and filler–binder interaction. This improvement is attributed to the fine particle size and high surface area of SBA, which enhanced mastic stiffness and load transfer within the asphalt matrix.

Table 8. Marshall stability results

SBA (%)	Bulk Specific Gravity	VMA (%)	VFA (%)	VTM (%)	Stability (N)	Flow (mm)	Stiffness (N/mm)
0	2.17	16.70	0	16.70	13922.43	4.356	3199.54
3	2.16	13.42	31.89	13.42	14766.77	4.279	3451.85
6	2.13	10.56	54.25	10.56	12809.11	4.318	2967.25
8	2.09	9.88	62.43	9.88	12385.84	4.301	2880.12
10	1.81	19.84	47.46	19.84	10387.86	4.370	2377.63

Beyond 3% SBA, Marshall stability gradually declined. At higher replacement levels (6–10%), excessive fine particles likely reduced aggregate friction and disrupted the aggregate–binder balance, resulting in lower resistance to deformation. Flow values remained within acceptable limits (approximately 4.36–4.37 mm) for all mixtures, indicating that SBA incorporation did not compromise mixture flexibility. However, stiffness values decreased markedly at higher SBA contents, confirming that excessive filler reduced mixture rigidity and structural integrity.

Volumetric analysis further supported these findings. Increasing SBA content resulted in a reduction in bulk specific gravity and variations in void-related parameters. Mixtures containing 3% SBA exhibited a favorable balance of air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA), promoting adequate densification and durability. In contrast, mixtures with 8–10% SBA showed excessive voids and reduced cohesion, suggesting inefficient

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binder coating and increased susceptibility to performance degradation. Tables 8 present the Marshall stability results, while the trends in Bulk Specific Gravity, VMA, VFA, VTM, Stability, Flow and Stiffness are illustrated in Figures 16 to 22.

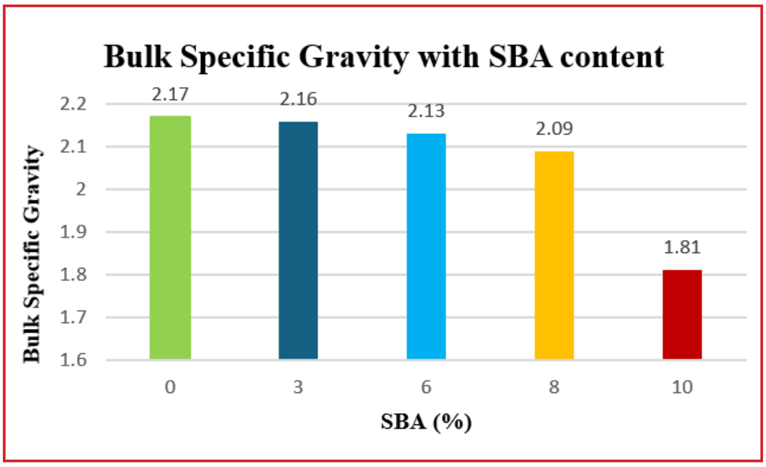

Figure 16. Variation of bulk specific gravity with SBA content

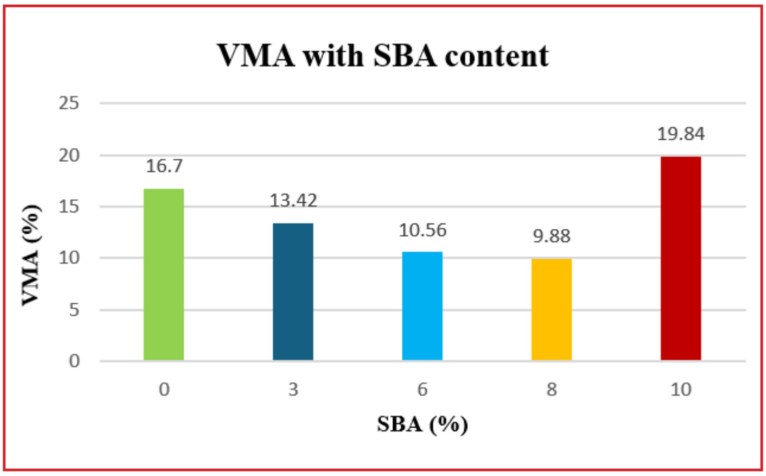

Figure 17. Variation of VMA with SBA content

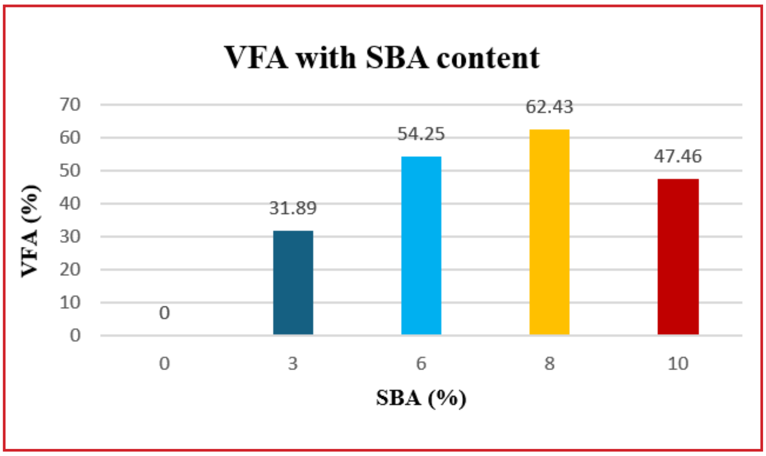

Figure 18. Variation of VFA with SBA content

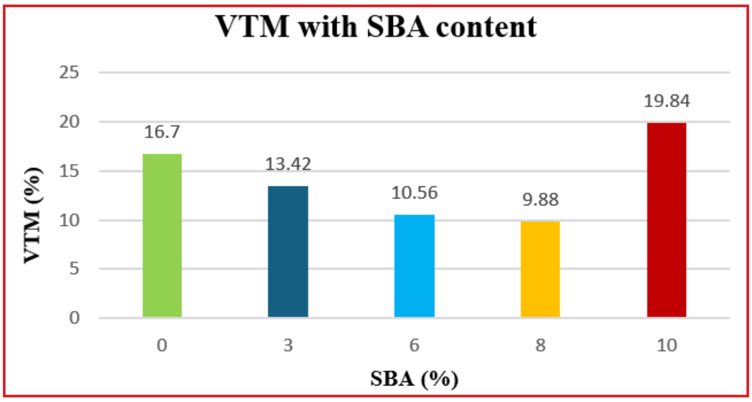

Figure 19. Variation of VTM with SBA content

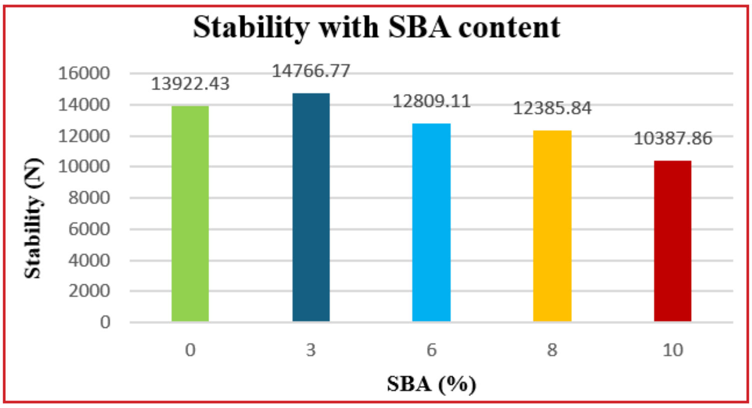

Figure 20. Variation of stability with SBA content

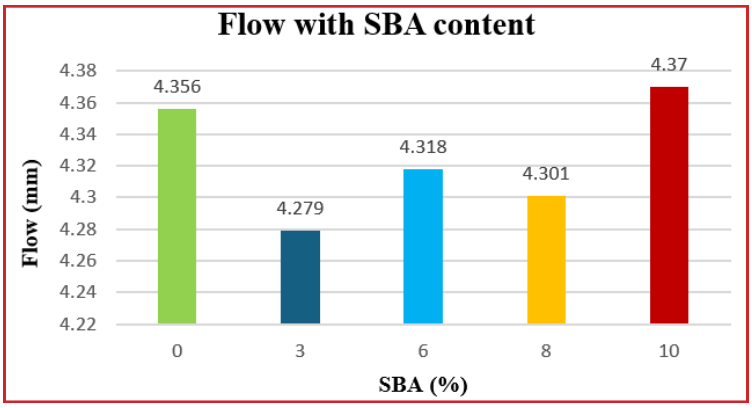

Figure 21. Variation of flow with SBA content

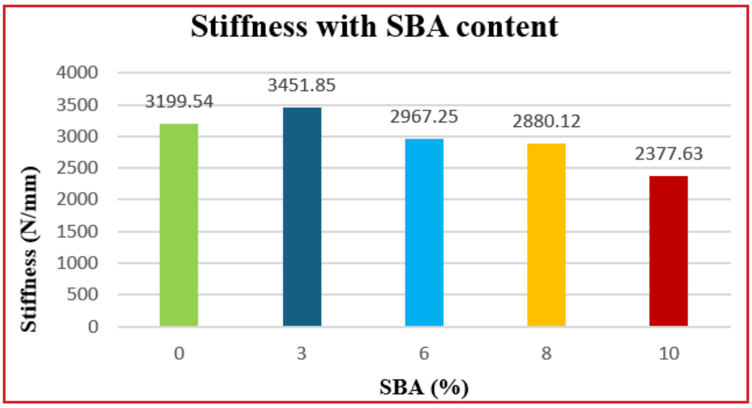

Figure 22. Variation of stiffness with SBA content

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Indirect Tensile Strength Performance

Indirect Tensile Strength (ITS) results demonstrated a similar trend to Marshall stability. The control mixture exhibited moderate and consistent tensile strength, with ITS values ranging between 0.518 and 0.664 MPa. The addition of 3% SBA significantly enhanced tensile performance, producing the highest recorded ITS value of 0.727 MPa. This improvement indicates enhanced crack resistance, likely due to improved filler dispersion and stronger binder–aggregate bonding facilitated by SBA's silica-rich composition.

At higher SBA contents (≥6%), ITS values decreased progressively. Mixtures containing 10% SBA exhibited the lowest tensile strength, indicating a weakened internal structure. Excessive SBA likely led to an overabundance of fines, which hindered effective binder coating and reduced stress distribution across the aggregate skeleton. These findings highlight the critical importance of optimizing SBA content to maximize mechanical performance without compromising mixture cohesion. Figure 23 illustrates the variation of ITS with SBA content.

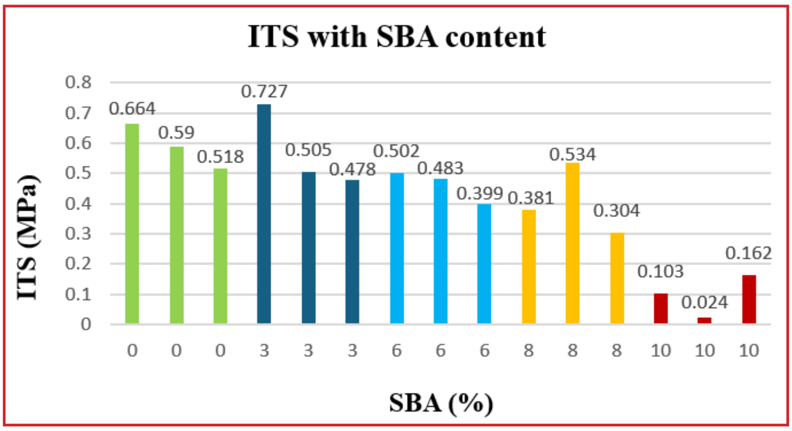

Figure 23. Variation of ITS with SBA content

Figure 24. SBA sample image prior to SEM analysis

Microstructural Observations

Scanning Electron Microscopy (SEM) analysis revealed that SBA particles possessed an irregular, porous, and rough surface morphology. Such characteristics enhance mechanical interlocking and binder adhesion at low replacement levels, explaining the improved performance observed at 3% SBA.

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However, the presence of numerous pores and unreacted particles at higher SBA contents suggests incomplete integration within the asphalt matrix, contributing to reduced mechanical strength and increased void concentration. Figure 24 and Figure 25 present the microstructural features of the SBA sample before and during SEM analysis.

Figure 25. SEM picture displaying the sample's rough and porous surface shape

Overall Performance Assessment and Statistical Significance

The combined mechanical, volumetric, and microstructural results indicate that SBA can effectively function as a partial replacement for conventional limestone filler when used at an optimal dosage. Low SBA content enhances mixture stiffness, stability, and tensile resistance through improved filler–binder interaction, while excessive substitution leads to performance deterioration due to excessive fines and reduced aggregate interlock.

Although no formal statistical hypothesis testing was conducted, the variations observed in Marshall stability and indirect tensile strength (ITS) across different SBA contents exhibited consistent and systematic trends. The performance enhancement recorded at 3% SBA content was substantially greater than the inherent variability among replicate specimens, indicating that the observed improvements were primarily attributable to SBA incorporation rather than experimental scatter. Conversely, the progressive reduction in mechanical performance at higher SBA contents (≥6%) further confirms the sensitivity of asphalt mixture behavior to filler dosage. The consistency of these trends across multiple performance indicators suggests that the influence of SBA content on asphalt mixture performance is both statistically meaningful and practically significant.

Conclusion

This study evaluated the feasibility of utilizing Sugarcane Bagasse Ash (SBA) as a sustainable filler in asphalt mixtures by examining its effects on Marshall stability, volumetric properties, and indirect tensile strength. Based on the experimental findings, the following conclusions can be drawn:

1. The incorporation of SBA significantly influences the mechanical and volumetric performance of asphalt mixtures, with performance strongly dependent on filler content.

2. An optimum SBA content of 3% by filler weight was identified, providing the highest Marshall stability and indirect tensile strength while maintaining acceptable flow and volumetric characteristics.
3. Low SBA content enhances filler–binder interaction, improves aggregate interlocking, and promotes a denser asphalt matrix, resulting in improved load-bearing and crack resistance.
4. Excessive SBA substitution (≥6%) adversely affects mixture performance due to excessive fine particles, reduced binder coating efficiency, and weakened internal structure.
5. Microstructural observations confirm that SBA's porous and irregular morphology contributes positively to performance at low contents but becomes detrimental when present in excess.

Overall, Sugarcane Bagasse Ash demonstrates strong potential as an eco-friendly alternative filler for asphalt mixtures when used at an optimized proportion. Its application supports sustainable pavement construction by reducing dependence on conventional mineral fillers and promoting the reuse of agricultural waste. Future studies should focus on long-term durability, moisture damage resistance, and field-scale validation to further establish the suitability of SBA-modified asphalt mixtures under real service conditions.

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Conflicts of Interest

The author has no conflicts of interest to declare.

Author Contributions

Zulaika Nor Aishah Mohammad Rosman: formal analysis, investigation, writing-original draft preparation. **Wan Noor Hin Mior Sani:** conceptualization, supervision, validation, writing-review & editing. **Nik Nur Dina Nik Azmi:** methodology, software. **Indra Mawardi:** validation, writing-review & editing.

References

[1] N. S. Mashaan, D. O. Oguntayo, and C. Dassanayake, "Waste by-products in asphalt pavement construction: A review," MDPI (Basel, Switzerland), vol. 18, no. 17, Art. no. 4092, Sep. 01, 2025, doi: http://dx.doi.org/10.3390/ma18174092

[2] S. A. Gani, E. E. Putri, B. M. Adji, A. Hakam, and J. Makinda, "Investigation on the Performance of Limestone as Filler on Various Pavement Mixtures," Civil and Environmental Engineering, vol. 19, no. 2, pp. 618-629, Dec. 2023, doi: http://dx.doi.org/10.2478/cee-2023-0056

[3] A. Murodif, A. M. Fauzi, Erizal, and L. Karlinasari, "Environmental Impact of Limestone Mining Using A Life Cycle Assessment Method," Jurnal Pengelolaan Sumberdaya Alam

dan Lingkungan (JPSL), vol. 15, no. 1, Art. no. 122, Jan. 07, 2025, doi: http://dx.doi.org/10.29244/jpsl.15.1.122

[4] P. Babashamsi, N. I. M. Yusoff, H. Ceylan, and N. G. M. Nor, “Recycling Toward Sustainable Pavement Development: End-Of-Life Considerations in Asphalt Pavement,” Highway and Transportation Engineering, vol. 78, no. 7-2, July. 27, 2016, doi: http://dx.doi.org/10.11113/jt.v78.9470

[5] B. Xing, C. Fang, X. Lyu, W. Fan, and Y. Lyu, “Influence of mineral filler characteristics on the filler–asphalt interfacial behavior,” Advanced Powder Technology, vol. 35, no 10, Art. no. 104636, Oct. 2024, doi: http://dx.doi.org/10.1016/j.apt.2024.104636

[6] Guangxun E, J. Zhang, Q. Shen, P. Ji, J. Wang, and Y. Xiao, “Influence of Filler Type and Rheological Properties of Asphalt Mastic on the Asphalt Mastic–Aggregate Interaction,” MDPI (Basel, Switzerland), vol. 16, no 2, Art. no. 574, Jan. 06, 2023, doi: http://dx.doi.org/10.3390/ma16020574

[7] H. F. A. Alabady, and A. H. Abed, “Effect of Quality and Quantity of Locally Produced Filler on Moisture Damage Hot Asphaltic Mixtures,” Transportation Science and Technology, E3S Web Conf., vol. 427, Art. no. 03039, pp. 8, Sep. 13, 2023, doi: http://dx.doi.org/10.1051/e3sconf/202342703039

[8] A. H. Aljassar, S. Metwali, and M. A. Ali, “Effect of Filler Types on Marshall Stability and Retained Strength of Asphalt Concrete,” International Journal of Pavement Engineering, vol. 5, no. 1, pp. 47-51, Jan. 31, 2007, doi: http://dx.doi.org/10.1080/10298430410001733491

[9] A. D. Bortoli, “Understanding the environmental impacts of virgin aggregates: critical literature review and primary comprehensive Life Cycle Assessments,” Journal of Cleaner Production, vol. 415, Art. no. 137629, Aug. 20, 2023, doi: http://dx.doi.org/10.1016/j.jclepro.2023.137629

[10] Z. Jwaida, Q. A. A. Quraishy, R. R. A. Almuhanna, A. Dulaimi, L. F. A. Bernardo, and J. M. D. A. Andrade, “The Use of Waste Fillers in Asphalt Mixtures: A Comprehensive Review,” MDPI (Basel, Switzerland), vol. 5, no. 4, pp. 801-826, Sep. 24, 2024, doi: http://dx.doi.org/10.3390/civileng5040042

[11] L. Pratiwi, E. E. Putri, B. M. Adji, and A. Satriawan, “Sustainable Asphalt Mixtures Using Agricultural Waste Fillers: A Systematic Review of Rice Husk Ash, Bagasse Ash and Palm Shell Ash,” Civil and Environmental Engineering, Oct. 08, 2025, doi: http://dx.doi.org/10.2478/cee-2026-0014

[12] L. Ou, H. Zhu, R. Chen, C. Su, and X. Yang, “Effect of Industrial Solid Waste as Fillers on the Rheology and Surface Free Energy of Asphalt Mastic,” MDPI (Basel, Switzerland), vol. 17, no. 5, Art. no. 1125, Feb. 29, 2024, doi: http://dx.doi.org/10.3390/ma17051125

[13] Asebiomo, J.O., Aderinola, O.S., Ejigboye, P.O. et al., “Evaluation of Corn Cob Ash as Mineral Filler in Asphalt Mixture,” Int. J. Pavement Res. Technol, vol. 18, no. 7, pp. 1574-1585, May. 16, 2024, doi: http://dx.doi.org/10.1007/s42947-024-00440-0

[14] R. Tisnawan, R. R. Husaini, A. Kurnain, and R. Saputra, “Marshall Performance Analysis of Eggshells and Cement as Filler in Asphalt Concrete Mixtures (AC-WC),” JIM, vol 2, no. 1, Feb. 02, 2024, doi: http://dx.doi.org/10.58794/jim.v2i1.633

[15] N. Sathiparan, A. Anburuvel, and V. V. Selvam, “Utilization of agro-waste groundnut shell and its derivatives in sustainable construction and building materials – A review,”

Journal of Building Engineering, vol. 66, Art. no. 105866, May. 01, 2023, doi: http://dx.doi.org/10.1016/j.jobe.2023.105866

[16] U. U. Imoh, A. O. Adeboje, E. R. Adekola, E. R. Adekola, and M. M. Rad, "Effect of Sugarcane Bagasse Ash on the sustainable performance of hot-mix asphalt: A case study of experimental and numerical analysis," Case Studies in Construction Materials, vol. 24, Art. no. e05769, Jul. 2026, doi: http://dx.doi.org/10.1016/j.cscm.2026.e05769

[17] P. K. Akarsh, G. O. Ganesh, S. Marathe, and R. Rai, "Incorporation of Sugarcane Bagasse Ash to investigate the mechanical behavior of Stone Mastic Asphalt," Construction and Building Materials, vol. 353, Art. no. 129089, Oct. 24, 2022, doi: http://dx.doi.org/10.1016/j.conbuildmat.2022.129089

[18] A. Zia, and A. A. Khan, "Effectiveness of bagasse ash for performance improvement of asphalt concrete pavements," SN Appl. Sci, vol. 3, Art. no. 502, Mar. 25, 2021, doi: http://dx.doi.org/10.1007/s42452-021-04502-x

[19] M. Sarir, Z. Wu, R. Khan, M. Alam, B. Ali, S. Laib, and G. Khan, "Evaluation of stability and flow properties of bagasse ash as a filler in asphalt concrete for sustainable infrastructure," Adv. Sci. Technol. Res. J., vol. 19, no. 5, 2025, doi: http://dx.doi.org/10.12913/22998624/202290

[20] H. K. Sanij, R. Babagoli, and R. M. Elyasi, "Enhancing stone matrix asphalt performance with sugarcane bagasse ash: Mechanical properties and machine learning-based predictions using XGBoost and random forest," Case Studies in Construction Materials, vol. 23, Art. no. e05186, Dec. 2025, doi: http://dx.doi.org/10.1016/j.cscm.2025.e05186

[21] P.K. Akarsh, S. Marathe, H. K. Sapal, and Akshaya Krishna N., "Synergistic effects of natural fibres and agro-waste ash on the engineering and sustainability of stone-matrix asphalt mixes," International Journal of Transportation Science and Technology, Mar. 01, 2025, doi: http://dx.doi.org/10.1016/j.ijtst.2025.02.010

[22] L. Mirzaei, T. Ghebrab, C. B. Fedler, "Review and Evaluation of Agricultural Biomass Ashes as Supplementary Cementitious Materials for Sustainable Concrete," MDPI (Basel, Switzerland), vol. 13, no. 11, Art. no. 3571, Nov. 05, 2025, doi: http://dx.doi.org/10.3390/pr13113571

[23] ASTM D5, "Standard Test Method for Penetration of Bituminous Materials," ASTM International, West Conshohocken, PA, USA, 2020

[24] ASTM D36, "Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)," ASTM International, West Conshohocken, PA, USA, 2020

[25] BS EN 933-1, "Tests for geometrical properties of aggregates - Determination of particle size distribution. Sieving method," London: BSI., 2012

[26] BS 812-110, "Testing aggregates - Methods for determination of aggregate crushing value (ACV)," London: BSI., 1990

[27] BS 812-112, "Testing aggregates - Method for determination of aggregate impact value (AIV)," London: BSI., 1990

[28] ASTM D6927, "Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures," ASTM International, West Conshohocken, PA, USA, 2022

[29] ASTM D6931, "Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures," ASTM International, West Conshohocken, PA, USA, 2017