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Evaluation of stability and flow properties of bagasse ash as a filler in asphalt concrete for sustainable infrastructure

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ABSTRACT

Bagasse ash (BA), a by-product of the sugarcane industry, is produced in substantial amounts and typically discarded, leading to environmental degradation and the misuse of valuable agricultural land. While BA has shown potential as a filler in asphalt concrete, limited research exists, particularly in Pakistan, regarding its effects on the stability and flow characteristics of asphalt mixtures. This study addresses this research gap by investigating the impact of varying proportions of locally sourced BA on asphalt concrete performance. Key material properties, such as surface texture and chemical composition, were analyzed using techniques like scanning electron microscopy (SEM), energy dispersive X-Ray spectroscopy (EDX), and fourier transform infrared spectroscopy (FTIR). The study was conducted in two phases: initially, asphalt mixtures with filler contents of 3%, 4.5%, and 6% were tested; subsequently, BA was used to replace these fillers at rates of 10%, 20%, and 100%. Marshall tests were performed to measure stability, flow, and the Marshall quotient, alongside an evaluation of volumetric properties such as air voids (Va), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). The results indicated that replacing 20% of the filler with BA at 6% filler content achieved the highest Marshall stability, recorded at 16.1 kN. These findings suggest that BA can be a viable and sustainable alternative filler in asphalt concrete, with optimal performance observed at the 20% replacement level.

Keywords: bagasse ash, filler, asphalt concrete, marshall stability, scanning electron microscopy, volumetric properties.

INTRODUCTION

The sustainable utilization of industrial by-products in civil engineering applications has gained significant attention in recent years. One such material is bagasse ash (BA), a by-product of the sugarcane industry, which is produced in substantial quantities globally [1]. In Pakistan, BA is typically treated as waste and is often dumped in open fields near sugar industries, occupying valuable land and contributing to environmental pollution. The country produces approximately 42 million metric tons of sugarcane annually, generating around 0.26 million metric tons of BA. The improper disposal of BA poses environmental and logistical challenges, necessitating the exploration of alternative uses for this by-product [2]. Sugar production requires a substantial heat input, primarily derived from the incineration of sugarcane bagasse, which results in the generation of BA as a waste by-product. Approximately 26% of sugarcane, based on a moisture content of 50%, yields residual bagasse, which accounts for 0.62% of the total weight [3]. Currently, sugarcane industries are disposing of this ash in pits and neighboring areas, which leads to significant environmental contamination and storage challenges. Compared to other types of pavements, asphalt pavement is widely used around the world, especially in Pakistan. Although it makes up a very small proportion, the filler material plays a crucial role in the overall strength of asphalt [4]. The effect of the dust-to-binder ratio was investigated by [5], whose study revealed that the dust-to-binder ratio significantly influences the stability as well as the volumetric properties of asphalt. In Pakistan, stone dust is used as a conventional filler material in asphalt pavements. In the current study, it is replaced by BA in varying proportions to evaluate the Marshall stability and volumetric properties while promoting the environmentally friendly utilization of BA. Numerous filler materials are being used globally, with various researchers having explored different waste materials as potential filler alternatives.

BA-modified asphalt concrete mixtures exhibited a high dynamic modulus and excellent resistance to deformation [6]. When volcanic stones are used to replace limestone in various proportions, the results are favorable due to their higher content of SiO_2 and Al_2O_3 [7]. Waste materials such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), and crumb rubber have also been incorporated into asphalt, leading to increased Marshall stability and enhanced rutting resistance [8]. The Marshall stability of asphalt concrete improved when crumb rubber and styrene-butdiene rubber were used as additives [9]. A shear thickening fluid (STF), such as ethylene glycol, was used as a modifier for bitumen to enhance its viscoelastic properties. The results indicated that incorporating 4% STF by weight of the binder improved both the high-temperature viscoelastic properties and the bitumen performance grading [10]. The addition of crushed glass at 5%, 10%, and 15% by aggregate weight improved the Marshall stability and flow characteristics of the asphalt concrete [11]. The incorporation of bamboo fiber in asphalt has enhanced properties such as moisture resistance, low-temperature cracking resistance, and rut resistance [12]. Furthermore, when fly ash was used to replace limestone at proportions of 25%, 50%, and 75%, the specimens exhibited improved resistance to water and frost, as well as enhanced indirect tensile strength [13]. The effect of different filler types and their concentrations on the rutting resistance of asphalt was investigated, including silica sandstone, Portland cement, and eggshell fillers. The evaluation involved conducting Marshall stability and static creep tests on the asphalt samples. The results revealed that both the type and concentration of the filler had a significant effect on the rutting resistance of asphalt concrete [14]. Additionally, the dynamic shear rheometer (DSR) test was used to evaluate the rheological properties of asphalt mastic with various fillers, and the results were promising [15].

Various properties, including fatigue resistance, moisture susceptibility, and tensile strength, of asphalt concrete were investigated using brick powder as a filler material to replace limestone dust [16]. Substituting 50% rice husk for conventional filler material resulted in a significant improvement in the Marshall stability of asphalt concrete [17]. The use of waste lime as a filler material significantly improved the rutting resistance characteristics of asphalt concrete [18]. Laboratory investigations showed that incorporating waste lime as a filler enhances stripping resistance in asphalt. Additionally, baghouse dust has proven to be an effective filler material for asphalt applications [19]. Coal waste powder used as filler exhibited enhanced performance characteristics when evaluated through tests for resilient modulus and stability [20]. The study examined the effects of various fillers, including ash, sand, and brick dust, on asphalt properties, categorizing them as conventional and non-conventional. Comprehensive performance tests, such as Marshall immersion and moisture susceptibility tests, were carried out and thoroughly analyzed. The findings indicated that the use of non-conventional fillers resulted in improved performance characteristics and enhanced asphalt properties [21]. Similarly, the incorporation of cement dust as a filler improved asphalt properties up to a certain replacement percentage, with 13% replacement being identified as the most cost-effective [22].

The use of powdered seashells as a filler material in asphalt concrete were evaulated. Performance evaluations through indirect tensile and fatigue tests demonstrated that this approach significantly improved resistance against rutting [23]. When conventional crushed gravel was replaced with limestone dust as a filler, the asphalt exhibited good stability and indirect tensile strength. However, stability and tensile strength decreased when the limestone dust content exceeded 4% [24]. A comparison of various waste materials, such as waste glass, brick dust, and rice husk, conducted by [25] demonstrated that asphalt mixtures incorporating brick dust and waste glass as replacements for stone dust showed increased resistance to deformation. The replacement of conventional filler with 4% fly ash exhibited improved performance characteristics [26]. The research examined marble dust (MD) as a mineral filler in hot-mixed asphalt (HMA). At 4% MD, the mix showed improved rutting resistance and high-temperature stiffness but reduced fatigue life. This indicates MD can enhance rut resistance and serve as a partial substitute for stone dust, especially where MD waste is abundan [27]. This study examines coal bottom ash (CBA) as a mineral filler in HMA to improve rutting, stiffness, and fatigue resistance. Testing various CBA percentages (1.5%, 3%, and 4.5%) with stone dust, Marshall mix design identified 3% CBA and 4.53% bitumen as optimal. This mix enhances performance and provides a practical disposal solution for CBA [28]. Resilient tests, including the indirect tensile test and resilient modulus test, were conducted on asphalt mixtures containing water treatment and sewage sludge. The results indicated that both materials improved resistance under monotonic loads and exhibited higher stiffness under cyclic loads [29]. Moreover, the addition of 0.3% kenaf fiber to porous asphalt improved the Marshall stability and volumetric properties of the asphalt mixtures [30]. The use of waste-based geopolymer in asphalt concrete positively impacted performance characteristics such as stability, fatigue resistance, and rutting, while also contributing to sustainability and environmental benefits [31].

The researchers demonstrated that incorporating fillers significantly increased bitumen viscosity, leading to the formation of a more robust asphalt film around the aggregates, which enhanced the asphalt's resistance to moisture-induced damage and weathering [32]. Various fillers, including a mix of hydrated lime and dust extraction system by-products, were used to assess the non-linear viscoelastic characteristics of asphalt mastic. Rheological tests, such as DSR and analyses based on the Schapery non-linear viscoelasticity model, revealed a strong correlation between the non-linear viscoelasticity parameters and mastic properties [33]. Furthermore, incorporating slate-modified asphalt mixtures as fillers significantly improved both stability and tensile strength [34]. Moreover, the study showed that partially replacing limestone with cement waste enhanced the Marshall stability of the asphalt [35]. Replacing conventional filler with 8% waste glass content resulted in even greater stability [36]. Additionally, the use of granite fines as filler material in asphalt demonstrated their potential for enhancing asphalt properties [37].

Among the various civil engineering applications, asphalt pavement construction presents a promising avenue for the utilization of industrial by-products. Asphalt pavement is the most widely used road surfacing material in Pakistan, and its performance depends significantly on the type and proportion of filler materials incorporated into the mix. Typically, stone dust is used as a filler in asphalt pavements to enhance mechanical performance and durability. However, replacing conventional filler materials with alternative and sustainable options, such as BA, can contribute to resource conservation and environmental sustainability. Although previous studies have explored the use of various waste materials as fillers in asphalt mixtures, there remains a notable research gap regarding the impact of BA on the stability and flow characteristics of asphalt concrete, particularly in the Pakistani context. While international studies have demonstrated that BA-modified asphalt exhibits promising mechanical properties, localized investigations are required to evaluate its feasibility under regional material availability, climatic conditions, and construction practices. This study aims to fill this gap by evaluating the influence of different proportions of locally sourced BA as a filler material in asphalt concrete. Key parameters, including Marshall stability, flow, and volumetric properties, were assessed to determine the optimal BA replacement level. Advanced analytical techniques such as SEM, EDX, and FTIR spectroscopy will be employed to analyze the morphological and chemical characteristics of BA. The findings of this research will provide valuable insights into the feasibility of BA as an environmentally friendly filler alternative in asphalt mixtures, promoting sustainable infrastructure development in Pakistan and other regions with significant sugarcane industries.

RESEARCH METHODOLOGY

Materials

Asphalt binder

A bituminous binder of 60/70 penetration grade was utilized for the preparation of the test specimens. The selection of this binder was based on its compatibility with the requirements for flexible pavement construction. The physical characteristics of the bitumen were thoroughly analyzed to ensure compliance with standard specifications. The detailed properties of the asphalt binder are summarized in Table 1.

Aggregate

The aggregates used in this study were locally sourced from Margalla, with particle sizes ranging from 19 mm to 0.075 mm. The physical properties of these aggregates were evaluated through various tests, as outlined in Table 2.

Filler

The asphalt institute characterizes a mineral filler as a finely ground material in which no more than 3% is retained on the 0.800 mm (No. 30) sieve, and a minimum of 70% passes through the 0.075 mm (No. 200) sieve. Typical materials that serve as mineral fillers include crushed limestone, stone dust, hydrated lime, Portland cement, fly ash, and certain naturally occurring fine mineral deposits [39]. In accordance with ASTM D242/AASHTO M17 standards, the filler used in this study meets specific grading requirements, with 100% passing through sieve #16, 97 to 100% passing through sieve #30, 95 to 100% passing through sieve #50, and 70 to 100% passing through sieve #200 [39]. The BA filler for this research was sourced from Khazana Sugar Mill, located on Charsadda Road, Peshawar, Pakistan, as shown in Figure 1.

LABORATORY EXPERIMENTS

Marshall stability and flow test/Asphalt mix design and its preparation

The Marshall stability and flow tests were integral components of the experimental program, which involved the preparation and testing of 108 samples, as outlined in Table 3. These samples were prepared, compacted, and tested as per NHA Pakistan and MS-2 Asphalt Institute (2014), in alignment with AASHTO T245 and ASTM D6926 & D6927 standards. All aggregates were preheated and dried at a controlled temperature of 105 ± 5 °C before sample preparation. Various compositions of BA replacement were tested, including 10%, 20%, and 100%, resulting in a total of 108 samples being evaluated. The primary objective of the Marshall testing was to determine essential parameters such as stability values, flow values, and volumetric properties, which include Va, VFA, and VMA. These volumetric properties are critical for the comparative analysis, as they

Table 1. Properties of asphalt binder

Test description	Test code	Results	Recommended ranges by AASHTO
Softening point (°C)	AASHTO T53	49.5	46–56
Penetration grade (mm)	AASHTO T49	63.5	60–70
Flash & Fire point (°C)	AASHTO T48	261 & 283	≥235
Specific gravity	AASHTO T 228	1.03	1.01–1.06

Table 2. Basic properties of aggregates

Description	Reference specification	Results (%)	Recommended rangs by NHA* [38]
Absorption of aggregates test	AASHTO T85	0.83	2% (max)
Los Angeles abrasion test	AASHTO T96	14.3	15% (max)
Elongation test	ASTM D4791	5.34	10% (max)
Flakiness test	ASTM D4791	5.53	10% (max)

Note: *National Highway Authority.

Figure 1. Collection of BA from source location

Table 3. Sample matrix for testing

Bitumen content (%)	Filler content (%)	Replacement (%)	No. of samples
4	3	0	3
		10	3
		20	3
		100	3
	4.5	0	3
		10	3
		20	3
		100	3
	6	0	3
		10	3
		20	3
		100	3
4.3	3	0	3
		10	3
		20	3
		100	3
	4.5	0	3
		10	3
		20	3
		100	3
	6	0	3
		10	3
		20	3
		100	3
4.6	3	0	3
		10	3
		20	3
		100	3
	4.5	0	3
		10	3
		20	3
		100	3
	6	0	3
		10	3
		20	3
		100	3
Total			108

influence the performance of asphalt mixtures in terms of durability, deformation resistance, and the pavement life.

In this study, the samples were thoroughly prepared to evaluate their Marshall stability and flow values under controlled conditions. The stability test measures the peak load resistance of each specimen when subjected to a constant rate of deformation, reflecting the ability of the asphalt mixture to resist loads without excessive deformation. According to the MS-2 Asphalt Institute (2014) guidelines, stability is defined as the maximum load a specimen can withstand during testing, and the flow is the total deformation, comprising both elastic and plastic deformations, that occurs during the stability test. The Marshall stability was determined by applying a constant deformation rate of 50.8 mm per minute (2 inches per minute), while the specimens were conditioned in a 60 °C water bath for 30 minutes. The test continued until no further load increase was observed, and at this point, the flow values were measured using a flow gauge, which recorded vertical deformations at 0.25 mm intervals (or 0.01 inches) (MS-2 Asphalt Institute, 2014).

Volumetric properties of asphalt mixtures

Volumetric properties, including Va, VMA, and VFA, are critical for evaluating the performance of asphalt concrete. These parameters significantly impact asphalt pavement performance. Va represent the pockets of air between coated aggregates in the asphalt mix. Adequate air voids are necessary to allow for further compaction under traffic loads. Excessive air voids can lead to pavement damage, deformation, and water infiltration, while too few air voids may cause bitumen bleeding. Therefore, controlling Va is crucial for ensuring the durability and optimal performance of asphalt pavements. VMA is the total volume of voids within the aggregates, encompassing both air voids and the volume occupied by bitumen. VFA refers to the proportion of VMA that is filled with asphalt binder. Proper balance of these properties ensures optimal performance and longevity of the asphalt mixture. For the volumetric properties, such as Va, VFA, and VMA, the specifications from the NHA, MS-2 Asphalt Institute, and Marshall Method were employed for comparative analysis. Based on the data from the NHA and MS-2:

- Va were targeted at 4–7% (NHA) and 3–5% for light, medium, and heavy traffic as per the Marshall Method. This indicates that all samples should aim for air voids within this range to ensure proper compaction and durability of the asphalt mixture.
- VFA were recommended to range from 65-75% (NHA and MS-2) and up to 80% for light traffic in the Marshall Method. Ensuring the right VFA percentage is crucial for preventing excessive air voids that could lead to premature pavement distress.
- VMA varied based on the nominal maximum particle size, with NHA specifying 14% VMA, while the MS-2 provided more detailed specifications depending on the particle size (e.g., 21.5% for 1.18 mm particles and 12% for 19 mm particles). Higher VMA values are critical for ensuring sufficient space for asphalt binder, which contributes to the mixture's durability and flexibility.

The comprehensive analysis of these parameters ensures the pavement meets the necessary performance standards for different traffic conditions. The comparison of Marshall stability, flow, and volumetric properties across different sample compositions highlights the impact of BA replacement on the asphalt mixture's mechanical properties and performance.

RESULTS AND DISCUSSION

EDX, FTIR and SEM

To analyze the internal structure and chemical composition of the BA filler, several chemical tests were performed. EDX was used to determine the elemental composition of BA. The presence of key oxides such as silica (SiO_2) and alumina (Al_2O_3) is crucial in enhancing the performance of asphalt mixtures. Identifying these elements helps in assessing BA's potential as a filler replacement. EDX analysis was utilized to determine the elemental composition of the filler, showing that it mainly consists of Oxygen and Silicon (Fig. 2). FTIR analysis was conducted to investigate the functional groups present in BA, providing insights into the chemical interactions between BA and asphalt binder. Identifying specific functional groups aids in understanding the reactivity and potential modifications required for optimal performance in asphalt concrete. FTIR spectroscopy was also employed to identify the

Element	Weight%	Atomic%
C K	18.37	27.20
O K	46.25	51.42
Mg K	0.70	0.51
Al K	0.44	0.29
Si K	27.80	17.60
P K	0.60	0.35
K K	3.37	1.54
Ca K	2.45	1.09
Totals	100.00	

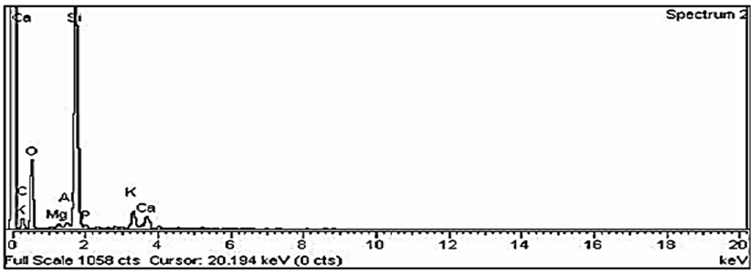

Figure 2. EDX analysis of BA

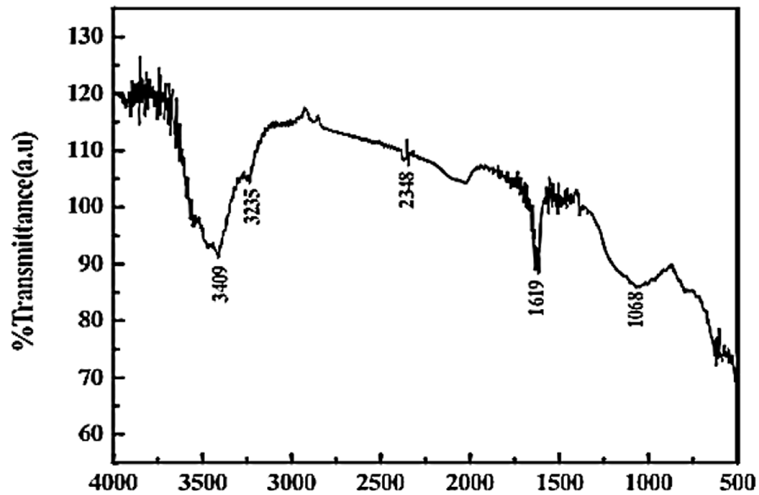

Figure 3. FTIR plot of BA

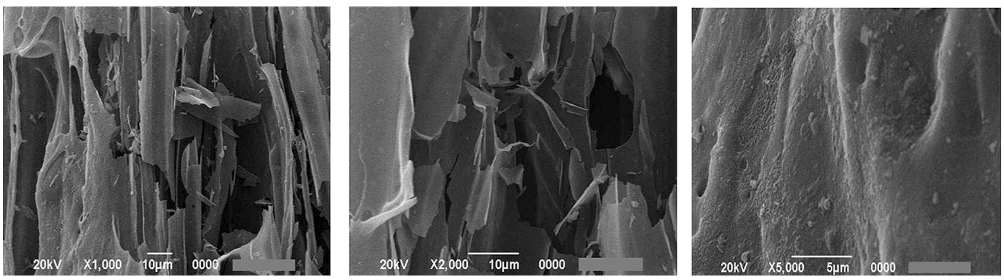

Figure 4. SEM morphology of BA

functional groups present in the BA samples using FTIR analysis plot (Fig. 3). Additionally, SEM images of the BA filler show its surface morphology at different magnifications (Fig. 4). The SEM micrographs indicate a pronounced surface roughness, which is expected to enhance frictional properties and increase the viscosity of the asphalt cement, leading to improved stability and desirable volumetric properties in the asphalt mixture. The selection of these methods ensures a comprehensive evaluation of BA's physical and chemical properties, facilitating an informed assessment of its feasibility as a sustainable alternative to conventional fillers.

Marshall properties of conventional and modified asphalt mixtures

Samples were prepared and evaluated through the Marshall mix design method to determine bulk density (G_{mb}), theoretical maximum density (G_{mm}), as well as Marshall stability and flow values. These results were then utilized to compute the volumetric properties. The tested samples included: a conventional asphalt mixture with stone dust as filler, denoted by "C"; a 10% BA-modified asphalt mixture, denoted by "10C"; a 20% BA-modified asphalt mixture, denoted by "20C"; and a 100% BA-modified asphalt mixture, denoted by "100C". Filler contents varied at 3%, 4.5%, and 6%. All samples were prepared with an optimum binder content of 4.3%. The Marshall quotient (MQ), which is the ratio of stability to flow, was also calculated to assess resistance to deformation. Table 4 provides a comparison of stability, flow, and volumetric properties of the control and BA-modified samples.

Asphalt mix design and its preparation

The aggregate gradation followed the NHA specifications (1998), Pakistan. A comprehensive sieve analysis was performed, with the

Table 4. Comparison of conventional and BA-modified asphalt concrete mixtures for 3%, 4.5% and 6% filler content

Filler content (%)	Mix type	Marshall stability (kN)	Flow (mm)	Va (%)	VMA (%)	VFA (%)	MQ (kN/mm)
3	C	11.72	10.63	8.21	17.5	53.08	1.10
	10	14	11.8	7.47	16.79	55.51	1.19
	20	15.71	12.68	5.89	15.31	61.54	1.24
	100	12.29	17.79	7.04	16.26	56.71	0.69
4.5	C	12.7	11.28	7.19	16.47	56.37	1.13
	10	15.1	12.31	6.32	15.68	59.66	1.23
	20	16.06	13.76	3.76	13.34	71.79	1.17
	100	12.87	18.51	6.02	15.34	60.76	0.70
6	C	13.43	12.55	7.15	16.49	56.65	1.07
	10	16.1	14.23	5.99	15.39	61.09	1.13
	20	17.22	15.42	5.12	14.59	65.91	1.12
	100	13.75	19.72	5.3	14.68	63.88	0.70

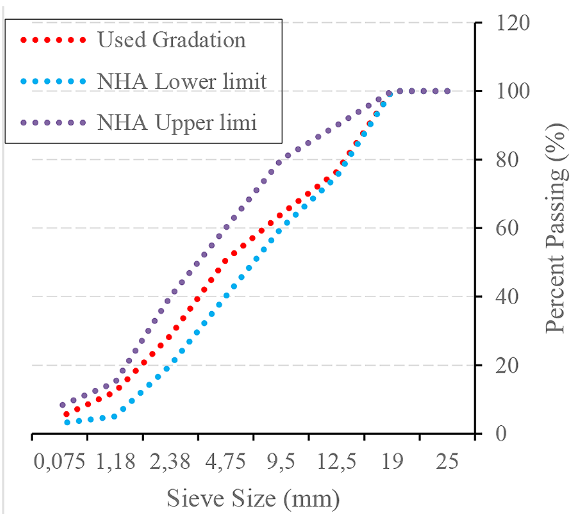

Figure 5. Blend gradation-1 for 3% filler

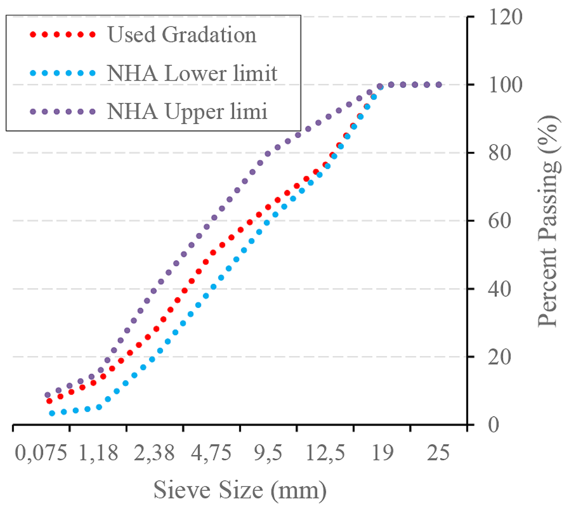

Figure 6. Blend gradation-2 for 4.5% filler

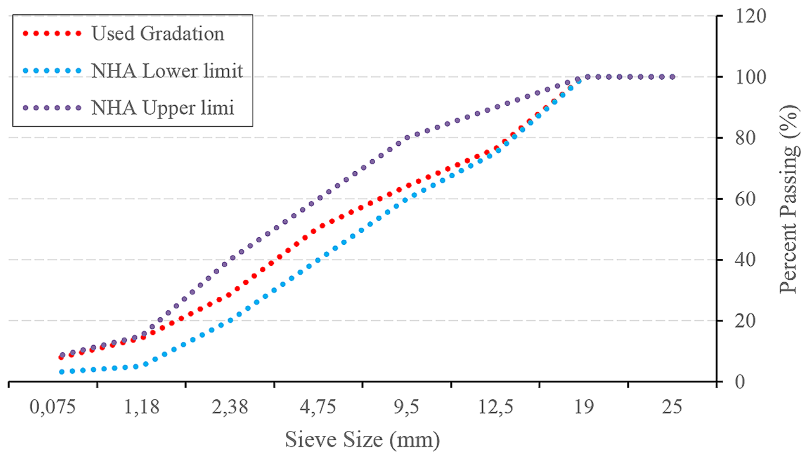

Figure 7. Blend gradation-3 for 6% filler

gradation curves depicted in Figures 5, 6, and 7. The study utilized varying filler proportions – 3%, 4.5%, and 6% – resulting in three different blended gradation curves: blend gradation-1 for 3% filler, blend gradation-2 for 4.5% filler, and blend gradation-3 for 6% filler. The Marshall mix design procedure was applied to assess the stability, flow characteristics, and volumetric properties of the samples. Stone dust, the conventional filler, was substituted with BA at replacement rates of 0%, 10%, 20%, and 100%. The properties of the BA-modified samples were compared to evaluate the effects of BA substitution.

Marshall stability

Figure 8 illustrates that the stability of the asphalt mixture increases with the percentage of BA replacement up to 20%, beyond which it begins to decrease at a 100% replacement level. The data show that all BA-modified samples exhibited higher Marshall stability compared to conventional asphalt samples. The maximum stability is observed with a 20% BA replacement, showing a 34% increase compared to the control filler. The decrease in stability at higher BA replacement levels may be due to excessive filler content and reduced adhesion.

Marshall flow

The flow values fall within the range specified by the NHA General Specifications for all scenarios except the 100% replacement of BA. Figure 9 illustrates that the flow increases with both the percentage of replacement of the conventional filler and the amount of filler used. The control samples

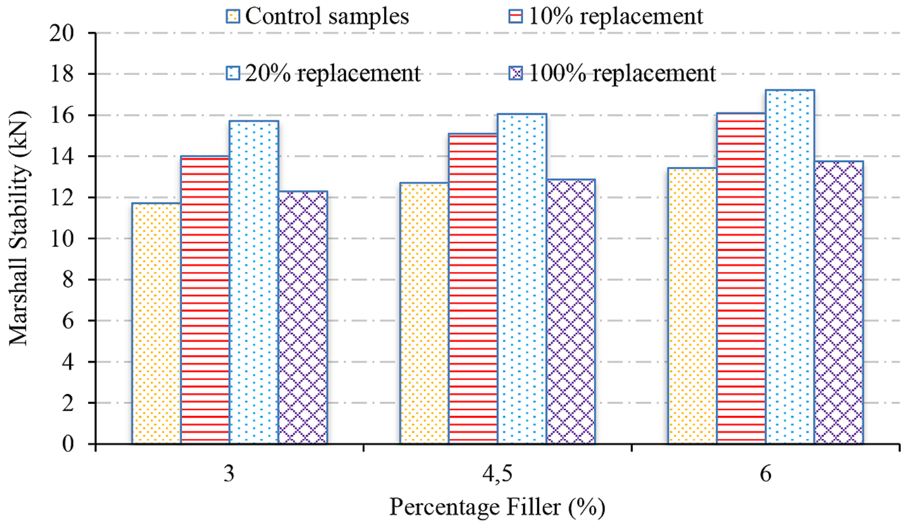

Figure 8. Marshall stability vs filler content for different replacements

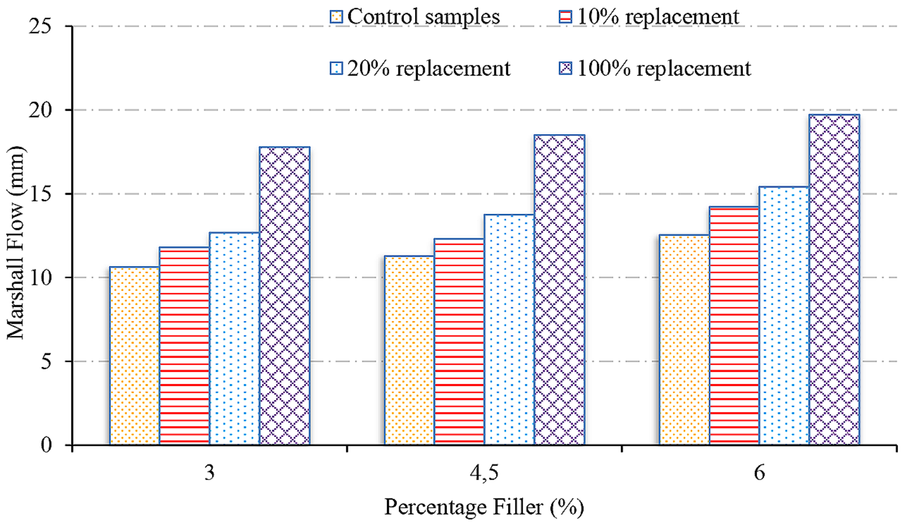

Figure 9. Marshall flow vs filler content for different replacements

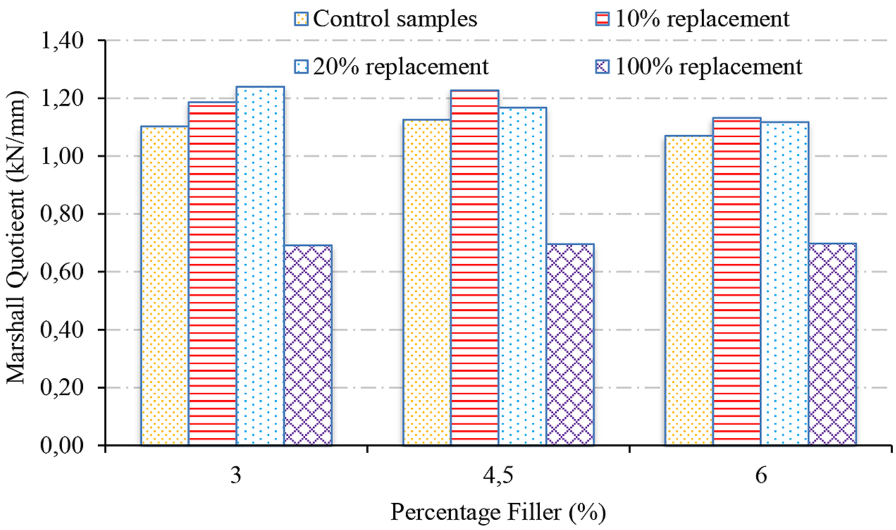

Figure 10. Marshall quotient vs filler content for different replacements

showed lower flow values compared to the BA-modified asphalt samples. Specifically, the 10% BA-modified samples had a reduced flow value of 11.8 mm. The flow values were significantly higher for the 100% replacement scenario. This increase may be due to a decrease in the surface area and reduced friction associated with the BA.

Marshall quotient

The MQ is used as an indicator of the resistance of asphalt concrete to deformation [40]. For this purpose, MQ values are calculated to evaluate the resistance to deformation of both control and BA-modified asphalt concrete samples. Higher MQ values indicate a stiffer asphalt mixture, signifying greater resistance to permanent deformation [41]. Figure 10 shows that the MQ value is highest for the 20% BA replacement with 3% filler content, indicating that these samples exhibit greater resistance to deformation.

CONCLUSIONS

The study led to the following conclusions:

- The study demonstrates that BA can effectively enhance the performance of asphalt concrete when used as a filler material. The highest Marshall stability (17.22 kN) was achieved with a 20% BA replacement at 6% filler content, representing a 34% improvement over conventional mixtures. Marshall flow values increased with BA replacement, with a peak of 19.72 mm at 100% BA substitution, indicating potential challenges in excessive replacement levels.
- The Marshall quotient (MQ), a key indicator of deformation resistance, showed the highest value (1.24 kN/mm) at 20% BA replacement, confirming the optimal performance balance. Additionally, volumetric properties such as voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) remained within acceptable limits, ensuring durability and resistance to deformation.

These findings suggest that BA, particularly at 20% replacement, can serve as a sustainable and cost-effective alternative to conventional fillers. Practical implications include improved pavement durability, reduced reliance on natural resources, and enhanced waste utilization, contributing to sustainable road construction practices.

While this study provides valuable insights into the feasibility of BA as a filler in asphalt concrete, some limitations should be acknowledged:

The chemical and physical properties of BA may vary depending on the source, processing methods, and combustion conditions of sugarcane bagasse. This variability could impact the consistency and performance of asphalt mixtures.

This study primarily focuses on short-term mechanical properties such as stability and flow. The long-term effects of BA on asphalt durability, aging, moisture susceptibility, and fatigue resistance require further investigation through field studies and extended laboratory testing.

The study was conducted under controlled laboratory conditions, which may not fully replicate real-world environmental factors such as temperature fluctuations, traffic loads, and exposure to moisture. These factors could affect the long-term behavior of BA-modified asphalt.

The study examined specific BA replacement levels (10%, 20%, and 100%). Further research is needed to explore additional replacement percentages to determine the optimal balance between performance and sustainability.

Addressing these limitations in future research will enhance the understanding of BA's role in asphalt applications and support its broader adoption in sustainable pavement construction.

Further research should focus on large-scale field applications to validate laboratory findings and assess the real-world performance of BA-modified asphalt under diverse traffic and environmental conditions. Additionally, investigating the long-term durability of BA as a filler in asphalt mixtures, including its resistance to fatigue, moisture damage, and temperature variations, is necessary for practical implementation.

Expanding the study to different asphalt mix types, including modified asphalt and warm-mix asphalt, would provide a broader understanding of BA's compatibility with various formulations. Furthermore, conducting research on the performance of BA-modified asphalt under different climatic conditions, such as extreme heat, cold, and humidity, would offer valuable insights into its global applicability. Future work should also explore the economic and environmental implications of using BA in asphalt, including cost-benefit analyses and life cycle assessments. Collaborations with industry stakeholders and government agencies could facilitate the adoption of BA as a standard filler material, contributing to more sustainable infrastructure development.

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