



Exploring the Suitability of Bambusa Vulgaris Leaf Ash as a Biomass Filler in Asphalt Mixtures

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Abstract

Utilizing waste as alternative materials in asphalt production preserves natural resources and reduces environmental impacts. This study investigates the potential of Bambusa Vulgaris Leaf Ash (BVLA) as a potential biomass filler in place of conventional mineral filler, Powdered Quarry Dust (PQD), in producing asphalt mixtures. Dried Bambusa Vulgaris leaves were obtained locally and calcined at 600 °C for 2 h, generating BVLA. PQD was replaced with BVLA at 0–100 wt. %. The effects of BVLA filler on the mechanical properties of asphalt mixtures were evaluated using Marshall Quotient (MQ) and indirect tensile strengths. Similarly, the durability of asphalt mixtures was assessed through moisture susceptibility (tensile strength ratio). The environmental impacts (embodied energy and global warming potential), sustainability score, and eco-strength efficiency of incorporating BVLA as a PQD alternative were evaluated using the cradle-to-gate boundary. The results revealed improved mechanical and durability properties with increased BVLA dosage in the asphalt mixtures. However, the optimum replacement level was found at 30 wt. % BVLA, resulting in 37.43, 22.22 and 22.39, and 4% higher MQ, wet and dry indirect tensile strengths, and tensile strength ratio compared to the control mixture (PQD-based asphalt mixture). With a 30 wt. % optimum BVLA dosage in the asphalt mixtures, the embodied energy and global warming potential decreased by 5 and 50%, while the sustainability score and eco-strength efficiency increased by 50 and 34%. These findings underscore the potential of BVLA to enhance pavement construction properties and promote sustainability.

Keywords Asphalt mixture · Biomass filler · Marshall quotient · Marshall stability · Mineral filler · Moisture susceptibility

Abbreviations

BVLA	Bambusa vulgaris leaf ash
PQD	Powered quarry dust
TSR	Tensile strength ratio
FESEM	Field emission scanning electron microscopy
EDX	Energy dispersive X-ray spectroscopy

1 Introduction

The quest to innovate cheap, eco-friendly, yet sustainable construction materials, especially in the production of asphalt mixture, is globally significant. Globally, road transportation remains the major means of transportation of goods and services, and the asphalt concrete is the most available road pavement structure. Relevant studies revealed that the properties of asphalt mixtures could be improved by incorporating fillers to meet pavement requirements [1, 2]. Asphalt mixtures comprise aggregates, fillers, and asphalt binder. The overall performance of an asphalt mixture depends on, amongst others, the properties of the constituent materials, which include aggregate, binder, and filler. Filler, a key component of the dense graded asphalt mixture, is added to fill the voids in the aggregate skeleton and to reduce the voids in the mixture [3]. Filler influences the properties and functionality of asphalt mixtures even though filler particles are extremely minute. For example, good packing of the coarse and fine aggregates and filler provides a strong backbone for the mixture [4]. Increased

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filler content strengthens the pavement because it improves the cohesiveness and internal stability of the asphalt. However, an excessive filler could weaken the asphalt mixtures by increasing the amount needed to coat the aggregates [5]. Portland Cement (PC), pulverized quarry dust, and limestone powder are conventionally used as mineral fillers in asphalt mixtures. However, limestone, shale, and clay are prepared, dried, ground, mixed, and heated at 1200–1450 °C to create powders [6]. Besides, PC production results in around one ton of greenhouse gas emissions per ton, and the PC manufacturing process accounts for 2–8% of the world's power consumption [6]. A major environmental problem is also caused by large-scale quarry dust (QD) production from quarries, aggregates, and decorative stone factories [1]. Thus, recycling waste materials as alternative fillers in asphalt mixtures cannot be over-emphasized.

Numerous studies have valorized non-biodegradable wastes as alternative fillers in asphalt mixtures, with encouraging results. These include amorphous carbon filler [7], oil shale powder [8], brake pad waste powder [9], carbon powder [10], recycled brick powder and alkali-activated binary blended cementitious filler [11], coal gangue [12], fly ash [13], and lime kiln dust and steel slag [14]. Furthermore, various biomass fillers have been investigated as alternatives to conventional mineral fillers in the production of asphalt mixtures. Tahami et al. [15] investigated the potential of using two biomass ashes, which are Rice Husk Ash (RHA) and Date Seed Ash (DSA), as filler material in Hot Mix Asphalt (HMA) at 0–100 wt. % of the conventional filler. In contrast to the control mixture, asphalt mixtures containing DSA and RHA fillers demonstrated greater stability and stiffness modulus. Utilizing biomass ashes also increased the mixtures' thermal sensitivity and the adhesive force between aggregates and asphalt, improving the HMA mixtures' resilience to rutting and fatigue. Other relevant studies revealed that replacing conventional mineral filler with a biomass filler (Wood Ash, WA) in asphalt mixture production improves fatigue performance, reduces permanent deformation, and increases the resilient modulus of the asphalt mixture [16, 17]. The inorganic micro powder filler, Steel Slag Powder (SSP), was replaced with Limestone Powder (LSP) to prepare asphalt mastic. The findings demonstrated that using SSP as a mineral filler instead of LSP in asphalt binder improved the asphalt mastics' fatigue life and resilience to deformation. As SSP concentration rises, asphalt mastics' shear modulus exhibits an increasing trend. A 30, 50, and 100 wt. % SSP asphalt mastic had a shear modulus that was 84.90, 118, and 256.10% higher than that of LSP asphalt mastic [18]. A study used steel slag and lime as fillers to compare the rheological qualities, chemical compositions, surface features, and thermal characteristics of asphalt mixtures. Due to the stiffness created by adding steel slag to asphalt mixtures, the results showed that bitumen's

asphaltic acid and steel slag's alkaline components had a sufficient chemical bond; in other words, mixtures containing steel slag fillers outperformed those containing lime fillers in terms of resistance to deformation at high temperatures [19]. Four fillers, cement, limestone filler, slaked lime, and steel slag powder, were used in manufacturing asphalt mixtures, and their moisture resistance and aggregate adhesion were examined. It was found that 25% steel slag powder can be used in place of limestone as filler, reducing the asphalt's vulnerability to moisture. Steel slag also improved the asphalt aggregate's adhesion and resistance to cracking when mixed with slaked lime [20]. Quarry dust was evaluated as a 9 and 25 wt. % substitute for lime, the traditional filler in asphalt mixtures. The findings indicated that the pozzolanic characteristics of quarry dust contributed to its efficacy in enhancing the strength of asphaltic concrete at a replacement rate of 21% [21]. Despite several studies on utilizing waste materials, there has been little to no research on using *Bambusa Vulgaris* Leaf Ash (BVLA) as a biomass filler in asphalt mixture production. This is the justification for the research.

Bambusa vulgaris (L.) (Poaceae), known as bamboo, is found in tropical and subtropical areas, especially in the monsoon and wet tropics. Bamboo is used extensively worldwide in producing food and medicine, handicrafts, and building materials because of its abundant supply of raw materials and consistent quality of preparation. The approximately 1450 species of bamboo found worldwide are grouped into many families [22]. It has been widely used for household products and extended to industrial applications due to advances in processing technology and increased market demand [23]. BVLA is used in a variety of ways with promising results, including cement additive in concrete production [24], stabilization of soft soil [25], and reinforcement material to create green metal matrix composites [26]. Studies have examined the behavior of BVLA and its potential as a supplemental cementitious material (SCM), although its application in concrete is relatively new. The use of BVLA for cement replacements has several benefits. Due to its high silica concentration, BVLA was shown to effectively replace PC by 5–20 wt. % [27–30]. Without increasing the energy required to obtain concrete strength comparable to a PC, replacing PC with 10 wt. % BVLA improves the sustainability of concrete manufacturing by lowering CO₂ emissions, embodied energy, and cost by 19, 15, and 10% [31]. Composites produced with BVLA exhibited greater compressive strength than the control and other SCM at higher curing ages (28 and 90 days) because of late pozzolanic reactivity [27, 31, 32]. Besides, replacing PC with 20 wt. % BVLA [27] and 10 wt. % BVLA [33] for mortars and concrete production resulted in less porous composite and improved chemical resistance. Pertinent studies assessed the pozzolanic characteristics of BVLA that were produced at

a calcination temperature of 600 °C. BVLA demonstrated higher reactivity compared to silica fume in terms of performance [29, 30]. Similar research found that calcining bamboo leaf at 600 °C significantly improves the mechanical and durability properties of concrete, indicating its viability as a SCM [24].

Over the past two decades, Life Cycle Assessment (LCA) has been used to study the environmental effects of asphalt pavement. Understanding asphalt materials' properties and long-term performance is essential when developing LCA models and tools. Recently, research has focused on lowering the operational Embodied Energy (EE) and Embodied Carbon (EC) from pavement materials. The total energy used for direct and indirect material-related operations within cradle-to-gate limits is measured by the EE, while EC measures the sum of fuel-related carbon emissions within the cradle-to-gate, cradle-to-site, and cradle-to-grave boundaries [34]. Cradle-to-gate refers to all material input and output flows from the ground up to the industry gate of the last processing activity [34]. Energy, Green House Gas (GHG) emissions, and cost reductions differ from project to project based on assumptions, system boundaries, and geographic location [35]. For instance, In comparison to those with a lesser proportion of aged binder, Recovered Asphalt Pavement (RAP) mixtures with 30 wt. % aged binder exhibited lower energy consumption, greenhouse gas emissions, and costs [36]. The incorporation of RAP to asphalt mixtures at 30–50 wt. % [37] and 15 wt. % [38] reduced the energy and carbon emissions by 7–12% and 13–14%. An assessment of the life cycle of asphalt mixtures modified with new lignin fiber composite and diatomite powder does not pose an undue risk to the environment or its applications since their substitutes for the basic asphalt mixture do not significantly deteriorate the environmental profile [39]. A comparative LCA was conducted using a “cradle-to-laid” methodology to assess the possible environmental effects of using 15–45 wt. % Recycled Concrete Aggregates (RCAs) in place of some of the coarse natural aggregates used in manufacturing HMA. The findings demonstrated that mixtures with 15 and 30 wt. % RCA can be regarded as environmentally acceptable substitutes for the traditional combination, which has no RCA component since they enable scores to be lowered in all impact categories. Conversely, the mixture with RCA at 45 wt. % showed worse environmental performance than the control mixture [40]. The effect of nano-silica on the Global Warming Potential (GWP) of asphalt mixtures was investigated using the LCA approach, and the results were compared to those of conventional asphalt mixtures. The results indicated that nano-silica asphalt mixtures exhibited a GWP of 7.44563×10^3 kg CO₂-eq per Functional Unit (FU) compared to 7.41900×10^3 kg CO₂-eq per FU of the conventional asphalt mixture. The EC, GWP, and sustainability scores of using BVLA as a substitute filler for powdered

quarry dust (PQD) in the production of asphalt mixtures are not well studied, despite the previously mentioned studies on the LCA of asphalt mixtures. This is the rationale for conducting the study.

This study investigates the suitability of BVLA as a biomass filler in the production of asphalt mixtures. Bamboo leaf was valorized at a controlled temperature, obtaining BVLA. The BVLA was used as a replacement for Powdered Quarry Dust (PQD) at 0–100 wt. %. Binder properties, Marshall properties of asphalt mixtures, rutting resistance, and cracking resistance were examined. The effects of replacing BVLA with PQD on EC, GWP, sustainability scores, and eco-strength efficiency of asphalt mixtures were evaluated within cradle-to-gate confinement. Additionally, all materials' energy and emission factors were derived from the existing literature and the Inventory of Carbon and Energy (ICE). The microstructures and elemental compositions of the asphalt mixture samples were analyzed using Field Emission Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDX). Findings from this research would reduce reliance on traditional PQD fillers, which have a higher environmental impact. It will assist in determining the crucial factors and conditions for impact reduction when evaluating the environmental and sustainable potentials of asphalt mixtures modified with BVLA.

2 Materials and Methods

2.1 Materials

Dried bamboo leaves (Fig. 1a), sourced from a bamboo plantation along Adeleke University Road, Ede, Nigeria, were calcined at 600 °C for 2 h, obtaining BVLA. The BVLA was milled and sieved below 75 μm (Fig. 1b). Coarse aggregate (granite, 4.75–12.5 mm sizes) and fine aggregate (quarry dust, ≤ 4.75 mm size), as shown in Fig. 1c and d, were obtained from a local quarry in Ede, Nigeria. Besides, Quarry Dust (QD) was milled and sieved below 75 μm, obtaining Powdered Quarry Dust (PQD) as a conventional mineral filler. The BVLA and PQD have a specific gravity of 1.60 and 2.45. The binder used (VG-30 or 60/70 grade), as indicated in Fig. 1 (e), was obtained from the Ogun State bitumen plant in Nigeria. The chemical compositions of BVLA and PQD, analyzed by the X-ray fluorescence analyzer, are shown in Table 1.

A common metric for assessing fillers' pozzolanic and reactive properties is the sum of SiO₂, Al₂O₃, and Fe₂O₃. According to Table 1, BVLA and PQD had SiO₂, Al₂O₃, and Fe₂O₃ totals of 85.60 and 89%, which are higher than 50% following the ASTM C 618 [41]. The higher value suggests better reactivity and pozzolanicity, improving asphalt mixture performance. The LOI values obtained



Fig. 1 Materials used **a** Dry *Bambusa vulgaris* leaf, **b** *Bambusa vulgaris* leaf ash, **c** Coarse aggregate, **d** Fine aggregate, and **e** Asphalt binder

Table 1 Chemical compositions of BVLA and PQD

Chemical compositions (%)	BVLA	PQD
SiO ₂	76.39	71.78
Al ₂ O ₃	6.43	14.59
Fe ₂ O ₃	2.63	2.78
SO ₃	0.29	-
MgO	3.33	2.41
K ₂ O	1.38	2.86
CaO	4.30	2.72
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	85.60	89
Loss Of Ignition (LOI)	1.25	0.90

for BVLA and PQD were below the 6% stipulated by the ASTM C 618 [41]. BVLA and PQD have specific gravities of 1.60 and 2.45.

In this study, crushed aggregates were used to prepare asphalt mixtures. Table 2 presents the physical properties of the aggregates, while Table 3 shows the aggregate gradation derived from the pavement mineral aggregate mix design and evaluation of the Nigerian Federal Ministry of Works and Housing (FMWH) [42].

2.2 Sample Preparation and Design Methods

Eleven (11) asphalt mixtures were made, with BVLA serving as the filler in places of PQD in the dosages of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 wt. %. The reason for replacing PQD with BVLA at 10–100 wt. % is to explore the suitability of biomass filler (BVLA) in producing asphalt mixtures, reducing environmental pollution and enhancing sustainable performance. The asphalt binder with 60/70 degrees of penetration was used. The ASTM D 1559–89 [43] and Asphalt Institute manual series MS-2 [44] were used to perform Marshall samples. In contrast to the Superpave method that takes into account a variety of climatic and traffic factors to predict pavement performance under various conditions [45, 46], this study adopted the Marshall mix design method due to its simplicity, lower initial cost, local adaptation, and suitability for the current research, where a basic assessment of asphalt binder content is the primary concern [47].

Following the aggregate's sieving, washing, and drying processes, a specimen weighing 1200 g was prepared. The fillers and aggregate were heated to 160 °C. After fully mixing the asphalt binder, fillers, and aggregates at 160 °C, the material was compacted using an automatic compactor (with 75 blows on each side) that produced Marshall samples

Table 2 Physical properties of coarse and fine aggregates used

Tests	Coarse aggregate	ASTM standard	Fine aggregate	ASTM maximum specification	Remarks
SG	2.80	[83]	2.60	3	Adequate
AIV, %	19.20	[84]	–	30	Adequate
ACV, %	42.40	[84]	–	45	Adequate
LAA, %	48.92	[84]	–	60	Adequate
FI, %	19.70	[85]	–	30	Adequate
EI, %	19.12	[85]	–	30	Adequate

Table 3 Gradation of coarse and fine aggregates used

Sieve (mm)	20	14	9.50	6.30	2.36	1.18	0.60	0.30	0.15	0.075
Lower-upper limits	100	85–100	75–92	65–82	50–65	36–51	26–40	18–30	13–24	7–14
Passing (%)	100	100	90.10	71.60	56.40	44	32.70	22.10	16.30	11.50

measuring 50 mm in height and 100 mm in diameter. The Marshall samples were cooled at room temperature before extruding from the moulds. The Optimum Binder Content (OBC) is considered as binder content corresponds to 4% of percentage air voids (VA) of prepared samples [44].

The OBC of the control mixture was found to be 6.30% with respect to the total weight (1.20 kg) of the asphalt mixture. This OBC was maintained constant for all mixtures. Hence, the mix ratios of mixtures for asphalt binder, coarse aggregate, fine aggregate, and filler were 6.30, 35.15, 51.10, and 7.45% of the total weight of asphalt mixture. Conventional filler (PQD) was substituted with biomass filler (BVLA) at weight percentages ranging from 0–100%. The detailed mix design proportions of asphalt mixtures are presented in Table 4. Three samples of each type of filler were made, and the average values were determined and used.

2.3 Experimental Tests

2.3.1 Tests on Asphalt Binder

Tests on asphalt binder were conducted to determine its conformity with acceptable values of some engineering properties required for the asphalt mixtures. As shown in

Fig. 2, different tests were conducted on the binder per ASTM standards. The tests included penetration, softening point, flash point, ductility, viscosity, and specific gravity. Table 5 lists the binder tests for a comparative examination of the findings using ASTM specifications. Penetration measures the consistency or hardness of asphalt binder. It determines the depth a standard needle can penetrate the asphalt binder sample under specific conditions [48]. The softening point is the temperature at which asphalt binder starts to flow when heated under a specific load [49]. It is a crucial characteristic that shows the range of temperatures at which asphalt can be manufactured and applied to the pavement and maintenance of roads. The ductility measures the ability of the binder to expand without breaking [50]. The resistance of asphalt binder to flow and deformation under applied stress is known as its viscosity. Higher viscosity, which is determined by the composition of the binder, especially the amount of asphalt, temperature, and other factors, indicates a thicker, more resilient binder [44]. The lowest temperature at which the binder releases enough vapour to ignite is known as the flash point [51]. The specific gravity of asphalt binder" refers to the ratio of the density of a given asphalt binder to the density of water at a specified temperature [44].

Table 4 Mix design proportions of asphalt mixtures (kg)

	Asphalt binder	Coarse aggregate	Fine aggregate	Filler		% BVLA replacement level
				PQD	BVLA	
	0.0756	0.4218	0.6132	0.0894	0	0
	0.0756	0.4218	0.6132	0.08046	0.00894	10
	0.0756	0.4218	0.6132	0.07152	0.01788	20
	0.0756	0.4218	0.6132	0.06258	0.02682	30
	0.0756	0.4218	0.6132	0.05364	0.03576	40
	0.0756	0.4218	0.6132	0.04470	0.04470	50
	0.0756	0.4218	0.6132	0.03576	0.05364	60
	0.0756	0.4218	0.6132	0.02682	0.06258	70
	0.0756	0.4218	0.6132	0.01788	0.07152	80
	0.0756	0.4218	0.6132	0.00894	0.08046	90
	0.0756	0.4218	0.6132	0	0.0890	100

Fig. 2 Tests on asphalt binder **a** Penetration, **b** Softening point, and **c** Ductility



Table 5 Properties and test results of the asphalt binder used

Test	Unit	ASTM standard	Results	Comparison with International Standards FMWH ASTM AI		
Penetration at 25 °C, 100 g, 5 s	mm/10	[48]	68	60–70	60–70	–
Softening point	°C	[49]	55	48–56	49–56	> 50
Ductility at 25 °C	cm	[50]	105	≥ 100	≥ 100	5–100
Viscosity at 60 °C	P	[62]	2105	–	2000±400	–
Viscosity at 135 °C	cst	[63]	309	–	≥ 300	–
Flash point	°C	[51]	275	≥ 250	≥ 230	–
Specific gravity at 25 °C	°C	[64]	1.02	1.01–1.06	1.01–1.06	–

2.3.2 Tests on Asphalt Mixtures

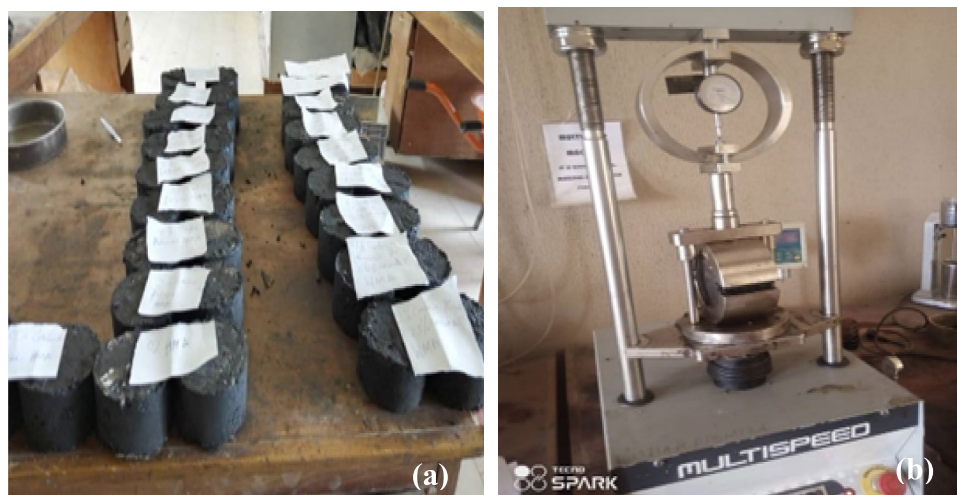
The Marshall properties of the asphalt mixtures with varying percentages of BVLA were examined. Marshall stability and flow of 11 asphalt mixture samples, as indicated in Fig. 3, were determined per ASTM D 6927 [52]. Marshall stability measures the resistance of the asphalt mixture to deformation under load; a greater stability value signifies a better resistance to deformation. Flow measures the deformation of the asphalt mixture under a standard load. Volumetric properties, namely percentage of Air Voids (VA), Voids in Mineral Aggregates (VMA), and Voids Filled with Binder (VFB), were measured following the Asphalt Institute [44]'s methods. Percentage of Air Voids (VA) represents the proportion of voids occupied with air within compacted asphalt mixtures. The Voids in Mineral Aggregate (VMA) signifies the space within the mineral aggregate particles in the asphalt mixtures. Voids Filled with Binder (VFB) represents the void space in the asphalt mixtures filled with binder.

2.3.3 Rutting Resistance

A Marshall Quotient (MQ) metric is used to gauge a mixture's resistance to rutting, shear stress, and permanent deformation [53]. The ratio of Marshall stability (kN) to flow (mm) at OBC is called MQ. Higher MQ asphalt mixtures are stiffer, better at distributing applied load, and more resistant to creep deformation [1].

2.3.4 Cracking Resistance

The indirect tensile strength (σ , kPa) of compacted asphalt mixtures, which is related to its cracking resistance, was determined per ASTM D 6931 [54] and AASHTO T 283 [5]. The Marshall samples were divided into wet (conditioned) and dry (unconditioned) subsets. The conditioned samples were partially vacuum-saturated with water and sealed. After that, the samples were placed in a plastic bag containing about 10 ml of potable water and subjected to a freezing cycle for 16 h at -18 °C. This was followed by placing the samples in a 60 °C water bath (samples had a minimum of 25 mm of water above their surface) for 24 h. At the end of the cycle, samples were placed in a water bath for 2 h at 25

Fig. 3 Modified asphalt **a** Samples and **b** Marshall test

°C, and their indirect tensile strengths were determined. The samples of the dry (unconditioned) subsets were immersed in a water bath at 25 °C for 2 h, and their strengths were tested. All tests were conducted at 25 °C by loading the Marshall samples diametrically in compression (Fig. 3b) with steel strips having a steady pace of 50 mm/min. The indirect tensile strength was computed using Eq. (1):

$$\sigma = \frac{2000P_{max}}{\pi DT} \quad (1)$$

where P_{max} is the peak load, N

D is the diameter of the Marshall sample, mm

T is the thickness of the Marshall sample, mm

2.3.5 Moisture Susceptibility

Using unsuitable filler in the modified asphalt mixtures leads to asphalt-aggregate bond failure due to moisture susceptibility. Retained Marshall Stability (RMS) or Tensile Strength Ratio (TSR) test per AASHTO T 283 [55] is used to determine the moisture susceptibility of both conditioned and unconditioned samples. A higher TSR value signifies an asphalt mixture that is more resistant to moisture. Thus, TSR is determined by the relationship illustrated in Eq. (2):

$$TSR = \frac{\sigma_{conditioned}}{\sigma_{unconditioned}} \times 100 \quad (2)$$

2.3.6 Characterizations of Asphalt Mixture Samples

Field Emission Scanning Electron Microscopy (FESEM) is an innovative technique for capturing the microstructure image of materials. Zeiss Crossbeam 340 was used to obtain the microstructure picture to characterize the modified asphalt mixture samples in this investigation per ASTM E989 [56]. Before morphological examination, the samples were sliced into approximately 5 × 5 × 5 mm pieces and coated with aurum [57]. Besides FESEM, the same samples were subjected to the Energy Dispersive X-ray spectroscopy (EDX) using Zeiss Smart EDX. EDX is an X-ray technique that identifies the elemental compositions of materials. These devices are add-ons for electron microscopes, using the microscope's image power to identify samples of interest.

2.4 Lifecycle Assessments

The assessments of asphalt mixtures modified with BVLA were limited to energy and environmental impacts within cradle-to-gate confinement. The majority of GHG

emissions, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), categorized by the Kyoto Protocol, are converted into CO₂-eq through GWP [34, 58, 59]. The mixture's EE and GWP functional units are MJ-eq and kgCO₂-eq. Likewise, the sustainable index (S_i) and eco-strength index (E_i) functional units are kgCO₂-eq mm kN⁻¹ and \$ mm kN⁻¹. A material's sustainability index decreases as its sustainability score increases [60, 61]. The widespread use of any material as a substitute in the construction sector is contingent upon its relative cost at the consumer level [36]. Therefore, the eco-strength index compares each mixture's cost viability to its Marshall Quotient value and overall production cost. The EE coefficient (EE_{coff}) and GWP coefficient (GWP_{coff}) were obtained using the energy and carbon inventory data. When the inventory methodology is applied to actual case studies, it demonstrates that it is more accurate and flexible than alternative methods [34]. Furthermore, the inventory approach avoids complex processes involving chemical equations using EE_{coff} and GWP_{coff} [34]. Table 6 presents the EE_{coff} and GWP_{coff} for the asphalt mixture components based on the energy and carbon inventory. Thus, EE, GWP, and S_i are evaluated via the illustrations shown in Eqs. (3)–(6) [34, 60].

$$EE = (1.22) \sum_{i=1}^n (W \times EE_{coff}) \quad (3)$$

$$GWP = (1.19) \sum_{i=1}^n (W \times GWP_{coff}) \quad (4)$$

$$S_i = \frac{GWP + (0.050 \times EE)}{\text{Marshall Quotient}} \quad (5)$$

$$E_i = \frac{\text{Total cost of 1 kg of each asphalt mixture}}{\text{Marshall Quotient}} \quad (6)$$

where W represents the weight of each constituent (kg).

Table 6 Embodied energy and global warming potential coefficients of asphalt mixture components (cradle-to-gate)

Material	EE _{coff} (MJ-eq kg ⁻¹)	GWP _{coff} (kgCO ₂ -eq kg ⁻¹)	Reference
Asphalt binder	4.0890	0.0775	[34]
Coarse aggregate	0.0830	0.0052	[34]
Fine aggregate	0.0810	0.0051	[34]
PQD	0.8500	0.0200	[34]
BVLA	0.0340	0.000012	[81, 86]

3 Results and Discussion

3.1 Asphalt Binder

The characteristics of the asphalt binder used in the asphalt mixture are listed in Table 5. The results were found to be appropriate for the intended purpose. The penetration value (67 mm) was within the FMWH [42] and ASTM D5 [48] of 60–70 mm, indicating that the binder possesses the desired level of hardness. The obtained value of 52 °C softening met the FMWH [42] of 48–56 °C, ASTM D36 [49] of 49–56 °C, and Asphalt Institute (AI) [44] of above 50 °C, signifying that the binder has the appropriate softening point. The obtained value of 105 cm indicated good ductility, surpassing the minimum requirement of 100 cm per FMWH [42] and ASTM D113 [50]. Furthermore, the obtained values of viscosity at 60 °C (2105 P) and 135 °C (309 cst) fell within the ASTM D2171 [62] and ASTM D2170 [63] recommendations, indicating favorable flow characteristics. The binder's strong resistance to ignite was demonstrated by the obtained value of 275 °C, higher than the minimum requirement of 230 and 250 °C per ASTM D92 [51] and FMWH [42]. The specific gravity influences the binder's density in relation to water. From Table 5, the specific gravity obtained (1.02) was within the standard range of 1.01–1.06 recommended by ASTM D70 [64] and FMWH [42].

The penetration, ductility, and softening point of pure binder utilized in expanded polystyrene bead-based asphalt mixtures demonstrated values of 68.10 mm, 95 cm, and 50 °C, supporting the findings shown in Table 5 [65]. The results shown in Table 5 are further supported by penetration, ductility, specific gravity, and softening point of VG-30 grade employed in asphalt mixtures, which produced 62 mm, 100 cm, 1.02, and 52.50 °C [1]. Ultimately, the properties highlighted in Table 5 show that asphalt binder used is suitable, demonstrating good durability, workability, and resilient when applied as a binding material in asphalt concrete pavement.

3.2 Asphalt Mixtures

The results of the asphalt mixtures are depicted in Fig. 4. From Fig. 4a, the bulk specific gravity of the modified asphalt mixtures decreased with increasing BVLA content, with values ranging from 2.14–2.27 g cm⁻³ compared to the control sample with 2.29 g cm⁻³. The percentage of air voids (VA) of modified asphalt mixtures, as shown in Fig. 4b, decreased as the BVLA content in the mixture increased. At 10–100 wt. % of BVLA substitution, the VA varied between 4.44 and 5.29% compared to the control

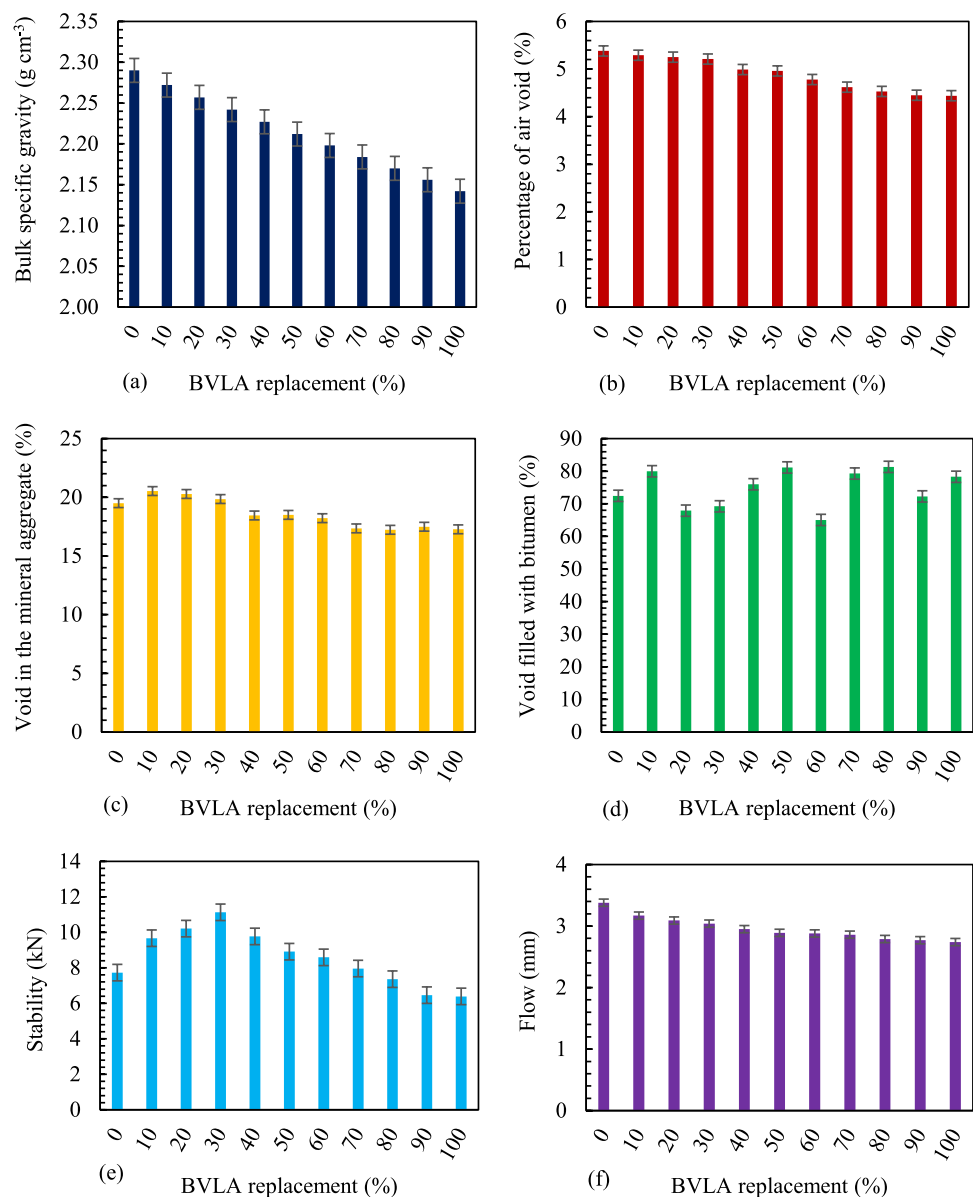
sample with a VA of 5.38%. This can be ascribed to the filler effect of BLVA, trapping interstitial space and reducing the air voids in the mixture [66, 67]. Ultimately, the results satisfied the 3–8% and 3–5% VA recommendations that FMWH [26] and AI [28] specified.

The VMA results shown in Fig. 4c revealed a slight increase in VMA at 10–30 wt. BVLA by 2–5%; however, there was a 5–12% decrease in VMA at 40–100 wt. % BVLA substitution compared to the control sample. Higher VMA values indicate a greater void space available for binders to fill, contributing to better coating and adhesion.

The findings in Fig. 4d revealed that, at 10–100 wt. % BVLA substitution, the VFB values ranged from 65.05–79.98%, whereas the control sample had 72.45%. Performance evaluation of asphalt mixtures having stone dust and copper tailings as fillers exhibited VFB values of 74.61 and 71.96% [68]. Higher VFB values indicate a greater percentage of voids filled with binder, promoting better durability and strength. Thus, these results met FMWH [42] and AI [44]'s recommendations, specifying 65–82% and 65–80% VFB.

Figure 4e shows the stability of the asphalt mixtures. The stability increased with increasing BVLA content at 10–70 wt. %, with values ranging from 7.96–11.13 kN compared to the control asphalt mixture with 7.73 kN. This indicates that BVLA has better stability than PQD. The suitable effect of BVLA as a biomass filler on the enhancement of adhesion among aggregates in modified asphalt mixtures can be attributable to the porous structure of this filler, resulting in a strong tendency to adsorb asphalt binder. The percentage of free asphalt binder decreases, producing a thicker asphalt binder film on aggregates. Consequently, the overall load-bearing capability of the asphalt mixtures increases due to the greater adhesive force between the aggregates and asphalt mastic. Besides, particles with low specific gravity concentrate in the interfacial zone between aggregate and binder matrix, filling voids (filler effect) and promoting better coating and adhesion [69]. According to pertinent studies, the stability of asphalt mixtures with 25 and 100% DSA filler was 12 and 36% higher than that of samples containing 100% conventional filler (stone dust). Likewise, the stability value of the mixture with 25 and 100% RHA filler was 10 and 28% greater than the control sample [15]. From Fig. 4e, the asphalt mixture modified with 30 wt. % exhibited the highest stability with about 31, 14, 9, 13, 20, 23, 29, 34, 42, and 43% higher than 0, 10, 20, 40, 50, 60, 70, 80, 90, and 100 wt. % BVLA replacement levels. These results also indicate that the stability declined after 70 wt. % BVLA replacement compared to the control sample. There was about 5–17% lower stability at 80–100 wt. % BVLA substitution than the control asphalt mixtures. This demonstrated that BVLA's reduced affinity for asphalt caused it to reduce matrix cohesion and adhesion above 70 wt. % replacement

Fig. 4 Effects of BVLA (biomass filler) on **a** Bulk specific gravity, **b** Percentage of air void, **c** Void in the mineral aggregate, **d** Void filled with bitumen, **e** Stability, and **f** Flow of asphalt mixtures



level, which reduced stability. Ultimately, the stability of all BVLA mixtures satisfied the minimum stability values of 3 and 9 kN specified by FMWH [42] and AI [44].

Figure 4f presents the flow of asphalt mixtures, indicating the plastic deformation of asphalt mixtures under load. From Fig. 4f, the flow slightly decreased as the amount of BVLA in the asphalt mixtures increased. This outcome demonstrates the effectiveness of BVLA as a filler and its capacity to lower the mixture's susceptibility to brittleness or plastic deformation. This efficiency is due to the reactivity of the silica (SiO_2) in BVLA, which lowers the binder content and lessens lubrication between the aggregate particles [66, 67]. As indicated in Fig. 4f, the control sample's flow was approximately 7, 9, 10, 13, 15, 15, 16, 18, 18, and 19% higher than asphalt mixtures incorporating 10, 20, 30,

40, 50, 60, 70, 80, 90, and 100 wt. % BVLA replacement levels. These findings are consistent with pertinent research demonstrating reduced flow with bamboo leaf ash as a filler compared to steel slag powder and quarry dust fillers in the wearing and binder courses [47]. The flow for all BVLA-based asphalt mixtures satisfied the 2–6 mm flow requirement stated in the FMWH standard [42].

3.3 Rutting Resistance

Figure 5 shows the Marshall Quotient (MQ) of the modified asphalt mixtures. The Marshall quotient increased with increasing BVLA content in the mixtures. This signifies that the low specific gravity (fine filler) of BVLA, compared to PQD, had an influence on the MQ of the asphalt mixtures.

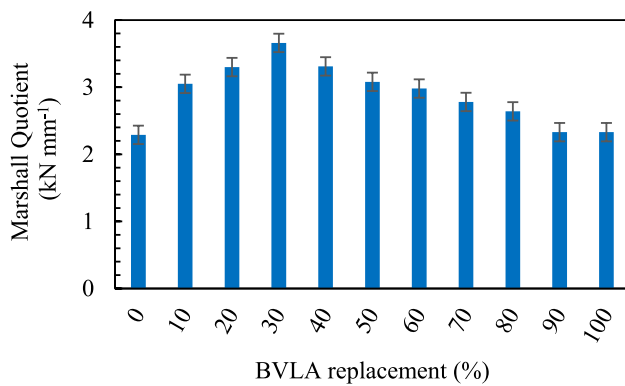


Fig. 5 Effect of BVLA (biomass filler) on rutting resistance

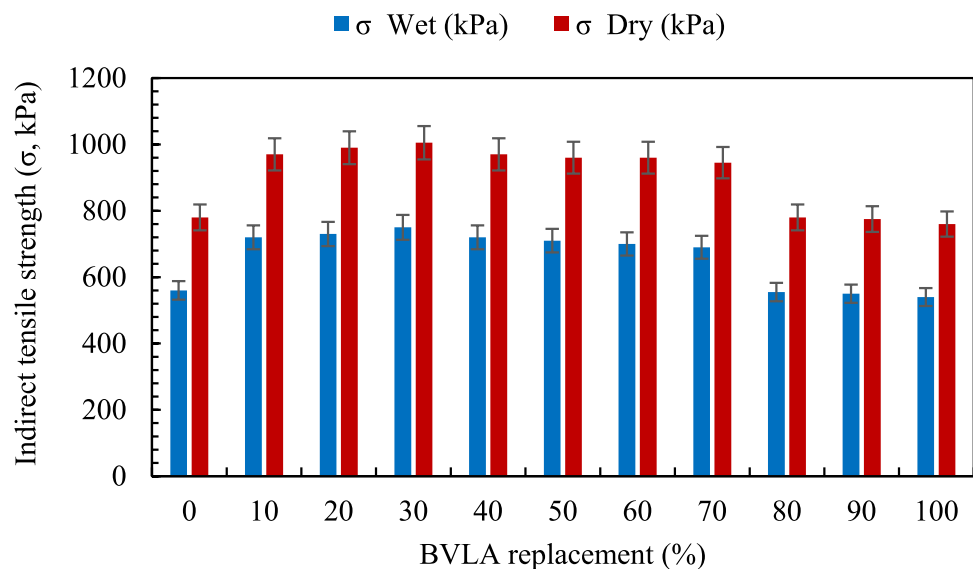
Prior studies have indicated that adding fine fillers to the asphalt mixture increases its stiffness [70–72]. Thus, from Fig. 5, the MQ values ranged from 2.33–3.66 kN mm⁻¹ compared to the control asphalt mixtures with MQ of 2.29 kN mm⁻¹. The asphalt mixture modified with 30 wt. % BVLA yielded the highest rutting resistance, which was about 38, 17, 10, 10, 16, 19, 24, 28, 36, and 36% higher than 0, 10, 20, 40, 50, 60, 70, 80, 90, and 100 wt. % BVLA replacement levels. These results align with relevant findings, such that copper tailings (finer filler) exhibited higher MQ (4.93 kN mm⁻¹) than stone dust-based asphalt mixtures (4.66 kN mm⁻¹) [68]. The wearing course showed that steel slag powder had the highest MQ (5.74 kN mm⁻¹) compared to bamboo leaf ash (5.12 kN mm⁻¹) and quarry dust (5.05 kN mm⁻¹) [47]. A higher MQ value suggests better overall performance. Furthermore, the results in Fig. 5 show variations in the Marshall properties as the percentage of BVLA changes. The 30 wt. % BVLA asphalt mixtures demonstrated higher stability and lower flow than other replacement levels,

resulting in the highest MQ (3.66 kN mm⁻¹). These results support a relevant finding that asphalt mixtures, including biomass fillers (DSA and RHA), showed greater resilience to rutting at 100 wt. % substitution than mixtures containing conventional mineral filler (stone dust) [15].

3.4 Indirect Tensile Strength

Figure 6 displays asphalt mixtures' wet and dry indirect tensile strength results. The results demonstrated that the wet indirect tensile strength values were less than the dry ones. This is because water weakens the binding between the aggregates and binder, which reduces the asphalt concrete's ability to withstand traffic stresses [73]. The 10–70% BVLA replacement fillers outperformed the control asphalt mixtures in wet and dry conditions. At 10–70% BVLA substitution, wet and dry indirect tensile strengths varied between 690–710 kPa and 945–1005 kPa compared to the control asphalt mixtures with 560 and 780 kPa. Finer fillers have a greater capacity for homogeneous distribution, resulting in void filling and an integrated structure in the asphalt mixtures, improving the mixtures' stiffness and indirect tensile strength [1, 70]. An asphalt mixture is more resistant to fatigue and low-temperature cracking if its indirect tensile strength value is higher [1]. At increasing filler content, an indirect tensile strength of the asphalt mixture will unavoidably increase as filler proportion increases and binder percentage decreases simultaneously [74]. Thus, a 30 wt. % BVLA substitution exhibited superior performance with about 27, 6, 4, 6, 7, 8, 10, 27, 28, and 28% higher in wet condition and 23, 4, 2, 4, 5, 5, 9, 23, 23, and 25% greater in dry condition than 0, 10, 20, 40, 50, 60, 70, 80, 90, and 100 wt. % BVLA replacement levels. These findings align with earlier research that found that asphalt mixtures containing

Fig. 6 Effects of BVLA (biomass filler) on indirect tensile strength of asphalt mixtures



DSA and RHA fillers exhibited better strength against permanent deformation than stone dust fillers [15].

3.5 Moisture Susceptibility

A higher Tensile Strength Ratio (TSR) of an asphalt mixture indicates its increased resistance to moisture. TSR values for each asphalt mixture are shown in Fig. 7. The results revealed increased TSR with increasing BVLA content in the mixture with the optimum ratio of 0.73 at 70 wt. % BVLA substitution compared to the control asphalt mixture with a TSR of 0.72. However, the best performance was found at 30 wt. % BVLA substitution with a TSR of 0.75, signifying the best replacement for an increased resistance to moisture. The content of calcium oxide (CaO) in BVLA was about 37% higher than PQD's (Table 1); fillers mainly composed of insoluble calcium-based compounds demonstrated superior moisture resistance and promoted asphalt-filler adhesion [75]. This could be a reason for an increased resistance to moisture with increasing BVLA content. In Fig. 7, the TSRs for 0, 10, 20, 40, 50, 60, 70, 80, 90, and 100 wt. % BVLA replacement levels were approximately 6, 3, 3, 3, 3, 4, 2, 7, 7, and % lower than 30 wt. % BVLA substitution. As displayed in Fig. 7, all asphalt mixtures satisfied a 70–80% degree of saturation [55]. This study infers a 30 wt. % BVLA substitution as a filler in asphalt mixture production for the best moisture resistance.

3.6 Characterizations of Asphalt Mixtures

The FESEM micrographs are shown in Fig. 8a and b for the control mixture incorporated with PQD (0 wt. % BVLA) and the 30 wt. % BVLA-based asphalt mixtures. The FESEM micrographs offered performance with a resolution of 100 μm at 15 kV, at working distances of 11.30 and

11.90 mm. The micrographs revealed an amorphous structure with particles of different shapes and sizes. However, the internal structure of the asphalt mixture incorporating BVLA at 30 wt. %, as indicated in Fig. 8b, was more compact than the control mixture (Fig. 8a). This demonstrated the filler capacity of BVLA, filling the matrix voids, increasing asphalt binder-filler adhesion, and strengthening the asphalt mixtures [76], as evident in indirect tensile strength and tensile strength ratio results.

Figure 9a and b show the Energy Dispersive X-spectroscopy (EDX) of the control mixture and the 30 wt. % BVLA-based asphalt mixtures. Figure 9a shows multiple prominent peaks that reveal the presence of various elements in the sample. The designated peaks in the material under analysis correspond to the distinctive X-ray energies of elements like silicon (Si), oxygen (O), sodium (Na), bromine (Br), calcium (Ca), potassium (K), molybdenum (Mo), and rubidium (Rb) with 25.34, 27.69, 2.41, 15.34, 7.07, 5.70, 10.10, and 6.34 wt. %. These elements contributed to the performance of the control mixture, especially silicon, calcium, and molybdenum, by improving pore structures and mechanical properties [77]. Similarly, several significant peaks in Fig. 9b indicated the presence of different elements in the sample. These elements were aluminium (Al), silicon (Si), potassium (K), strontium (Sr), hafnium (Hf), and plutonium (Pu) with 13.07, 14.47, 8.87, 24.67, 9.85, and 29.77 wt. %. These elements can be attributable to higher rutting, cracking, and moisture resistance in the asphalt mixtures with BVLA than the control mixture. Relevant studies confirmed that strontium and plutonium are cement-forming ions [78] and ettringite enhancers [79], improving the composite's pore structures and mechanical characteristics. The addition of hafnium at 7.33 wt. % to $\text{Zr}(\text{Hf})_x\text{CN}$ coatings exhibited excellent mechanical properties and corrosion resistance [80].

Fig. 7 Effects of BVLA (biomass filler) on tensile strength ratio

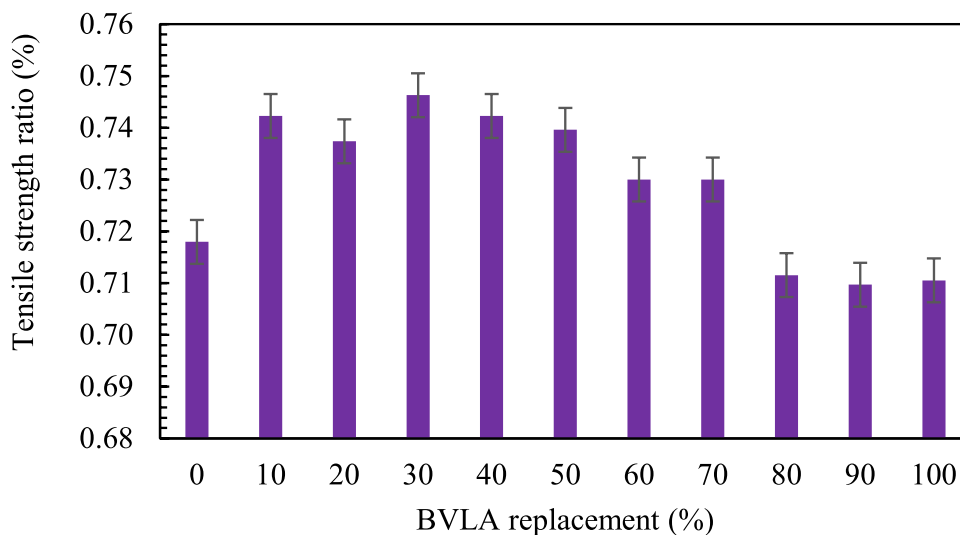
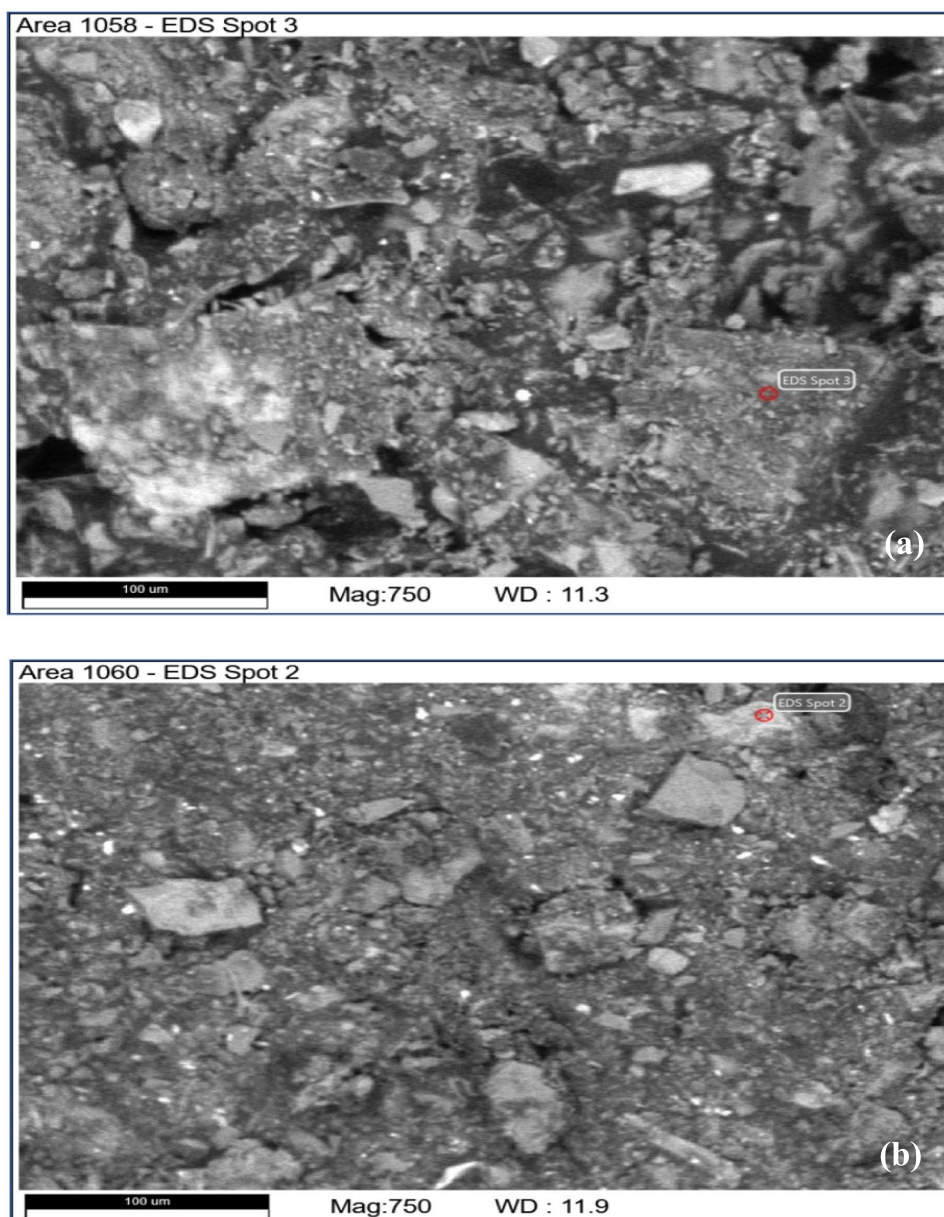


Fig. 8 FESEM images of **a** Control asphalt mixture and **b** 30 wt. % BVLA-based asphalt mixture



3.7 Lifecycle Assessments

3.7.1 Embodied Energy

Figure 10 displays the embodied energy of the asphalt mixtures. The results revealed decreased EE with increased BVLA dosage in the mixtures. This can be attributed to the BVLA's EE coefficient, which is about 96% lower than that of PQD. From Fig. 10, as the BVLA level in the asphalt mixtures increased from 10–100 wt. %, the EE decreased by about 1–15%. Although, the literature on LCA of asphalt mixtures incorporating biomass fillers is scarce. However, this outcome supports BVLA's ability to reduce energy consumption in concrete manufacturing,

lowering energy requirements by 5.42% at a 15 wt. % replacement level [81]. Furthermore, recycling biomass waste materials decreases the EE of blended cement concrete. For instance, there was about a 3% reduction in EE of blended cement concrete at every 5 wt. % shea nutshell ash (SNA) replacement level [60]. A 5–15 wt. % of Calcite Powder (CP) and Sugarcane Bagasse Ash (SBA) blends resulted in 8–25% decrease in EE of blended cement concrete. In addition, the use of waste material (RAP) in asphalt mixture production resulted in 99.50–99.61% and 20.31–41.61% reduction in EE compared to asphalt binder and aggregate productions [36]. Ultimately, the replacement of conventional filler (PQD) with biomass filler (BVLA) while manufacturing asphalt mixtures can

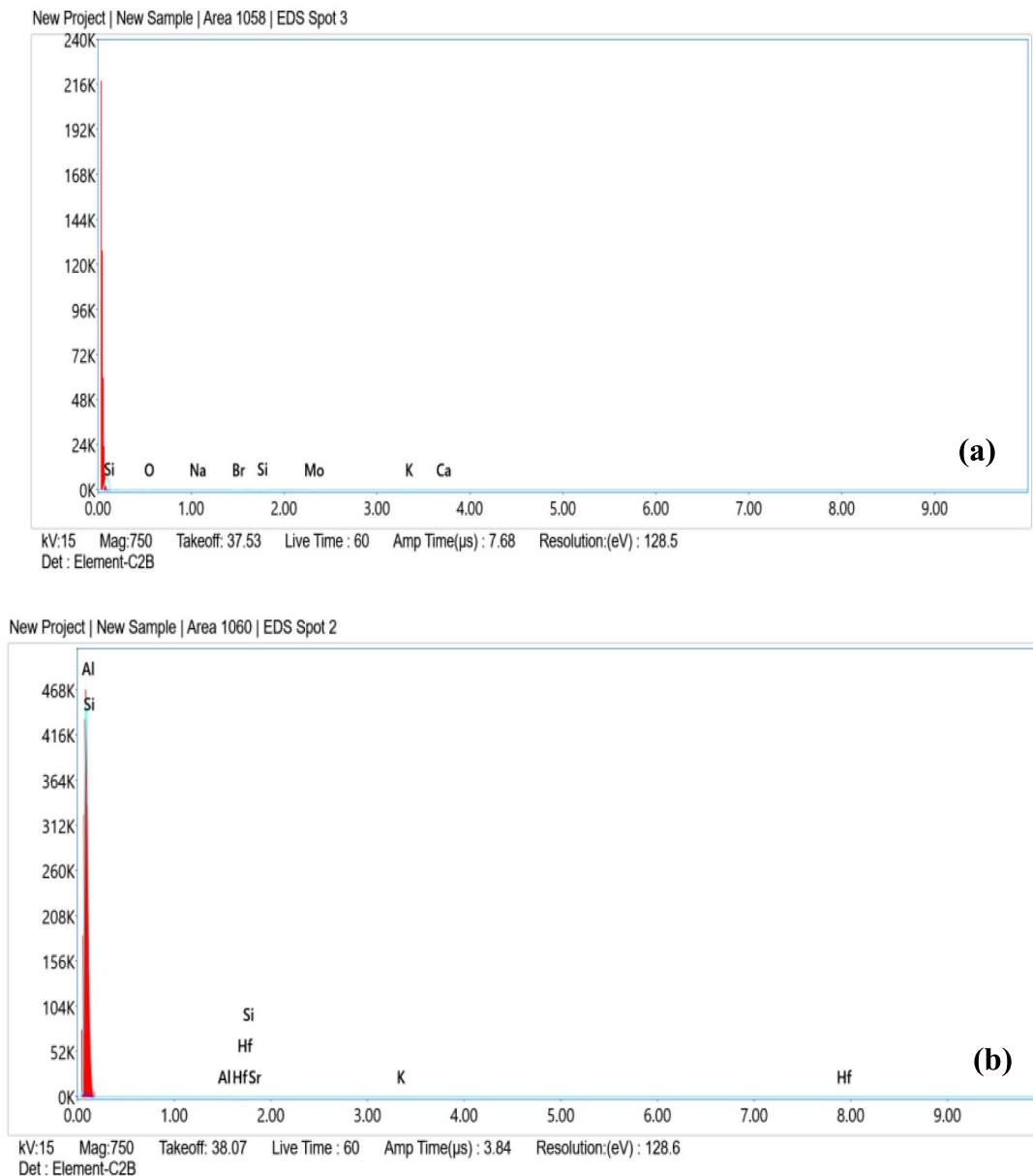


Fig. 9 EDX of **a** Control asphalt mixture and **b** 30 wt. % BVLA-based asphalt mixture

offset the EE of the mixtures, resulting in a sustainable pavement material.

3.7.2 Global Warming Potential

Like EE in Fig. 10, the GWP in Fig. 11 decreased with increased BVLA content in the asphalt mixtures. This can be associated with the GWP of BVLA, which is 99.94% lower than that of PQD. However, between 10 and 20 wt. % BVLA replacement levels, the asphalt-BVLA-based mixtures maintained the same emissions as the control mixture, indicating a similarity between the combusted EE and

process-related carbon emissions. This indicates that CO₂-eq emissions are reduced at a BVLA replacement level of more than 20 wt. %. Similar research also noted an energy saving at 30 wt. % RAP mixture of aged binder (65.34–75.35 MJ ton⁻¹) compared to 15 wt. % (11.20–12.65 MJ ton⁻¹) [36]. From Fig. 11, as BVLA content increased from 30–100 wt. %, the GWP of asphalt mixtures decreased by 50%. This supports pertinent research, which reported a 13.12% reduction in GWP of blended cement concrete at 15 wt. % BVLA replacement level in place of cement [81]. Using biomass ashes, such as SNA [60] and SBA [82], decreases the GWP of blended cement concrete by 5–20% and 8–25% at

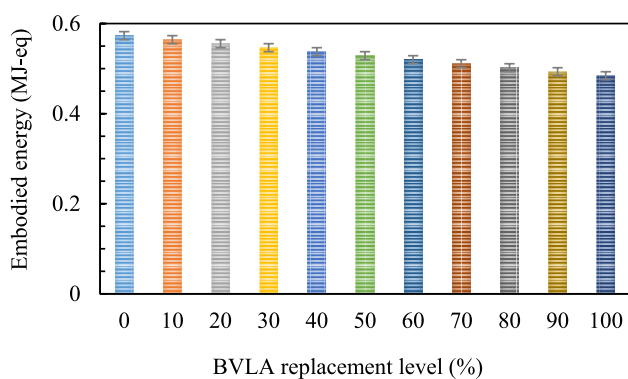


Fig. 10 Embodied energy of asphalt mixtures

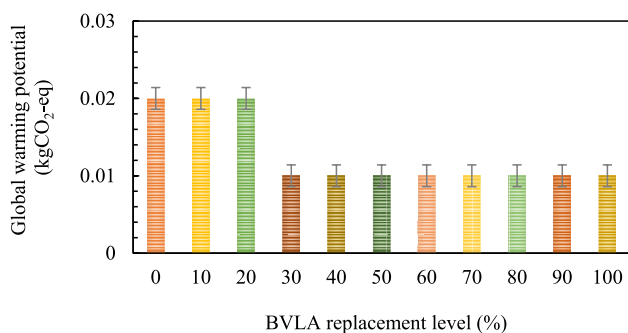


Fig. 11 Global warming potential of asphalt mixtures

5–20 wt. % SNA and 5–15 wt. % SBA replacement levels. Compared to manufacturing asphalt mixtures with asphalt binder and aggregate, the RAP-based production resulted in 99.30–99.56% and 11.54–38.10% reductions in GWP [36]. Therefore, using BVLA as a PQD substitute in asphalt mixture production offers ecologically beneficial possibilities for pavement material that reduces the negative consequences of global warming.

3.7.3 Sustainability Index

Figure 12 displays the sustainability index for asphalt mixtures. With higher BVLA dosages of up to 80 wt. % replacement level in the mixtures, the sustainability index dropped, as shown in Fig. 12. However, the index rose after 80 wt. % BVLA substitution and maintained the same value as the control mixture. Asphalt mixtures are sustainable with 10–80 wt. % BVLA replacement, as seen by approximately 50% drop in the sustainability index at these levels. Accordingly, the BVLA-based-asphalt mixture generated a sustainability score that was 50% greater than the control mixture. The reasons can be credited to the comparatively higher MQ to the lesser EE and GWP exhibited by BVLA –based-asphalt mixtures than the control mixture. The replacement

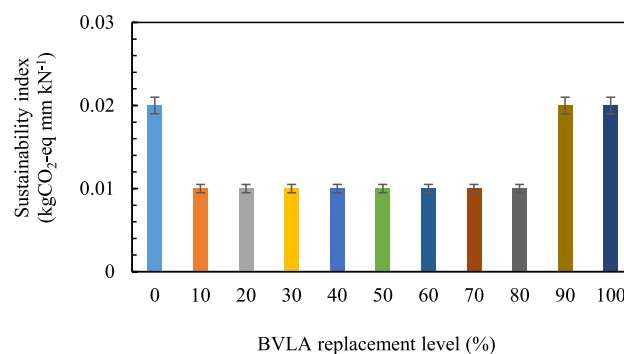


Fig. 12 Sustainability index of asphalt mixtures

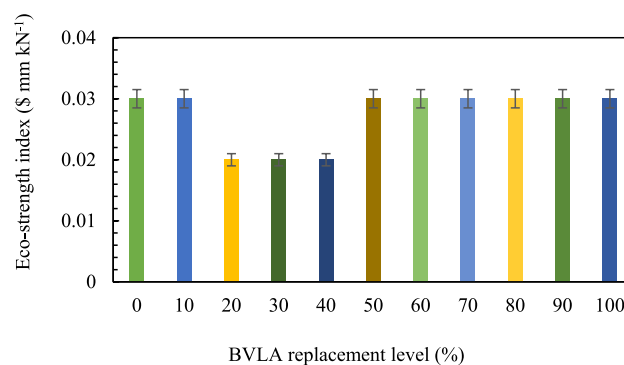


Fig. 13 Eco-strength index of asphalt mixtures

of biomass ashes with PC has been found to increase the sustainability scores of blended concrete. For example, the sustainability scores of concrete incorporating SNA at 5–20 wt. % increased by 1–5% compared to the control sample [60]. The inclusion of SBA at 5–15 wt. % replacement level increased the sustainability scores of blended cement concrete by 4–6% [82]. Hence, utilizing BVLA to produce asphalt mixtures allows for a more environmentally friendly material for pavement applications than PQD without hampering the strength performance. Furthermore, a 30 wt. % BVLA substitution, which yielded the maximum MQ along with low EE and GWP, is recommended in producing asphalt mixtures for pavement application.

3.7.4 Eco-strength Index

Figure 13 indicates the eco-strength index for asphalt mixtures. As shown in Fig. 13, the eco-strength index decreased with increased BVLA content at 20–40 wt. % substitution due to higher MQ. Besides, the unit cost of PQD per kg is about 97% higher than BVLA. Compared to other asphalt mixtures, there was about a 34% reduction in the eco-strength index, signifying that asphalt mixtures with 20–40 wt. % BVLA dosages are more economically efficient than

other asphalt mixtures. Using waste material (RAP) in asphalt mixture production results in about 98 and 71% cost savings compared to asphalt binder and aggregate materials [36]. Likewise, incorporating biomass ash (SNA) at 5–20 wt. % substitutions result in a marginal increase in the economic efficiency of blended concrete by 1–2% [60]. Thus, the economic prospect of asphalt mixture incorporating BVLA as a biomass filler is viable at an optimum substitution of conventional filler (PQD) with 30 wt. % BVLA.

4 Conclusions

This research investigated the effects of a biomass filler (BVLA) as a replacement with a conventional mineral filler (PQD) on the mechanical and durability performance of asphalt mixtures. Based on the experimental findings, the following conclusions can be drawn:

The Marshall stability of asphalt mixtures increased with increased BVLA dosage. There was a 38% increase in Marshall Quotient (rutting resistance) at 30 wt. % of BVLA content compared to the control mixture. The indirect tensile strength (cracking resistance) of asphalt mixtures increased with increased BVLA content. There were about 23% higher wet and dry indirect tensile strengths in the BVLA-based asphalt mixture than in the control. BVLA improved the moisture resistance of asphalt mixtures. The optimum performance was attained at 30 wt. % BVLA substitution with 4% higher moisture resistance than the control asphalt mixture. The filler effect of BVLA filled the voids of the asphalt mixture, increasing asphalt binder-filler adhesion and strengthening the mixture. At 30 wt. % BVLA optimum replacement level, environmental impacts (EE and GWP) of asphalt mixtures decreased by 5 and 50%; whereas, the sustainability score and eco-strength efficiency increased by 50 and 34%.

This finding is significant as it demonstrates that valorizing BVLA at a 30 wt. % maximum substitution improves asphalt mixtures and promotes sustainability by reducing reliance on traditional fillers (PC and PQD), which have a higher environmental impact, potentially revolutionizing the construction industry.

5 Recommendations

Future studies can investigate the effects of BVLA on the long-term chloride and chemical resistance, water permeability and porosity, skid and relling resistance, rutting resistance with the wheel-track test, fatigue, and economic feasibility of asphalt mixtures. The current study is limited to cradle-to-gate analysis of LCA. Further studies can employ the cradle-to-grave method, where cradle-to-gate,

operation, and end-of-life processes are considered in the analysis.

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Author contributions All authors contributed to the study conception and design. MA, SO, OJ, and JA performed material preparation, data collection and analysis. MA, OJ, and JA wrote the first draft of the manuscript. SO, SS, and LS reviewed and edited the first draft of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The author declares that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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