Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 03, March, 2026

Sustainable Pavement Design: Synergistic Effects of Buton Rock Asphalt and Recycled PET on Asphalt Performance

Daud Nawir [1*], Achmad Z. Mansur [1]

[1] Department of Civil Engineering, Faculty of Engineering, Borneo Tarakan University, North Kalimantan 77115, Indonesia.

Received 16 August 2025; Revised 19 January 2026; Accepted 28 January 2026; Published 01 March 2026

Abstract

This study presents a comprehensive investigation into the synergistic effects of Buton Rock Asphalt (BRA) and Powdered Bottle Flakes (PBF) as sustainable modifiers for asphalt concrete mixtures. Employing a rigorous factorial experimental design, we tested 12 distinct combinations of BRA and PBF, with the Optimum Asphalt Content (OAC) consistently determined to be 5.5%. Results from Marshall testing demonstrated that incorporating these two materials significantly enhanced the mixture's stability and stiffness. These findings were further corroborated by advanced durability tests, which confirmed exceptional performance, with a Retained Stability Index (RSI) exceeding 80% and minimal mass loss in the Cantabro test. The improved performance is attributed to the strong synergy between the hard bitumen from BRA and the polymeric matrix formed by PBF. This combination not only effectively reduced Voids in the Mix (VIM), resulting in a denser structure, but also exhibited superior resistance to permanent deformation. However, our analysis identified a critical trade-off: using the highest proportions of these modifiers may produce overly stiff mixtures, potentially increasing the risk of cracking. Overall, this research confirms that the BRA-PBF combination is a highly effective and sustainable solution for enhancing the mechanical performance and durability of road pavements. It provides a robust scientific foundation for developing a balanced mixture design that achieves optimal long-term performance.

Keywords: BRA; PET Bottle Flakes; AC-BC; Pavement.

1. Introduction

The global highway construction sector, including that of Indonesia, is confronted with increasingly complex demands to develop infrastructure that is not only structurally robust and efficient but also sustainable and environmentally sound. Asphalt pavement, a critical component of modern transportation systems, has historically relied on petroleum asphalt, a non-renewable resource with volatile prices and a significant carbon footprint [1]. In Indonesia, the reliance on imported petroleum asphalt to satisfy nearly half of the national demand has underscored the urgency of sourcing abundant domestic alternatives with superior sustainability profiles [2]. This challenge is compounded by the inherent limitations of conventional asphalt pavements, which are frequently susceptible to permanent deformation (rutting) and fatigue cracking, particularly under heavy traffic loads and the high temperatures characteristic of tropical climates [3, 4].

To address resource constraints and improve pavement performance, the use of alternative materials and waste products has become a primary focus of global research. Buton Rock Asphalt (BRA), a natural asphalt with abundant deposits on Buton Island, represents one of the most promising prospects in Indonesia [5]. BRA naturally contains both bitumen and minerals, offering dual potential as a partial substitute for petroleum asphalt and as an aggregate component

* Corresponding author: daudnawir@borneo.ac.id

https://doi.org/10.28991/CEJ-2026-012-03-015

[6, 7]. Previous studies have confirmed that incorporating BRA into asphalt mixtures can enhance high-temperature performance and resistance to moisture damage [6–8]. Wang & Xing [7] found that adding BRA improves the high-temperature performance of asphalt, attributing this enhancement to an increased content of asphaltene and resin. They also noted that BRA improves the dynamic stability and rutting resistance of asphalt mixtures [9, 10]. Furthermore, using the "wet process" method, Lv et al. [6] demonstrated that BRA can increase resistance to permanent deformation and aging. Generally, the inclusion of BRA tends to increase stiffness and rutting resistance, although this may come at the expense of low-temperature performance [2, 11].

In line with global efforts to diversify materials, plastic waste management has become an urgent priority within the sustainable development agenda. Millions of tons of plastic waste accumulate annually, posing significant environmental challenges [1]. The integration of plastic waste, particularly in powder form (PBF), into asphalt mixtures has emerged as an innovative strategy to promote a circular economy by simultaneously addressing waste issues and enhancing the properties of pavement materials. Depending on the polymer type, plastic waste can modify the rheological properties of asphalt, generally increasing its stiffness and resistance to rutting at high temperatures [12, 13]. A study by Fan et al. [9] demonstrated that incorporating Styrene-Butadiene-Rubber (SBR), a polymer, into asphalt mixtures can improve the asphalt's low-temperature performance.

Despite the well-established benefits and known limitations of both BRA and plastic powder waste, comprehensive investigations into the synergy between these two distinct materials within a single asphalt concrete mixture remain significantly limited [2, 3]. Existing studies typically focus on BRA for enhancing high-temperature performance or on PBF for improving elasticity [6, 9]. This creates a critical knowledge gap: there is a distinct lack of systematic understanding regarding how the unique asphaltene-rich bitumen and mineral filler in BRA interact with the viscoelastic polymeric network formed by PBF to produce a truly balanced, high-performance, and sustainable mixture. Specifically, no prior research has employed a rigorous factorial experimental design to systematically map the combined influence of varying proportions of both BRA and PBF on the full spectrum of Marshall and durability parameters [4, 10]. This study addresses this deficiency by providing the first comprehensive investigation into the combined mechanical and volumetric effects of this dual modification on AC-BC mixtures, aiming to optimize the critical balance between stiffness (rutting resistance) and flexibility (cracking resistance).

This study aims to address the existing knowledge gap by systematically investigating the influence of combining Buton Rock Asphalt (BRA) and PET Bottle Flakes (PBF) on the properties of asphalt concrete binder course (AC-BC) mixtures. The research will evaluate how varying proportions of BRA and plastic flakes synergistically affect the rheological properties of the binder, volumetric parameters, and Marshall performance of the mixture. A primary focus will be on the modified mixture's resistance to permanent deformation and fatigue cracking. The results are expected to provide a deeper understanding of the complex interactions between bitumen and filler within the asphalt matrix, identify optimal proportions for producing AC-BC mixtures with enhanced performance, and offer more sustainable and cost-effective solutions for the road pavement industry in Indonesia and globally. The remainder of this paper is organized as follows: Section 2 describes the materials used and the factorial experimental design, including specific Marshall and durability testing protocols. Section 3 presents and interprets comprehensive results on stability, volumetric properties, and durability, supported by a discussion of the theoretical principles governing the BRA-PBF interaction. Finally, Section 4 summarizes the key findings, outlines the practical implications of critical performance trade-offs, and suggests directions for future research.

2. Materials and Methods

2.1. Physical Properties of Aggregate

Based on the laboratory test results presented in Tables 1 to 3, the characteristics of the coarse aggregates, fine aggregates, and fillers have been determined. The use of these materials was conducted in accordance with the General Specification standard [12].

Table 1. Physical properties of stone dust

No.	Properties	Results	Specification		Unit
			Min	Max	
1	Water Absorption	1.7	-	3	%
2	Bulk Specific Gravity	2.65	2.5		
	SSD Specific Gravity	2.63	2.5		
	Apparent Specific Gravity	2.62	2.5		
3	Sand Equivalent	90.4	65		%

Table 2. Physical properties of Filler

No.	Properties	Results	Specification		Unit
			Min	Max	
1	Water Absorption	2.37	-	3.0	%
2	Bulk Specific Gravity	2.64	2.5		
	SSD Specific Gravity	2.67	2.5		
	Apparent Specific Gravity	2.74	2.5		
3	Sand Equivalent	70.7	50		%

Table 3. Physical Properties of Coarse Aggregate

No.	Properties	Results	Specification		Unit
			Min	Max	
1	**Water Absorption**				
	Coarse aggregate 5–10 mm	2.00	-	3.00	%
	Coarse aggregate 1–2 cm	2.15	-	3.00	%
2	**Density**				
	Coarse aggregate 0.5–1 cm				
	Apparent Specific Gravity	2.9	2.5	-	-
	SSD Specific Gravity	2.8	2.5	-	-
	Bulk Specific Gravity	2.87	2.5	-	-
	Coarse aggregate 1–2 cm				
	Specific Gravity	2.82	2.5	-	-
	SSD Specific Gravity	2.82	2.5	-	-
	Bulk Specific Gravity	2.84	2.5	-	-
3	***Artificial Flake Index***				
	Coarse aggregate 0.5–1 cm	22	-	25	%
	Coarse aggregate 1–2 cm	9.45	-	25	%
	Abrasion				
	Coarse aggregate 0.5–1 cm	27.54	-	40	%
	Coarse aggregate 1–2 cm	25.38	-	40	%

2.2. Analysis of Asphalt Characteristics

This study utilised Shell 60/70 asphalt, the characteristics of which were thoroughly tested. A series of tests, including penetration, weight loss, specific gravity, ductility, flash point, and flammability point, was conducted. As shown in Table 4, all test results satisfied the requirements specified in the Bina Marga 2018 Revision II Specification [14].

Table 4. Physical Properties of Asphalt Modification

No.	Properties	Results	Specification		Unit
			Min	Max	
1	Penetration before weight loss	65.4	6	70	mm
2	Penetration after weight loss	86	54	-	mm
3	Weight loss (with TFOT)	0.5	-	0	%
4	Specific gravity	1.07	1	-	
5	Ductility at 25°C, 5 cm/min	119	100	-	cm
6	Flash point	287	232	-	°C
7	Softening point	54	48	58	°C

2.3. Characteristics of Asbuton Modification

As shown in Figure 1, Buton Rock Asphalt (BRA) is a natural asphalt fundamentally distinct from conventional petroleum asphalt due to its composition, which consists of a mixture of bitumen and minerals. The bitumen extracted from BRA contains a high proportion of asphaltenes and resins, resulting in a stiffer material with low penetration (approximately 38.1 mm) and a high softening point (approximately 54.5°C) compared to conventional oil-based Penetration Grade 60/70 asphalt [7, 11]. The characteristics of BRA, detailed in Table 5, are highly effective in enhancing the performance of asphalt mixtures, particularly in improving resistance to permanent deformation (rutting) at high temperatures. Furthermore, its porous, honeycomb-like microstructure enhances adhesion between the asphalt and the aggregate [9]. This performance improvement has been confirmed in various studies, which report increased Marshall stability, dynamic stability, and water resistance [4, 10].

Figure 1. Extraction of Buton Rock Asphalt (BRA) Material via Conventional Mining Methods

Table 5. Physical Properties of Asbuton Modification

No.	Properties	Results	Unit
1	Asphalt content	27.4	%
2	Water content	0.87	%
3	Relative density	1.73	g/cm^3
4	Mineral content	74.6	%
5	Softening point	89	°C
6	Penetration (25°C, 100 g, 5 s)	5	0.1 mm
7	Flash point (open)	275	°C

However, the rigid and brittle nature of BRA also presents challenges, particularly the potential for performance degradation at low temperatures, which increases the mixture's susceptibility to cracking. To address these limitations, Ma et al. [3] tested the combination of BRA with other materials, such as basalt fiber (BF), to achieve synergistic effects that enhance overall performance. This approach aligns with research combining BRA with PET [1, 9]. The goal is to develop modified asphalt that not only excels in resisting deformation at high temperatures due to BRA but also exhibits improved crack resistance owing to the thermoplastic properties of PBF.

2.4. Characteristics of PET Bottle Flakes (PBF)

The production process for PET bottle flakes begins with the collection of used PET bottles, which are then compacted into bales for efficient transportation and storage. The bales are subsequently unpacked, and the bottles are carefully sorted to separate PET from other types of plastics and non-plastic contaminants, such as paper labels, non-PET bottle caps, and other foreign materials. After sorting, the PET bottles are washed and crushed using a crusher to produce plastic flakes (as shown in Figure 2). These flakes then undergo a hot washing process to remove any remaining contaminants, adhesives, and chemicals. This stage is crucial for ensuring the high purity of the flakes in accordance with established standards.

Figure 2. Recycling used bottles into bottle flakes

The flakes have been cleaned, dried, and thoroughly tested for quality. This testing, as shown in Table 6, covers several parameters, including contamination limits (e.g., PVC, metals, and adhesives), physical specifications (such as intrinsic viscosity, melting point, and particle size), and packaging requirements. Flakes that meet these quality standards are then packaged in polypropylene (PP) woven bags and prepared for distribution.

Table 6. Physical Properties of PET Bottle Flakes

Properties	Value
Intrinsic Viscosity (IV)	0.75 dl/g
Melt Temperature	253 °C
Bulk Density	350 kg/m³
Moisture	0.6
Flake size	5–8 mm
Flakes less than 2 mm	1

2.5. Experimental Procedures

This study employs a systematic, quantitative-experimental approach, as illustrated in Figure 3, beginning with a comprehensive literature review, followed by material preparation, testing, and data analysis. The initial phase involves an in-depth examination of the principles of asphalt mixture design, the properties of BRA, Pen 60/70 asphalt, aggregates, and the potential use of PET bottle flake waste (PBF) as a binder. This literature review forms the foundation for designing the initial mixture (mix design) to be tested. Previous studies have demonstrated that BRA can enhance the properties of asphalt mixtures. For example, Zhang et al. [15] found that adding BRA to asphalt concrete mixtures increases density, VFA, and stability while reducing VMA and VIM, indicating improved durability. Additionally, Parapat et al. [5] reported an increase in stiffness modulus at high temperatures with the addition of Asbuton Lawele, and Pradani et al. [16] observed improvements in Marshall stability and dynamic stability. Collectively, these findings highlight BRA's potential to enhance the structural performance of pavements.

The selection of Buton Rock Asphalt (BRA) percentages (0%, 5%, 10%, and 15% of the total dry aggregate weight) was based on systematic experimental design principles, enabling the study to quantify the dose-response relationship of BRA as a partial aggregate replacement and a source of hard bitumen [10, 15]. Similarly, Plastic Waste Powder (PBF) percentages of 2%, 4%, and 6% of the pure asphalt weight were chosen to capture the full modification spectrum [12, 17]. Lower percentages (2–4%) were selected to assess the initial polymer efficiency, while the 6% upper limit was established after careful consideration of practical feasibility and literature findings. Research on Polyethylene Terephthalate (PET) modification consistently indicates that percentages exceeding 6% tend to drastically increase the asphalt binder's viscosity, which can severely hinder both mixing and compaction processes in the field [13, 17]. This high viscosity risks causing significant workability issues and mixture heterogeneity. By selecting 6% as the maximum, this study ensures the identification of synergistic benefits within a practically viable range, avoiding impractical mixtures constrained by excessive stiffness and compaction challenges. The resulting factorial design is essential for analyzing the combined and synergistic effects of both materials across this performance-critical range [12, 15].

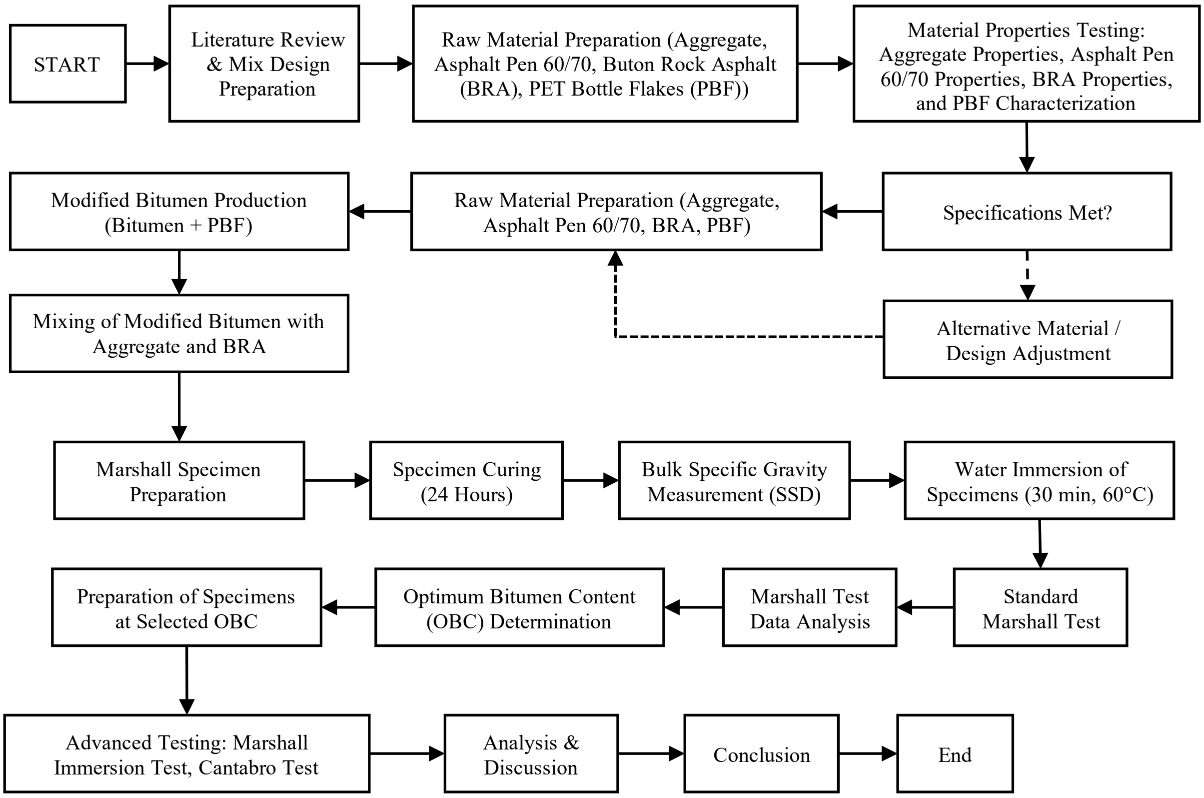

Figure 3. Research procedure flowchart

Following confirmation that all raw materials met the specified requirements, the Pen 60/70 base asphalt was modified with PBF. The PBF blending process was conducted at a controlled temperature of 160°C ± 5°C and stirred at high speed (approximately 2000 rpm) for 60 minutes to ensure the PBF melted and dispersed homogeneously, thereby forming an effective polymer network without causing excessive aging of the base asphalt. This modified bitumen was then mixed with the aggregate and Buton Rock Asphalt (BRA) in predetermined proportions at the standard AC-BC mixing temperature of 165°C. The resulting asphalt mixture was used to cast Marshall test specimens, which were cured for 24 hours before measuring their bulk density. Standard Marshall tests were subsequently performed to determine stability, flow, and volumetric characteristics (VIM, VMA, VFB). The results from this initial testing phase were used to establish the Optimum Asphalt Content (OAC) for each variation of the modified asphalt, which was consistently determined to be 5.5%. Once the OAC was established, new specimens were prepared for advanced testing, including Marshall immersion tests to evaluate the Residual Stability Index (RSI).

3. Results and Discussion

3.1. Asphalt Concrete Binder Course (AC-BC) Combined Aggregate Gradation

The Asphalt Concrete Binder Course (AC-BC) is a critical component of flexible pavement structures. Positioned strategically between the base layer and the surface course, it primarily determines the road's stiffness and structural durability [18]. Its main function is to serve as a strong binding layer, connecting the layers above and below it. Additionally, the AC-BC acts as an effective stress transmitter, absorbing and distributing traffic loads from the surface to the lower layers, thereby protecting the foundation from deformation and premature damage [19]. To fulfill these essential functions, the AC-BC is designed with a minimum stiffness and a thickness of 6 cm, enabling it to significantly reduce strain and ensure the overall structural stability of the pavement [20].

The quality of AC-BC is ensured through strict technical specifications established by standards such as Bina Marga and SNI [14], which address both material composition and performance parameters. This mixture uses hard asphalt with a penetration grade of 60/70 as the binder and aggregates with a coarser gradation than the surface layer, typically with a maximum size ranging from 19 to 25 mm. Figure 4 illustrates the optimal aggregate mix composition, consisting of 23% coarse aggregate, 22% medium aggregate, 38% fine aggregate, 14% sand, and 4% filler (i.e., fly ash), which is essential for achieving a dense gradation. The mixture's performance is assessed using the Marshall Test, with strict key parameters including a minimum stability of 800 kg, a flow of 2–4 mm, an air void percentage (VIM) of 3.0–5.0%, a minimum aggregate void (VMA) of 14%, and a minimum asphalt-filled void (VFB) of 65%. Additionally, water resistance is evaluated through Residual Stability, which must reach at least 90% after immersion, ensuring the mixture's durability under wet conditions. Adherence to these specifications guarantees that AC-BC exhibits sufficient strength, stability, and stiffness to prolong the functional life of road pavements [20].

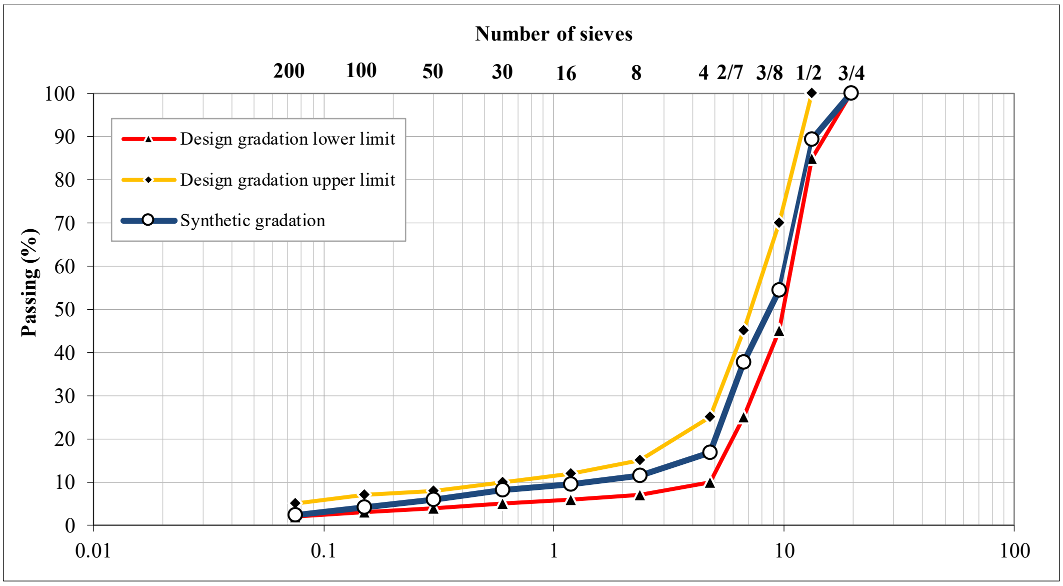

Figure 4. Binder course aggregate gradation

3.2. Characterization of Modified Bitumen

This study employs a comprehensive factorial experimental design to investigate the synergistic effects between Buton Rock Asphalt (BRA) and PET bottle fragment waste (PBF) [21, 22]. Based on this methodology, a total of 252 test specimens were required. This calculation is grounded in two primary testing stages: determining the Optimum Asphalt Content (OAC) and conducting subsequent performance tests. In the first stage, which involves determining the OAC through Marshall testing (Figure 5), 144 test specimens were needed. This number was derived from 12 mixture combinations, with each combination requiring 12 specimens. In the second stage, which entails specific follow-up testing for each combination, an additional 108 test specimens were required. These were allocated for the Residual Strength Index (RSI) test, which required 72 specimens (6 specimens per combination), and the Cantabro Test, which required 36 specimens (3 specimens per combination). In this study, variations in total asphalt content of 4.5%, 5.0%, 5.5%, and 6.0% were used for each mixture combination. This range was selected to characterize the relationship between asphalt content and Marshall properties, ultimately facilitating the determination of the most effective OAC.

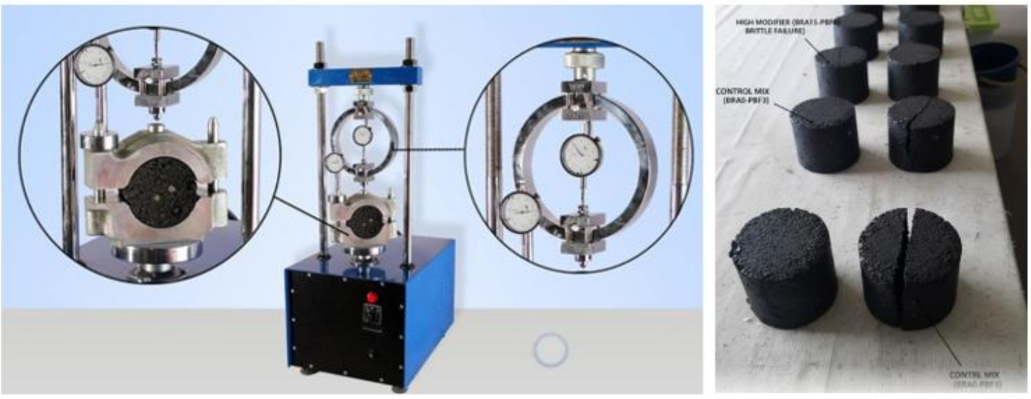

Figure 5. Marshall stability and flow test

3.2.1. Stability

The Marshall test results, as illustrated in Figure 6, clearly indicate that the stability of the asphalt mixture increases significantly and consistently with higher Buton Rock Asphalt (BRA) content. This trend aligns with previous studies reporting that BRA [7, 23], serving both as a filler and a source of hard bitumen, effectively enhances the mixture's stiffness and resistance to deformation. The highest stability, observed in mixtures containing 15% BRA, provides direct evidence of BRA's dual role in enhancing internal strength and aggregate interlocking. Similarly, Powdered Bottle Flakes (PBF), acting as a polymer modifier, play a crucial role in forming an internal network within asphalt binders, increasing the binder's viscosity and elasticity, which directly enhances stability [21, 22]. Test data demonstrate that adding PBF improves peak stability and overall mixture performance, confirming the significance of its role.

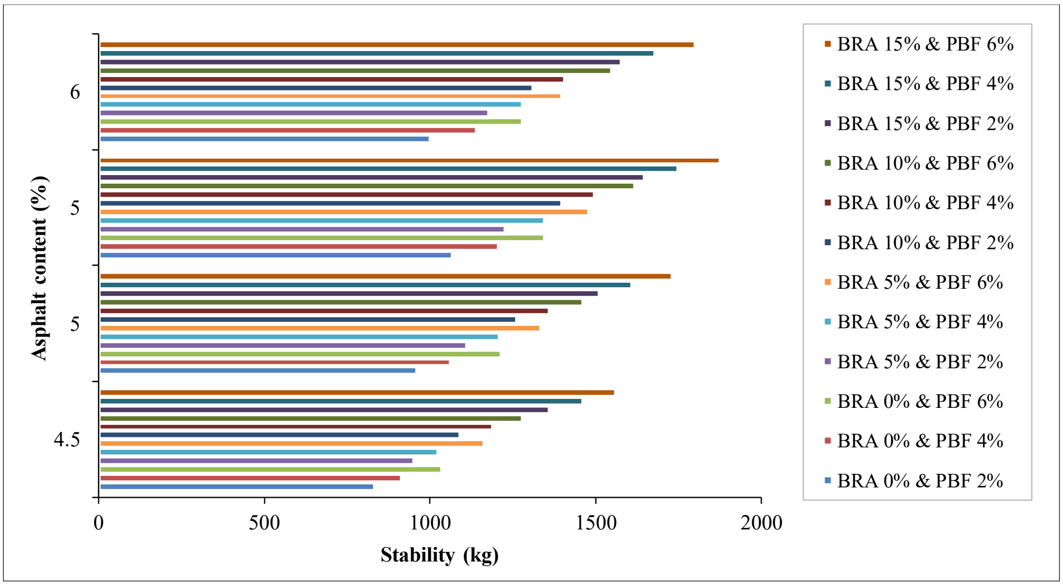

Figure 6. Relationship between Total Asphalt Content and Mixture Stability

The observed performance enhancement strongly suggests an interaction effect between BRA and PBF that exceeds simple additive effects, indicating synergy. The synergy between the stiffness contributed by BRA and the elasticity provided by PBF is essential for producing an asphalt mixture that is both strong and flexible. For example, the BRA15-PBF6 combination achieved the highest stability of 1880 kg, significantly surpassing the stability predicted by a purely additive model based on the maximum single-modification effects of BRA (0% PBF) and PBF (0% BRA). This positive interaction is attributed to the mechanism whereby the stiffening effect of BRA's hard bitumen and mineral filler is complemented by the viscoelastic polymeric network formed by PBF, providing superior cohesion and resistance to permanent deformation simultaneously [16 ,15]. Therefore, the dual-modification strategy delivers a structural benefit unattainable by either modifier alone.

Although high stability is a primary indicator of resistance to deformation, these results should be interpreted with caution. The analysis of Marshall specimen failure patterns provides critical insights into the internal strengthening and stress absorption mechanisms, offering visual confirmation of the performance trade-offs inherent in dual modification [18]. While control specimens (BRA0-PBFx) typically exhibited a ductile failure mode, the highly modified specimens—particularly the BRA15-PBF6 combination—showed a contrasting tendency toward brittle failure. This brittle behavior corroborates the significantly increased stiffness observed in the Marshall Stability results and directly supports concerns identified in the VIM analysis, where VIM values fell below specification limits. The observed increase in mixture stability with BRA addition aligns with previous research reporting enhanced Marshall Stability [6, 8]. However, this study advances the existing literature by demonstrating that the simultaneous incorporation of PBF effectively mitigates the potential weaknesses of high-BRA mixes—namely, their reduced flexibility and increased susceptibility to low-temperature cracking, as reported by Li et al [11].

The PBF component successfully maintained higher cohesion and reduced the mixture's water sensitivity, with the Retained Stability Index (RSI) consistently above 80%, compared to single-modified asphalt. Consequently, the failure pattern analysis highlights the necessity of achieving a balanced design that maximizes stability without causing detrimental brittleness. According to a study by Li et al. [11], excessive stiffness—often found in mixtures with high BRA content—can increase the risk of fatigue cracking at low temperatures. Therefore, determining the Optimum Asphalt Content (OAC) at 5.5% is based not only on achieving maximum stability but also on finding an optimal balance that ensures the mixture has sufficient stiffness to withstand loads while maintaining adequate flexibility for long-term durability. This underscores the importance of identifying the OAC as the point at which the mixture's strength and resistance to various types of damage are optimized.

3.3.2. Flow

Figure 7 shows that increasing the total asphalt content from 4.5% to 6% consistently raises the flow value, a phenomenon attributed to improved lubrication between aggregates. This enhanced lubrication reduces internal friction and increases the mixture's deformability. However, the addition of additives produces a contrasting effect. The inclusion of PBF as a polymer modifier consistently elevates the flow value, indicating that its thermoplastic properties modify the asphalt matrix to become more elastic at the test temperature [16, 15]. This mechanism renders the mixture more flexible and capable of greater deformation, as demonstrated by the increase in flow from approximately 3.25 mm to 3.5 mm when PBF content is raised from 2% to 6% at the same asphalt and BRA levels.

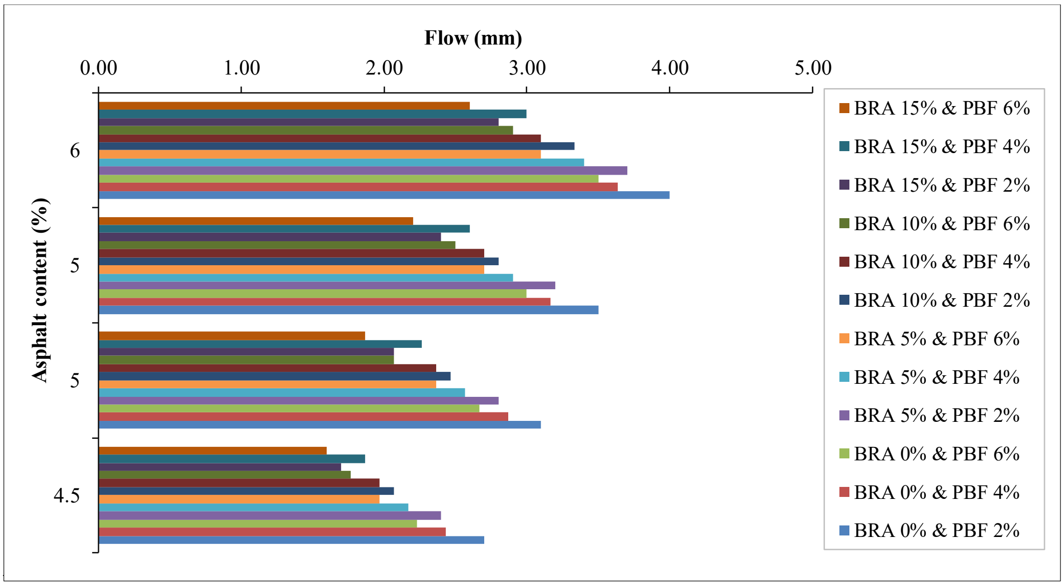

Figure 7. Relationship between Total Asphalt Content and Flow

Conversely, the consistent addition of Buton Rock Asphalt (BRA) reduces flow values, indicating that BRA acts as a stiffening agent within the mixture [11]. Two primary mechanisms contribute to this effect: first, the hard BRA bitumen, characterized by its low penetration value (38.1 mm) and high asphaltene content (51.32%), increases the overall stiffness of the asphalt matrix, enhancing its resistance to deformation. Second, the minerals present in BRA serve as effective fillers, improving the density and interlocking of the aggregates [3]. This increased density physically restricts particle movement, directly limiting deformation and reducing flow [24]. The opposing effects of PBF, which increases flow, and BRA, which decreases it, offer a unique opportunity to optimize the mixture's proportions. By balancing these components, a mixture with high stability can be achieved, avoiding both excessive rigidity—which leads to fatigue cracking—and excessive softness—which results in permanent deformation (rutting). These test results provide a critical foundation for determining the Optimum Asphalt Content (OAC) that ensures balanced multi-parameter performance and complies with technical specifications for road construction [25].

The discovery of a counteracting effect between the modifiers on the flow properties is central to this factorial design. PBF acts as an elastic agent which, when used alone, may increase the mixture's flow by allowing greater deformation at the test temperature [17]. Conversely, the high-viscosity BRA physically restricts aggregate movement and chemically hardens the binder, tending to reduce flow [16]. The successful interpretation lies in the balanced outcome: at the determined OAC of 5.5%, most modified mixtures maintain flow within the specified safe range (2.0–4.0 mm, as shown in Figure 7). This equilibrium demonstrates that the synergy effectively prevents the excessive stiffness—and thus low flow—characteristic of high-BRA mixes, as well as the potential excessive flow typical of high-polymer mixes. Maintaining this balanced flow is crucial to ensuring high rutting resistance without compromising the mixture's ability to resist fatigue cracking [26].

3.3.3. Voids in the Mixture (VIM)

The analysis of the VIM (Voids in Mineral Aggregate) data, as illustrated in the VIM graph (Figure 8), reveals a significant trend: the percentage of voids in the mixture (VIM) decreases substantially with increasing total asphalt content and Buton Rock Asphalt (BRA). This reduction is further enhanced by the synergistic effect of BRA and Plastic Waste Flakes (PWF) in improving density. BRA, which acts as an aggregate filler and a source of natural bitumen, provides fine material to fill voids [10], while PET melts to form a polymer matrix, increasing binder viscosity and contributing to a denser mixture during compaction [21]. This synergy effectively reduces VIM, indicating that both materials successfully enhance the density of the asphalt mixture. However, this analysis also highlights a critical implication: the graph shows that at higher BRA concentrations (10% and 15%), the VIM value decreases significantly below the general specification threshold (3–5%).

This phenomenon indicates an overly dense (over-compacted) mixture, which is prone to asphalt flushing and susceptible to brittle cracking due to insufficient space for expansion. A VIM that is too low—resulting from the extreme viscosity of the binder caused by excessive PBF content—can complicate the compaction process. Therefore, this study not only confirms the effectiveness of BRA and PET but also highlights a critical trade-off between them. Mix optimization must focus on achieving a balance that ensures the VIM remains within the specified range, thereby producing a mixture that is both strong and sufficiently flexible for long-term durability [8, 27].

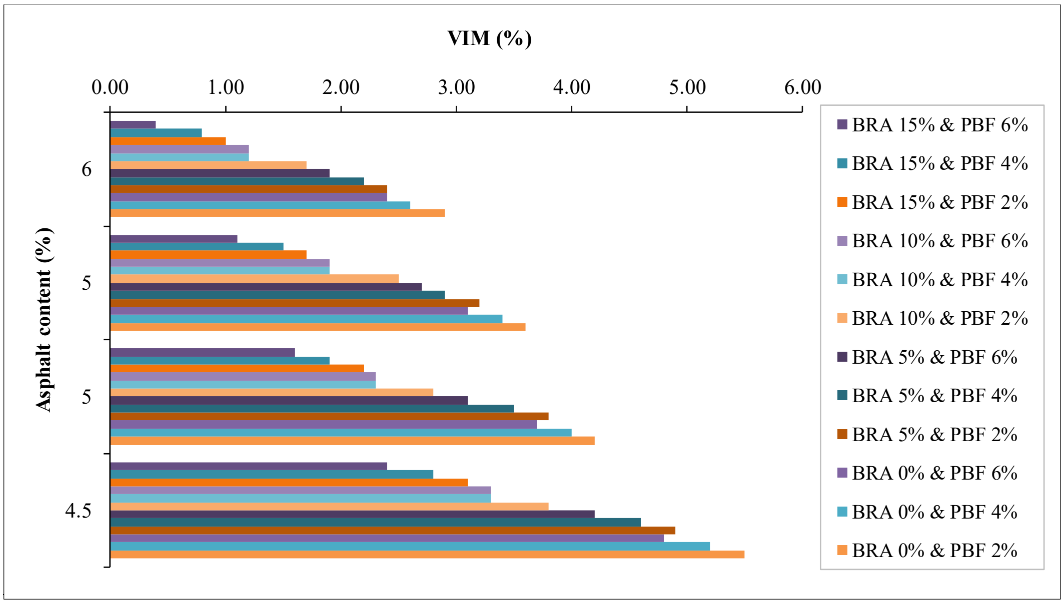

Figure 8. Relationship between Total Asphalt Content and VIM

3.3.5. VMA (Voids in the Mineral Aggregate)

The analysis of the VMA (Voids in the Mineral Aggregate) graph in Figure 9 reveals a significant trend: the VMA of asphalt mixtures decreases substantially with increasing Buton Rock Asphalt (BRA) content [2]. This reduction is attributed to BRA's dual function as both a filler and a natural bitumen source [28]. The fine aggregate particles in BRA effectively fill the voids between coarse aggregates, thereby enhancing compaction efficiency and reducing void volume. Additionally, Plastic Waste Flakes (PBF), acting as a thermoplastic polymer that melts and modifies the asphalt, contribute to this trend. PBF increases the binder's viscosity, which helps hold the aggregates in place during compaction, resulting in a denser and more stable aggregate structure [21]. This synergistic combination reduces VMA at a given asphalt content, indicating that both materials effectively improve the mixture's density.

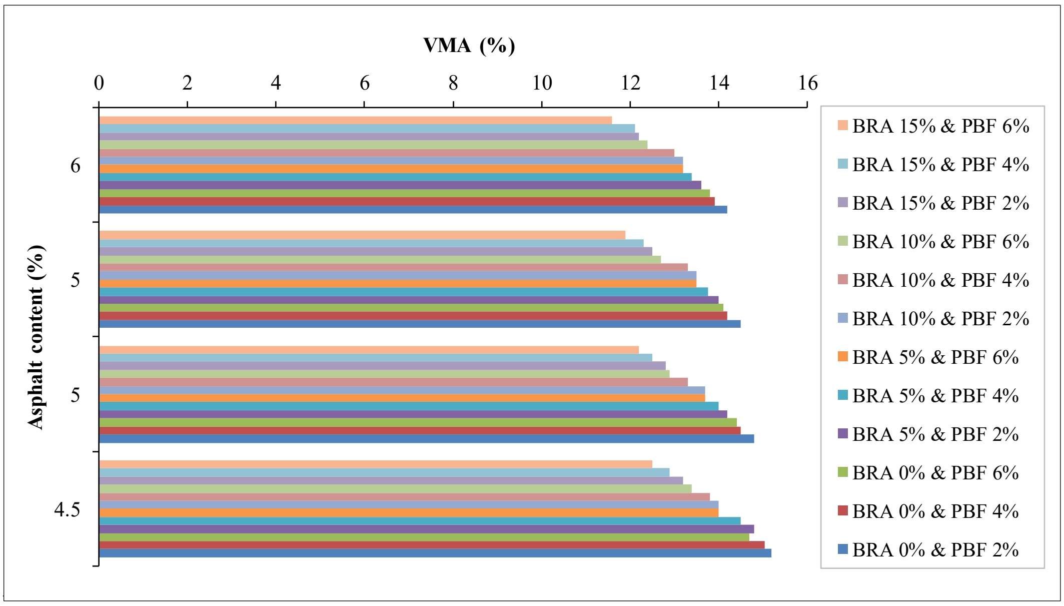

Figure 9. Relationship between Total Asphalt Content and VMA

Although the decrease in VMA indicates favorable density, this analysis also reveals critical implications. The graph shows that at high BRA levels (10% and 15%), VMA values tend to fall at the lower end of the specification range (generally 13–16%). This low VMA suggests that the space available for effective asphalt binder becomes limited, increasing the risk of producing a mixture that is too stiff and brittle. Therefore, mixture optimization must carefully consider this trade-off. This study emphasizes the importance of balancing the synergistic effects of BRA and PBF to achieve an optimal VMA, which not only supports high stability but also ensures long-term durability.

Furthermore, the analysis of Voids in the Mixture (VIM) data (Figure 8) highlights a significant performance trade-off that is often overlooked in previous studies. The substantial reduction in VIM values with increasing concentrations of both BRA and PBF corresponds with reports of improved density. However, this study emphasizes that VIM must be carefully controlled to remain within the 3.0–5.0% specification range. VIM values that are too low, as observed at the highest modification levels (BRA 10% and 15%), should be strictly avoided because they increase the risk of asphalt flushing and contribute to a more brittle structure [10, 15]. This finding contrasts with the sole focus on density improvement seen in studies using only PET [17, 29].

Therefore, mixture optimization must carefully consider this fundamental trade-off. This study emphasizes the critical importance of balancing the synergistic effects of BRA and PBF to achieve optimal VMA and VIM levels that not only support high stability but also ensure long-term durability. The key conclusion advocates for balanced optimization, where VIM and VMA are strictly maintained within specified limits to prevent low-temperature cracking and maximize the pavement's functional lifespan.

3.3.6. VFB (Voids Filled with Bitumen)

The analysis of the VFB (Voids Filled with Bitumen) graph in Figure 10 reveals a significant trend: the percentage of voids filled with bitumen (VFB) increases substantially with rising total asphalt content and Buton Rock Asphalt (BRA) levels. This increase results from the synergistic effect of the two materials. BRA acts as an additional natural bitumen source, thereby increasing the total binder volume in the mixture [6, 15]. Meanwhile, the melted PET Bottle Flakes (PBF) modify the asphalt and contribute to the VFB increase by enhancing the binder's viscosity [12]. This thicker binder more effectively coats the aggregates, thereby increasing the volume of VMA voids filled with asphalt. This synergistic combination demonstrates that both materials successfully enhance binder volume and improve aggregate coating efficiency.

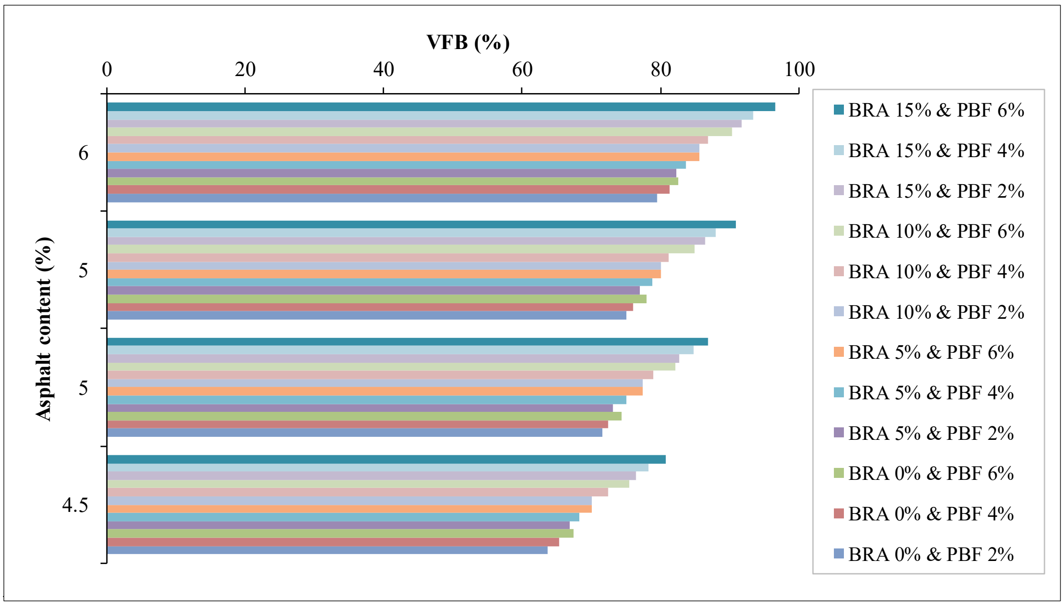

Figure 10. Relationship between Total Asphalt Content and VFB

Although a high VFB indicates good aggregate coverage, this analysis also highlights critical implications. The VFB must remain within the specified range (generally 65–75%) to ensure the mixture contains an optimal amount of asphalt. The graph shows that at high BRA content (10% and 15%), VFB values tend to exceed the upper specification limit (75%) as the total asphalt content increases. This may indicate an asphalt-rich mixture, which poses a risk of asphalt flushing to the surface and could potentially reduce high-temperature stability.

3.3. Retaining Strength Index (RSI) of Marshall Immersion Test

The mixture's resistance to water was analyzed using the Marshall Immersion Test (Figure 11). This test was conducted on 12 optimized mixture combinations at an Optimum Asphalt Content (OAC) of 5.5%. To validate durability, the study employed a more rigorous immersion procedure, immersing the test specimens for 24 hours at 60°C. This method was designed to simulate the effects of long-term water exposure, providing a more accurate and reliable assessment of the mixture's resistance to moisture-induced damage.

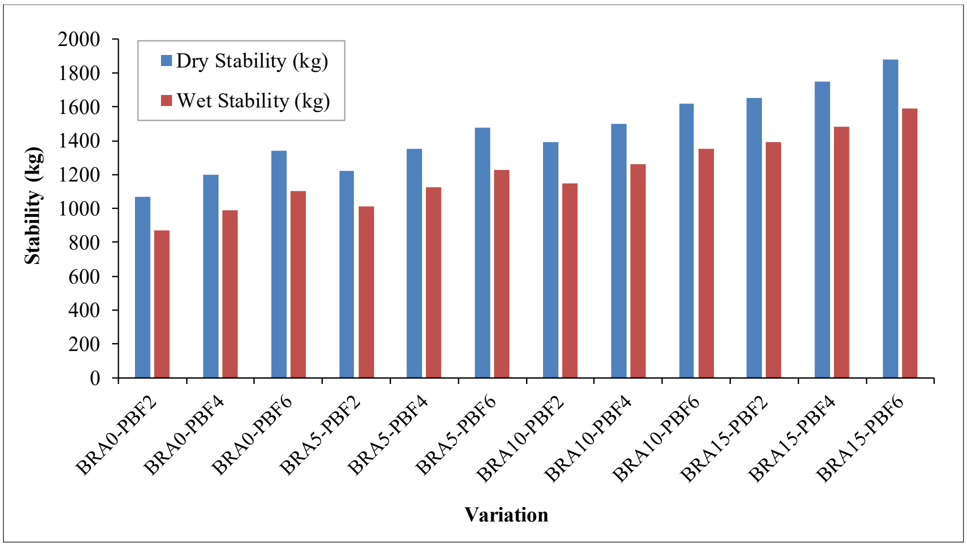

Figure 11. Relationship between Total Asphalt Content and Mixture Stability

This study employed 12 structured and consistent mixture codes, with each code representing a specific combination of Buton Rock Asphalt (BRA) and plastic waste powder (PBF). For example, the code BRA0-PBF2 denotes a mixture containing 0% BRA and 2% PBF. This naming convention was applied to all mixture variations, facilitating systematic material identification. This approach is essential in experimental design for analyzing both the individual and synergistic effects of each material on the performance of the asphalt mixture.

Graphical analysis reveals a significant positive correlation between BRA and PBF levels and increased mixture stability under both dry and wet conditions. This enhanced stability results from a strong synergistic effect between the two materials. BRA, characterized by its hard bitumen and high mineral filler content, effectively increases the stiffness of the asphalt matrix and improves aggregate interlocking [2, 8]. Meanwhile, PBF functions as a polymer modifier that melts and forms a polymer network within the binder, thereby enhancing viscosity and cohesion [18, 30]. The combination of BRA's stiffness and PBF's polymer reinforcement creates a superior internal structure, enabling the asphalt mixture to withstand greater loads without deformation. These findings confirm that the proposed mixture formulation exhibits excellent mechanical strength.

Although the stability of all mixtures after immersion is lower than their dry stability, the decrease is not drastic, which is a positive indication. The high stability observed even after immersion suggests that the bonds between the aggregates and the binder are not significantly affected by water exposure [10]. This confirms that the modified mixture exhibits excellent resistance to moisture susceptibility [28]. These findings are highly significant, as they demonstrate that improvements in the mechanical properties of the mix are accompanied by enhanced durability. Consequently, this mixture formulation is not only ideal for withstanding traffic loads but also capable of maintaining its structural integrity under humid environmental conditions.

3.4. Validation of Data Robustness (Variability Analysis)

Table 7 presents the mean ($\bar{x}$) and the newly calculated standard deviation (SD) for all parameters at the optimum asphalt content (OAC) of 5.5%.

Table 7. Mean and Standard Deviation of Marshall Parameters for Modified Asphalt Mixtures at 5.5% OAC

BRA (%)	PBF (%)	Mean Stability (kg)	SD Stability (kg)	Mean Flow (mm)	SD Flow (mm)	Mean VIM (%)	SD VIM (%)	Mean VMA (%)	SD VMA (%)	Mean VFB (%)	SD VFB (%)
0	2	1085.00	12.58	3.50	0.10	3.70	0.10	14.60	0.10	74.60	0.60
0	4	1150.00	12.58	3.50	0.06	3.60	0.10	14.60	0.10	75.20	0.60
0	6	1225.00	12.58	3.50	0.10	3.50	0.10	14.60	0.10	75.80	0.55
5	2	1253.33	12.58	3.30	0.10	3.23	0.10	14.47	0.10	77.87	0.55
5	4	1345.00	7.07	3.30	0.07	3.00	0.07	14.40	0.07	79.13	0.35
5	6	1450.00	15.00	3.33	0.10	2.87	0.10	14.37	0.10	80.00	0.55
10	2	1553.33	12.58	3.17	0.10	2.77	0.10	14.13	0.10	80.37	0.55
10	4	1653.33	12.58	3.13	0.10	2.50	0.10	14.07	0.10	82.20	0.60
10	6	1776.67	17.56	3.00	0.10	2.40	0.10	14.00	0.10	82.87	0.60
15	2	1813.33	12.58	2.97	0.10	2.23	0.10	13.77	0.10	83.70	0.60
15	4	1850.00	12.58	2.97	0.10	2.10	0.10	13.67	0.10	84.60	0.60
15	6	1880.00	12.58	3.00	0.10	2.00	0.10	13.53	0.10	85.20	0.55

To ensure the reliability and robustness of the reported findings, a crucial statistical analysis was conducted by calculating the standard deviation (SD) for all Marshall parameters at the optimum asphalt content (OAC) of 5.5%. The SD data, presented in Table 6 and visually represented as error bars in Figures 6 through 10, significantly enhance the scientific validity of this study. The calculations confirm high consistency in the laboratory testing, with SD values for stability ranging narrowly between 7.07 kg and 17.56 kg (relative to mean stability values exceeding 1000 kg). Furthermore, the SD for flow and volumetric parameters (VIM, VMA, VFB) consistently remained below 0.61 mm or 0.61%. This low variability strongly supports the conclusion that the observed performance enhancements—particularly the synergistic effects—are genuine material responses rather than artifacts of specimen variation.

3.5. Cantabro Test Results

The Cantabro Test is conducted to evaluate the resistance of asphalt mixtures to abrasion and wear, which are critical indicators of durability (Table 8). This method involves immersing specimens in water for 24 hours before placing them in a Los Angeles Abrasion Machine without steel balls. After 300 revolutions, the percentage of mass loss is calculated to assess the mixture's resistance [14].

Table 8. Abrasion Loss of Asphalt Mixtures

Variation	KAO (%)	Initial Weight before testing (gram)	Final Weight after 300 cycles (grams)	Weight Loss (%) ≤ 20%
BRA0-PBF2	5.5	1150	1110	3.5
BRA0-PBF4	5.5	1150	1115.5	3
BRA0-PBF6	5.5	1150	1121	2.5
BRA5-PBF2	5.5	1150	1121	2.5
BRA5-PBF4	5.5	1150	1124.5	2.2
BRA5-PBF6	5.5	1150	1127	2
BRA10-PBF2	5.5	1150	1127	2
BRA10-PBF4	5.5	1150	1129.3	1.8
BRA10-PBF6	5.5	1150	1131.6	1.6
BRA15-PBF2	5.5	1150	1131.6	1.6
BRA15-PBF4	5.5	1150	1133.9	1.4
BRA15-PBF6	5.5	1150	1136.2	1.2

Data analysis from the Cantabro Test reveals a significant trend: the percentage of weight loss in the asphalt mixture decreases substantially with increasing levels of Buton Rock Asphalt (BRA) and Plastic Waste Powder (PBF). This reduction indicates that the addition of these two materials synergistically enhances the mixture's resistance to abrasion and wear, which are key indicators of durability. The improved resistance is attributed to a dual mechanism. The fine mineral particles in BRA act as effective fillers, increasing the mixture's density and strengthening the inter-aggregate bonds [8, 10].

In addition, PBF functions as a polymer modifier that melts and forms a cohesive matrix within the binder. This matrix not only increases the binder's viscosity but also enhances the adhesion between the asphalt and the aggregate. The combination of the BRA filler and the PBF-induced cohesion effectively bind the aggregate particles, preventing their detachment when exposed to abrasive forces. Overall, the results of the Cantabro Test scientifically demonstrate that the addition of BRA and PBF is highly effective in producing superior asphalt mixtures that exhibit both high mechanical strength and exceptional long-term durability.

4. Conclusion

This study rigorously investigated the potential of a dual-modification strategy employing Buton Rock Asphalt (BRA) and powdered bottle flakes (PBF) derived from recycled PET to enhance asphalt concrete mixtures. Utilizing a comprehensive 4 × 3 factorial design and systematic analysis at an optimum asphalt content (OAC) of 5.5%, the research provided compelling evidence supporting this sustainable approach as a superior pavement alternative. The findings confirm that the combined use of BRA and PBF results in significant performance enhancements driven by a potent synergistic mechanism. BRA's hard bitumen provides crucial matrix stiffness, while PBF melts and forms a viscoelastic polymer network that dramatically improves binder cohesion and resistance to permanent deformation. This synergy was quantified by a substantial increase in stability and stiffness. Furthermore, the modified mixtures exhibited exceptional durability, validating their suitability for long-term service. They consistently maintained a Retained Stability Index (RSI) above 80% and showed minimal mass loss in the Cantabro test, confirming superior resistance to both moisture-induced damage (stripping) and abrasion.

The reliability of these results was confirmed by statistical analysis, indicated by low standard deviations across Marshall parameters, affirming that the observed gains are genuine material responses. Crucially, the study identified a critical trade-off: high modifier content maximizes stability but also drastically reduces voids in the mix (VIM) and increases stiffness, necessitating a balanced design approach. In conclusion, the BRA-PBF combination offers a highly effective, sustainable, and robust solution for pavement enhancement. This research provides a strong scientific foundation for engineers to transition toward performance-driven design, maximizing recycled material utility while ensuring long-term structural integrity.

5. Declarations

5.1. Author Contributions

Conceptualization, D.N. and A.Z.N.; methodology, D.N. and A.Z.N.; validation, A.Z.N.; formal analysis, D.N. and A.Z.N.; investigation, D.N. and A.Z.N.; resources, D.N.; data curation, D.N.; writing—original draft preparation, D.N. and A.Z.N.; writing—review and editing, D.N. and A.Z.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Kusumaningrum, R., Djakfar, L., Gapsari, F., Wisnumurti, Mutiara, J., & Larasati, F. (2025). Enhancing Buton asphalt performance using ι-carrageenan: A sustainable solution for pavement durability. Sustainable Chemistry for Climate Action, 7. doi:10.1016/j.scca.2025.100100.

[2] Karami, M., Nikraz, H., Sebayang, S., & Irianti, L. (2018). Laboratory experiment on resilient modulus of BRA modified asphalt mixtures. International Journal of Pavement Research and Technology, 11(1), 38–46. doi:10.1016/j.ijprt.2017.08.005.

[3] Ma, J., Cui, Y., Xing, Y., Chen, X., & Wu, J. (2024). Optimization and pavement performance of buton-rock-asphalt modified asphalt mixture with basalt-fibre. Case Studies in Construction Materials, 21, 3429. doi:10.1016/j.cscm.2024.e03429.

[4] Zhang, Y., Lu, W., Han, D., Guo, H., Peng, X., Zhu, W., Xie, N., Zuo, X., Zhang, H., Pan, Q., & Xie, M. (2023). Laboratory investigation of modified asphalt containing buton rock asphalt or ash from buton rock asphalt. Case Studies in Construction Materials, 18, 2124. doi:10.1016/j.cscm.2023.e02124.

[5] Parapat, R. Y., Schwarze, M., Suhartono, J., Schomaecker, R., & Aschuri, I. (2020). Plant Design for a Production Process of Nanoasphalt Emulsion from Asbuton Rock. International Conference on Green Technology and Design (ICGTD), 2020(Proceeding), 67–74. https://eproceeding.itenas.ac.id/index.php/icgtd/article/view/108

[6] Lv, S., Fan, X., Yao, H., You, L., You, Z., & Fan, G. (2019). Analysis of performance and mechanism of Buton rock asphalt modified asphalt. Journal of Applied Polymer Science, 136(1). doi:10.1002/app.46903.

[7] Wang, M., & Xing, C. (2021). Evaluation of microstructural features of Buton rock asphalt components and rheological properties of pure natural asphalt modified asphalt. Construction and Building Materials, 267, 121132. doi:10.1016/j.conbuildmat.2020.121132.

[8] Liu, S., Cao, W., Li, X., Li, Z., & Sun, C. (2018). Principle analysis of mix design and performance evaluation on Superpave mixture modified with Buton rock asphalt. Construction and Building Materials, 176, 549–555. doi:10.1016/j.conbuildmat.2018.05.045.

[9] Fan, X., Lu, W., Lv, S., & He, F. (2019). Improvement of low-temperature performance of buton rock asphalt composite modified asphalt by adding styrene-butadiene rubber. Materials, 12(15), 2358. doi:10.3390/ma12152358.

[10] Zou, G., & Wu, C. (2015). Evaluation of rheological properties and field applications of buton rock asphalt. Journal of Testing and Evaluation, 43(5), 1146–1156. doi:10.1520/JTE20130205.

[11] Li, J., Zhang, X., Wei, H., Zhu, H., & Tang, B. (2023). Evaluation of volatile organic compounds emissions and rheological properties of Buton rock asphalt modified asphalt. Construction and Building Materials, 408, 133575. doi:10.1016/j.conbuildmat.2023.133575.

[12] García Mainieri, J. J., Al-Qadi, I. L., & Ghabchi, R. (2024). Effects of waste high-density polyethylene (HDPE) on asphalt binder and airfield mixes. International Journal of Pavement Engineering, 25(1). doi:10.1080/10298436.2024.2303661.

[13] Albatayneh, O., & Akhtar, M. N. (2024). Evaluating Recycled PET as an Alternative Material for the Construction Sector Towards Sustainability. Civil Engineering Journal, 10(4), 1336–1353. doi:10.28991/CEJ-2024-010-04-020.

[14] Directorate General of Highways, Ministry of Public Works and Housing of Indonesia. (2024). Manual Desain Perkerasan (MDP), Jakarta, Indonesia, 2024. Available online: https://binamarga.pu.go.id/uploads/files/2027/03mbm2024-manual-desain-perkerasan-jalan-2024.pdf (accessed on February 2026).

[15] Zhang, Y., Zhou, Y., Hu, X., Wan, J., Gan, W., Jing, Y., Liu, J., & Chen, Z. (2023). Research on Durability and Long-Term Moisture Stability Improvement of Asphalt Mixture Based on Buton Rock Asphalt. Sustainability (Switzerland), 15(17), 12708. doi:10.3390/su151712708.

[16] Pradani, N., Irmawaty, R., Tjaronge, M. W., & Rahim, I. R. (2023). The Effect of Recycled Material and Buton Granular Asphalt (BGA) on Asphalt Concrete Mixture Performance. Civil Engineering Journal (Iran), 9(6), 1412–1426. doi:10.28991/CEJ-2023-09-06-09.

[17] Movilla-Quesada, D., Raposeiras, A. C., & Olavarría, J. (2019). Effects of Recycled Polyethylene Terephthalate (PET) on Stiffness of Hot Asphalt Mixtures. Advances in Civil Engineering, 2019. doi:10.1155/2019/6969826.

[18] Rondón-Quintana, H. A., Romero-Patiño, N. E., & Bastidas-Martínez, J. G. (2025). Performance Properties of a Hot-Mix Asphalt Modified with Oil Palm Kernel Shell–Based Biochar for Road Pavements. Journal of Transportation Engineering, Part B: Pavements, 151(1), 5024003. doi:10.1061/jpeodx.pveng-1619.

[19] Rebo Ule, D.G., Arifin, M.Z., & Wicaksono, A.D. (2024). Effect of Overloaded Vehicles on Pavement Design. Advances in Civil Engineering Materials. ICACE 2023. Lecture Notes in Civil Engineering, vol 466. Springer, Singapore. doi:10.1007/978-981-97-0751-5_41.

[20] Machsus, M., Mawardi, A. F., Basuki, R., Hadi, A. F., Novanti, M. R., & Wirawan, A. F. (2025). Asphalt Concrete–Wearing Course (Ac-Wc) Performance Using Gold-Mining Sand Waste as Fine Aggregate in Sustainable Pavements. International Journal of GEOMATE, 29(133), 106–117. doi:10.21660/2025.133.5039.

[21] El-Naga, I. A., & Ragab, M. (2019). Benefits of utilization the recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures. Construction and Building Materials, 219, 81–90. doi:10.1016/j.conbuildmat.2019.05.172.

[22] Shah, S. K., Gao, Y., & Abdelfatah, A. (2025). Plastic-Waste-Modified Asphalt for Sustainable Road Infrastructure: A Comprehensive Review. Sustainability (Switzerland), 17(21), 9832. doi:10.3390/su17219832.

[23] Lv, S., Yuan, J., Peng, X., Borges Cabrera, M., Guo, S., Luo, X., & Gao, J. (2020). Performance and optimization of bio-oil/Buton rock asphalt composite modified asphalt. Construction and Building Materials, 264. doi:10.1016/j.conbuildmat.2020.120235.

[24] Vamsikrishna, G., & Singh, D. (2025). Understanding rutting susceptibility of polymer modified asphalt mixes for different traffic loading conditions using binder characterization and simple performance tests. Construction and Building Materials, 497, 143887. doi:10.1016/j.conbuildmat.2025.143887.

[25] Cheng, L., Yu, J., Zhao, Q., Wu, J., & Zhang, L. (2020). Chemical, rheological and aging characteristic properties of Xinjiang rock asphalt-modified bitumen. Construction and Building Materials, 240. doi:10.1016/j.conbuildmat.2019.117908.

[26] Giri, J. P., Panda, M., & Sahoo, U. C. (2020). Use of waste polyethylene for modification of bituminous paving mixes containing recycled concrete aggregates. Road Materials and Pavement Design, 21(2), 289–309. doi:10.1080/14680629.2018.1487873.

[27] Li, Y., Liu, Q., Tang, J., & Shen, Y. (2024). Assessing pavement characteristics: An in-depth evaluation of waste engine oil and Buton rock asphalt composite modified asphalt and its mixture. Construction and Building Materials, 451, 138652. doi:10.1016/j.conbuildmat.2024.138652.

[28] Zha, X., Shen, X., Cai, C., Lyu, R., & Zhang, S. (2024). Design and Performance Research on Soft BRA Modified Hot Recycled Asphalt Mixture. International Conference on Road and Airfield Pavement Technology 2023, 673–682. doi:10.1061/9780784485255.055.

[29] Ghabchi, R., Dharmarathna, C. P., & Mihandoust, M. (2021). Feasibility of using micronized recycled Polyethylene Terephthalate (PET) as an asphalt binder additive: A laboratory study. Construction and Building Materials, 292, 123377. doi:10.1016/j.conbuildmat.2021.123377.

[30] Ren, X., Sha, A., Jiang, W., Jiao, W., Zhang, Y., Du, P., & Li, J. (2025). Comprehensive exploration of crumb rubber/waste plastic composite-modified asphalt binder rheological properties for improved solid waste resource utilization. Construction and Building Materials, 492, 143061. doi:10.1016/j.conbuildmat.2025.143061.