

Fatigue Behavior of Buton Asphalt Modified with Marine Fuel Oil and Styrene-Butadiene Rubber

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ABSTRACT

The service life of asphalt pavements is strongly influenced by their fatigue resistance, especially in tropical regions where high temperatures accelerate binder hardening. Conventional mix design methods often fall short in addressing this issue, highlighting the need for performance-based approaches. This study evaluates a Modified Asphalt (MA) binder produced from Extracted Buton Asphalt (EBA) and enhanced with 12% Marine Fuel Oil (MFO) and 2% Styrene-Butadiene Rubber (SBR). Asphalt mixtures were prepared with 6% binder and 94% aggregates using five MA-PA combinations: 0/100, 25/75, 50/50, 75/25, and 100/0. Cylindrical specimens were compacted using the Marshall method and tested for fatigue performance under repeated loading with a Dynapave UTM-30. Fatigue behavior was examined through resilient modulus, accumulated strain, and fatigue life. The results demonstrated that low MA contents ($\leq 25\%$) reduce cohesion and fatigue life due to MFO-induced softening. Intermediate MA levels (50–75%) exhibit a synergistic MFO-SBR effect, improving recovery and durability. At 100% MA, excessive stiffness leads to early cracking. The best performance occurs at 75% MA, where stiffness and flexibility are optimally balanced in accordance with the Balanced Mix Design (BMD) concept. Overall, MA derived from EBA with MFO and SBR demonstrates strong potential for heavy-traffic pavements in tropical climates. However, given that the current study was limited to laboratory conditions, further field validation and mechanistic-empirical modeling are proposed to refine long-term performance predictions.

Keywords-asphalt mixtures; buton asphalt; durability; fatigue resistance; modified asphalt

I. INTRODUCTION

The performance of asphalt pavements is influenced by their ability to withstand long-term, repeated traffic loading [1]. One of the most critical forms of deterioration is fatigue

cracking, which occurs due to the accumulation of repeated stress and strain at levels below the material's tensile strength. This mechanism initiates microcracks that gradually propagate into macrocracks, compromising the structural integrity of the pavement and significantly reducing its service life [2-5].

These effects are particularly significant in tropical regions, where elevated temperatures accelerate the age hardening of asphalt layers under heavy traffic loads, leading to more rapid crack propagation. Conventional volumetric-based mix design approaches are inadequate for predicting fatigue performance because they do not account for the mechanistic response of materials under actual traffic loading conditions. This limitation has prompted the adoption of performance-based mix design frameworks that focus on evaluating critical mechanical properties such as Modulus Resilience (MR), permanent deformation, and strain accumulation under cyclic loading conditions. Among these, fatigue testing has emerged as a key method for quantifying the balance between stiffness and flexibility, which directly influences the long-term durability of asphalt mixtures [6].

Polymer modification, particularly with Styrene SBR, has been investigated for improving the elasticity and fatigue performance of asphalt mixtures [7, 8]. SBR enhances the binder’s microstructure, increasing its resistance to cracking under repeated loading [9]. However, most studies have focused on petroleum-based binders, while relatively little attention has been given to natural asphalt sources such as Buton Rock Asphalt (BRA). BRA, found on Buton Island in Indonesia, represents one of the world’s largest natural asphalt reserves (alongside Trinidad), containing about 20% bitumen with total deposits estimated at 650–677 million tons, equivalent to 130–170 million tons of pure asphalt [10–12]. Despite this significant potential, research aimed at optimizing BRA with innovative additives to improve pavement durability remains limited. Since BRA tends to be stiff and brittle, modifications are required to achieve an appropriate balance between stiffness and flexibility. Authors in [13] demonstrated that incorporating 2.5% Rosin improved tensile strength, motivating further exploration of other modifiers. In this context, MFO and SBR have been added to BRA-based binders to enhance durability and fatigue resistance. MFO acts as a fluxing agent that reduces binder viscosity and improves workability, while SBR contributes elasticity, which is essential for accommodating repeated traffic-induced strains. Evaluating the fatigue performance of these modified binders is, therefore, crucial for understanding the stiffness–flexibility balance that governs long-term pavement durability. Accordingly, this study investigates MA produced from EBA modified with MFO and SBR to determine its influence on the durability of asphalt concrete mixtures, with a particular focus on fatigue resistance. The study aims to assess whether increasing MA content consistently enhances fatigue life and mechanistic properties, such as MR and permanent horizontal strain accumulation, and to identify the optimal MA proportion that achieves a balanced stiffness–flexibility profile for durable and sustainable pavement applications.

II. METHOD

This study was conducted under controlled laboratory conditions to evaluate the durability of asphalt mixtures, with fatigue resistance considered the primary performance indicator. The mixture is designed for the wearing course (surface layer) of flexible pavement. Five binder compositions of MA and PA were prepared with varying proportions: 0%

MA/ 100% PA, 25% MA/ 75% PA, 50% MA/ 50% PA, 75% MA/ 25% PA, and 100% MA/ 0% PA. The primary materials employed in this study were MA, PA, and mineral aggregates. MA was produced by modifying EBA with 12% MFO as a fluxing agent and 2% SBR as an elastomeric modifier, as shown in Figure 1.



Fig. 1. Components of MA binder.

The modification aimed to optimize flexibility and thermal stability, enhance fatigue resistance, and reduce the brittleness of EBA. For comparison, PA (60/70 penetration grade) exhibited relatively greater softness and ductility. A summary of these binder properties is presented in Table I.

TABLE I. SUMMARY OF BINDER PROPERTIES

Property	Test method	Unit value	EBA	MA	PA	Standard value
Penetration	[14]	0.1 mm	19.8	54.7	66.2	60-70
Ductility	[15]	mm	124	129.6	140	≥ 100
Softening point	[16]	°C	54	55.8	48	48-56
Flash point	[17]	°C	268	248	290	≥ 232
Specific gravity	[18]	–	1.06	1.08	1.04	≥ 1
Loss on heating	[19]	%	0.086	0.465	0.08	≤ 0.8

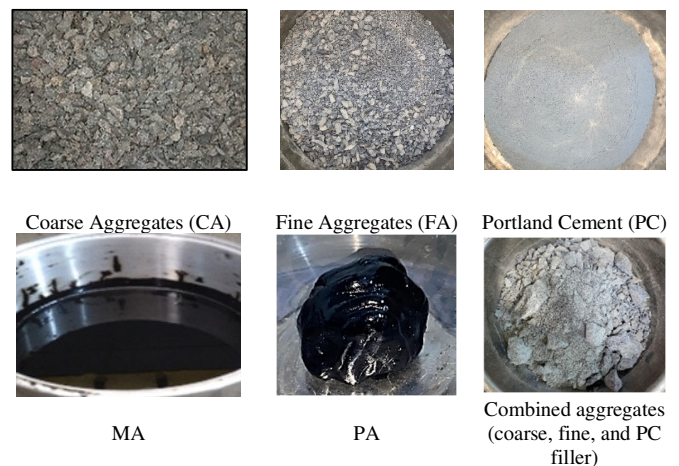


Fig. 2. Materials used for asphalt mixture samples.

The aggregates consisted of natural crushed stone with an AC-WC gradation combined with PC as filler, as depicted in Figure 2. The aggregate gradation comprised 48.5% CA, 44% FA, and 7.5% filler. CA exhibited bulk, apparent, and effective specific gravities of 2.71, 2.83, and 2.77, respectively, with

water absorption of 1.63%. FA showed respective values of 2.54, 2.61, and 2.57, with water absorption of 1.18%. All materials conformed to [20], ensuring their suitability for asphalt mixtures. The asphalt mixture for the sample was prepared with 6% asphalt (MA, PA) and 94% aggregate. Based on the aggregate gradation, the total mixture consists of 45.59% CA, 41.36% FA, and 7.05% filler. Five variations of cylindrical samples were produced deploying the Marshall Method. The fatigue resistance of asphalt mixtures was evaluated using a Dynapave UTM-30 equipped with automated software to simulate repeated loading conditions representative of actual traffic [21]. In the context of pavement systems, fatigue refers to cumulative cracking caused by repeated loading at stress levels generally lower than the material's tensile strength [22]. Fatigue life is primarily influenced by tensile strain and mixture stiffness, which define the relationship between the applied stress and the number of cycles to failure [23]. Fatigue performance was evaluated using a Dynapave UTM-30 in Indirect Tensile Fatigue Test (ITFT) mode, following [24, 25]. Cylindrical specimens (101.6 mm diameter, 63.5 mm height) were tested under sinusoidal or haversine loading at 40 ± 1 °C and frequencies of 1 Hz–10 Hz. Testing continued until visible fatigue cracking occurred or stiffness modulus decreased by 50% from its initial value. After completing all laboratory tests, an analysis was conducted to determine the effect of MA proportion on fatigue performance parameters, including MR, accumulated strain, and fatigue life (number of load cycles). For each mixture variation (0%, 25%, 50%, 75%, and 100% MA), the test data were compiled and analyzed through graphical trend evaluation to identify performance patterns.

III. RESULTS AND DISCUSSION

A. Fatigue Testing of Asphalt Mixtures with MA and PA

Fatigue testing on cylindrical specimens was conducted following the procedure portrayed in Figure 3. The test produced several key parameters indicative of the mixture's resistance to fatigue cracking [26, 27], including the number of load cycles to failure, the resilient modulus (MR, MPa) representing specimen stiffness under cyclic loading, and the accumulated permanent horizontal strain ($\mu\epsilon$), which reflects the total horizontal deformation developed during the test.

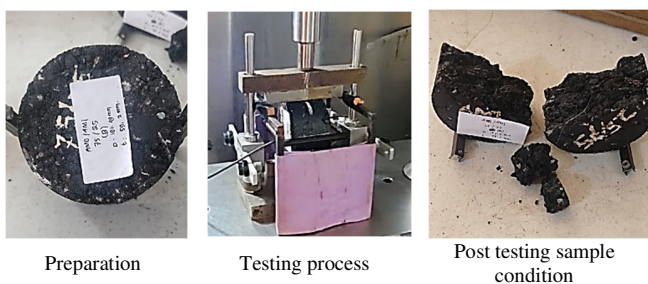


Fig. 3. Fatigue testing of asphalt mixtures incorporating MA and PA.

1) Number of Load Cycles (Fatigue Life)

Figure 4 illustrates the fatigue performance of asphalt mixtures with different MA–PA proportions. The control mixture (0% MA) represents the conventional use of 100% PA.

Relative to this control, fatigue life dropped sharply at 25% MA, increased at 50% MA, slightly decreased at 75% MA, and declined further at 100% MA. These trends indicate that increasing the MA content does not necessarily produce continuous improvements in fatigue resistance, and that excessive modification can be detrimental.

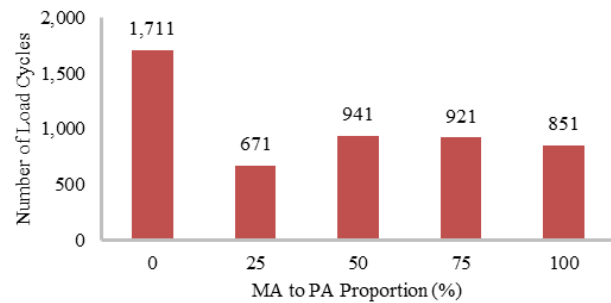


Fig. 4. Number of load cycles for different proportions of MA.

Figure 4 demonstrates that combining 25% MA, compared to the control mix (100% PA), reduced fatigue life from 1711 to 671 load cycles. At 50% MA, the number of cycles increases to 941 and then drops to 921 cycles at 75% MA. Even at the 100% MA, this number drops to 851 cycles. It is, thus, indicated that higher MA proportions can enhance mixture stability, but not in a linear manner up to 100% MA. These findings suggest that the MA addition does not proportionally improve fatigue life. This phenomenon reflects the critical balance between stiffness and elasticity within the binder system. At low MA contents, PA stiffness dominates, limiting the mixture's ability to dissipate stress under cyclic loading. At intermediate levels (25% MA–50% MA), the elastic contribution of MA is insufficient to compensate for the loss of cohesive strength, resulting in reduced fatigue resistance. At 75% MA, the elastic characteristics of the modified binder become dominant, enabling the mixture to accommodate repeated deflection better and delay crack initiation [28, 29]. Conversely, at 100% MA, the mixture tends to become excessively stiff, reducing its capacity for strain recovery and leading to premature cracking. The decline in fatigue performance at high MA levels ($\geq 75\%$) is attributed to increased elasticity and structural stiffness, which limit the mixture's ability to dissipate stresses under repeated loading [30, 31]. These findings emphasize the need to achieve a balanced stiffness–flexibility ratio, aligning with the principles of the BMD framework [32], which seeks to optimize pavement performance under repeated traffic loading. The results provide a basis for identifying an optimum MA content that enhances fatigue life while supporting the use of sustainable materials. Similar trends have been reported in [33], where polymer modification improved flexibility and fatigue resistance up to an optimal level, thereby extending fatigue life [34]. Beyond this optimum, however, excessive modification may increase brittleness or disrupt binder uniformity, ultimately reducing fatigue durability due to altered viscoelastic behavior [35].

2) MR Response Under Cyclic Loading

Figure 5 shows the relationship between resilient modulus and loading cycles for asphalt mixtures with different MA/PA ratios (0/100, 25/75, 50/50, 75/25, and 100/0). The resilient modulus decreases as the number of loading cycles increases, indicating stiffness degradation due to repeated loading. Mixtures with higher MA content exhibit higher resilient modulus and slower stiffness reduction, demonstrating improved resistance to fatigue damage. This trend shows that incorporating modified asphalt (MA) enhances elasticity, durability, and long-term performance under cyclic loading.

Figure 6 and Table II present the MR values at the initial cycles, indicating that the MA addition enhances the stiffness of asphalt mixtures, with the highest value observed at 25% MA (15,437 MPa). However, at 50% MA, a significant reduction occurred, dropping below the 0% MA level, suggesting the presence of an optimum threshold. At 75% and 100% MA, the MR values increased again but did not reach the peak level observed at 25% MA, confirming a non-linear effect.

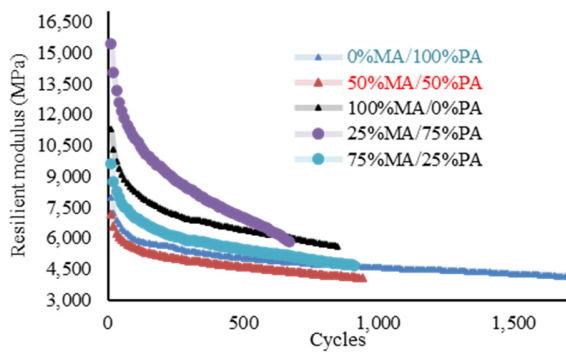


Fig. 5. MR with loading cycles for varying MA/PA ratios.

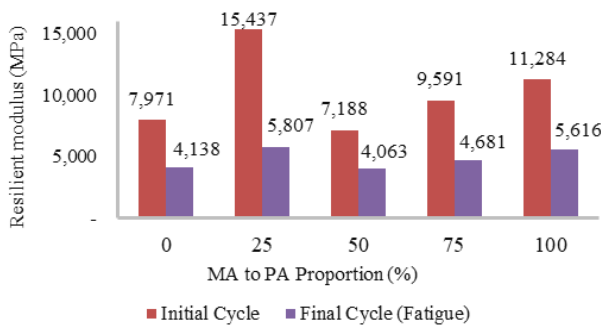


Fig. 6. MR at the initial and final of the cycle for different MA/PA ratios.

After fatigue loading, all mixtures showed a reduction in modulus due to cumulative damage. The 25% MA mixture retained the highest final MR (5,807 MPa), whereas the 50% MA mixture had the lowest (4,063 MPa), indicating its greater susceptibility to fatigue deterioration. In terms of modulus reduction, the 25% MA mixture experienced the largest decrease (62%), suggesting that mixtures with initially high stiffness may degrade more rapidly under cyclic loading. In contrast, the 50% MA mixture exhibited the smallest reduction

(43%) because its initial modulus was already low, resulting in a smaller relative decline despite its poor final performance. The mixtures containing 0%, 75%, and 100% MA showed moderate reductions ranging from 48% to 50%.

TABLE II. DECREASE IN INITIAL MR AND FATIGUE CYCLE MODULUS

MR	0% MA	25% MA	50% MA	75% MA	100% MA
Initial cycle (MPa)	7,971	15,437	7,188	9,591	11,284
Final cycle (fatigue) (MPa)	4,138	5,807	4,063	5,352	5,616
Percentage reduction (%)	48	62	43	44	50

This finding confirms that the selection of MA content should consider the balance between initial stiffness and fatigue resistance, with the optimum range depending on traffic conditions. This assertion aligns with the BMD framework [35], where polymer modification (SBR content) improves fatigue life only up to an optimum level [11]. The results further support rheology-based mix design principles, which emphasize optimizing modulus and phase angle to enhance long-term durability [36].

3) Accumulated Permanent Horizontal Strain

Figure 7 exhibits that the accumulated strain increases with the number of cycles, indicating progressive deformation under repeated loading. Mixtures with higher MA content exhibit lower strain accumulation, suggesting improved resistance to permanent deformation. This trend demonstrates that the addition of MA enhances the mixture's stability and reduces susceptibility to rutting under cyclic loading conditions.

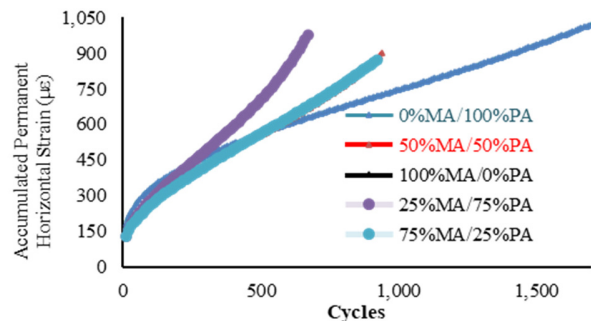


Fig. 7. Accumulated horizontal strain with loading cycles for varying MA/PA ratios.

At the initial cycle, the unmodified mixture (0% MA) exhibited the highest permanent horizontal strain (184 $\mu\epsilon$), whereas mixtures containing 25%–100% MA showed lower values of approximately 130 $\mu\epsilon$, indicating that MA effectively reduces early strain development. After fatigue loading, all mixtures displayed substantial increases in strain, ranging from 819 $\mu\epsilon$ to 1,028 $\mu\epsilon$. The 0% MA mixture continued demonstrating the highest final strain, while the 100% MA mixture had the lowest, suggesting that higher MA contents provide improved resistance to long-term strain accumulation. As shown in Table III, the percentage increase in strain ranged from 82% to 87%, with the 25% MA mixture showing the largest increase and the 100% MA mixture the smallest. These results reveal that although all mixtures experience strain

accumulation under repeated loading, the incorporation of MA slows fatigue-related damage and enhances durability.

The addition of MA reduces the initial accumulated permanent horizontal strain compared to the control mixture, indicating improved resistance to early strain development. After fatigue, all mixtures experience substantial increases; however, mixtures with higher MA content (75%–100%) recorded lower final strain values (862 $\mu\epsilon$ –819 $\mu\epsilon$) than the control (1,028 $\mu\epsilon$), reflecting better durability under repeated loading. The relatively high strain fluctuations with varying MA content are related to increased elasticity and structural stiffness, which help sustain performance under cyclic loading [30, 31]. This finding supports the theoretical concept that balancing stiffness and elasticity is crucial for extending fatigue life [37].

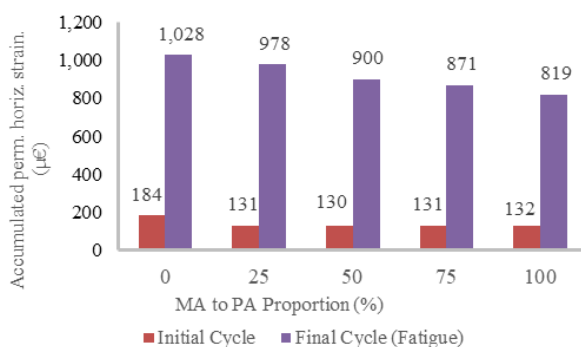


Fig. 8. Accumulated permanent strain at MA proportions.

TABLE III. ACCUMULATED PERMANENT HORIZONTAL STRAIN OF ASPHALT MIXTURES WITH DIFFERENT MA CONTENTS

Accumulated permanent horizontal strain	0% MA	25% MA	50% MA	75% MA	100% MA
Initial cycle	184	131	130	131	132
Final cycle (fatigue)	1,028	978	900	871	819
Percentage increase	82%	87%	86%	85%	84%

At 25% MA, the combined effect of PA flexibility and MA stiffness helps minimize strain accumulation. However, at 50% MA this balance is disrupted, leading to reduced performance. When the MA content reaches 75% or higher, the enhanced elasticity provided by MFO and SBR becomes dominant, resulting in lower lateral strain and improved fatigue endurance [38]. At 100% MA, however, the mixture becomes excessively stiff, limiting flexibility and increasing the likelihood of microcracking despite its higher modulus [39, 40]. Overall, mixtures containing 25%–75% MA achieve a more favorable stiffness–flexibility balance, making them suitable for high-stress pavement areas such as intersections, curves, and steep gradients [41, 42]. The unique rheological characteristics of BRA-based MA modified with MFO and SBR [43] further highlight the importance of rheology-focused mix design in optimizing modulus and phase angle to enhance fatigue resistance while supporting the sustainable utilization of locally available materials.

B. Fatigue and Durability Performance of Asphalt Mixtures with Modified Asphalt

Increasing MA content in BRA modified with MFO and SBR produced changes in fatigue life, resilient modulus, and permanent horizontal strain. The non-linear performance trend confirms that the fatigue behavior of the mixture is governed by the balance between stiffness and elasticity within the binder system. At low MA contents ($\leq 25\%$), MFO-induced softening reduces viscosity and weakens binder cohesion, accelerating fatigue cracking. At moderate MA levels (50%–75%), the added elasticity from SBR offsets this loss of cohesion, enhancing strain recovery and delaying crack propagation. In contrast, excessive modification (100% MA) results in an overly stiff binder, reducing flexibility and limiting the mixture's ability to dissipate repeated stresses, which leads to premature cracking. These observations align with previous findings, according to which polymer modification improves performance only up to an optimal threshold [44]. Additionally, the softening effect of oily additives assists the binder's natural self-healing capability at the microcrack level [45], and the resulting rheological behavior, particularly in stiffness, elasticity, and deformation resistance, corresponds well with earlier predictive models [46]. Emerging deep learning approaches also show potential for monitoring the crack evolution and self-healing processes in such materials [47]. Overall, MA contents in the range of 50%–75% provide the most advantageous combination of durability and rheological balance for the BRA–MFO–SBR system.

Overall, the observed trend confirms that the use of MA derived from Buton asphalt and enhanced with MFO and SBR does not consistently improve mixture durability. Instead, it requires careful optimization of the composition to achieve a proper balance between stiffness and flexibility. The intermediate proportion (50% MA) showed the worst fatigue performance, while the control mixture with 100% PA (0% MA) showed the highest fatigue life. However, when using MA, which has the potential to improve the initial stress distribution, careful attention must be paid to its proportion. Excessive proportions can reduce stress relaxation capacity, thus accelerating fatigue cracking. However, the current research acknowledges several limitations. It was conducted under laboratory conditions using specimens compacted at standard temperatures and loads. Hence, the results are not fully representative of field performance under variable traffic loads, temperature fluctuations, and humidity conditions. In addition, the limitations of the MA/PA ratio (0%, 25%, 50%, 75%, and 100%) and the enhancement of statistical analysis to determine the optimal mixture compositions are discussed. Furthermore, rheological characterization for MA is performed using a Dynamic Shear Rheometer (DSR). Further research is needed, involving field validation, optimization of MA proportions, and development of fatigue lifespan prediction models using a mechanistic-empirical approach that integrates binding rheology, fatigue-related parameters, and tropical climatic conditions.

IV. CONCLUSIONS

The fatigue performance and durability of asphalt mixtures incorporating Modified Asphalt (MA), which was derived from

Buton Rock Asphalt (BRA) and blended with Marine Fuel Oil (MFO) and Styrene-Butadiene Rubber (SBR), exhibited a non-linear response across different MA/PA ratios. The findings indicate that the balance between stiffness and elasticity strongly governs fatigue life, stiffness modulus, and permanent horizontal strain within the binder system. At low MA contents ($\leq 25\%$), excessive softening induced by MFO reduced cohesion and accelerated fatigue cracking. At intermediate MA levels (50%-75%), a synergistic interaction between MFO and SBR enhanced strain recovery, minimized permanent deformation, and improved fatigue resistance. However, at 100% MA, the mixture became overly stiff, resulting in decreased flexibility and increased susceptibility to early cracking. An increase in MA content positively affected the mixture performance up to an optimum level of approximately 75% MA, where the balance between MR and fatigue resistance was achieved. This proportion represents an optimal stiffness–flexibility ratio, consistent with the BMD framework. Although the laboratory findings are promising, this study acknowledges certain limitations, particularly the absence of field validation and complementary rheological testing, such as DSR analysis. Future research should incorporate field trials and develop mechanistic–empirical models to predict long-term fatigue and deformation behavior. Such efforts would strengthen the practical implementation of BRA–MFO–SBR MA for durable and sustainable pavement systems.

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