Exploring the Eco-Friendly Potential of Local Aggregates: A Study on the Use of Senoni Stone and Mahakam Sand in Asphalt Concrete Mixes

Didik S. Mabui
Department of Civil Engineering, Faculty of Engineering, Yapis University, Indonesia
mabuididik80@gmail.com

Miswar Tumpu
Disaster Management Study Program, Graduate School, Hasanuddin University, Indonesia
tumpumiswar@gmail.com (corresponding author)

Azlan Abas
Centre for Research in Development, Social and Environment (SEEDS), Faculty of Social Sciences and Humanities, Universiti Kebangsaan, Malaysia
azlanabas@ukm.edu.my

Irianto
Department of Civil Engineering, Faculty of Engineering, Yapis University, Indonesia
irian.anto@gmail.com

Eswan
Department of Civil Engineering, Faculty of Engineering, Universitas 17 Agustus, Samarinda, Indonesia
eswanstmt@gmail.com

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ABSTRACT

This study investigates the potential environmental benefits of employing locally produced materials, such as Senoni Stone (SS) and Mahakam Sand (MS), in asphalt concrete mixtures, aiming to achieve a balance between environmental sustainability and performance requirements. Since aggregateσ constitute 75%-85% of the total weight of asphalt mixtures, it serves as a primary component. The aggregates used in the specific mixtures are required to meet the Indonesian National Standard (SNI) specifications. In the current work, the Asphalt Concrete Wearing Course (AC-WC) combination was examined using SS as the coarse aggregate and MS as the fine aggregate, both of which originate from East Kalimantan. The volumetric metrics analyzed include Void in Mix (VIM), Void Mineral Aggregate (VMA), and Void Filled Bitumen (VFB). Asphalt concentration varied, with values of 4.5%, 5%, 5.5%, 6%, and 6.5% with increments of 0.5%. VIM values decreased as the asphalt quantity increased, with the corresponding VIM values being 9.26%, 4.51%, 4.33%, 4.17%, and 3.25%. The VMA values recorded for each asphalt content were 19.18%, 16.05%, 16.97%, 17.92%, and 18.56%, respectively, while the VFB values for the same contents were 51.7%, 71.87%, 74.49%, 76.68%, and 77.86%. It is therefore recommended that locally sourced materials, such as SS and MS, be prioritized in asphalt concrete mixtures to support sustainable construction practices. This approach not only reduces environmental impact, but also enhances resource efficiency and strengthens local economies.

Keywords-eco-friendly; AC-WC; Senoni stone, Mahakam sand

I. INTRODUCTION

The construction industry plays a significant role in environmental sustainability, as the sourcing and use of materials can heavily impact ecosystems. Asphalt concrete, a key material in infrastructure development, often relies on non-renewable and energy-intensive resources, raising concerns about its long-term environmental footprint [5]. Integrating local aggregates, such as SS and MS, is a key step toward reducing carbon emissions, conserving natural resources, and promoting sustainable construction practices. These locally sourced materials have the potential to minimize environmental impact while also supporting regional economic growth. Furthermore, incorporating eco-friendly aggregates into asphalt concrete mixes aligns with the global efforts to develop greener infrastructure solutions. Using materials that cause minimal environmental disruption helps reduce energy consumption during production and transportation, making them a more sustainable choice. The study of SS and MS as local aggregates provides valuable insights into their suitability for use in asphalt concrete, focusing on their performance, durability, and potential to meet environmental standards. This research aims to identify sustainable construction practices while addressing the urgent need for environmentally conscious development in East Kalimantan and beyond. In many regions, aggregate reserves are insufficient to meet the required quality standards [1-3]. As a result, East Kalimantan Province has relied on importing aggregates from other locations to meet the growing demand for road materials. Specifically, aggregates from Central Sulawesi Province have been brought in for use in road construction and other infrastructure projects. As one of Indonesia's emerging provinces, East Kalimantan requires a well-developed transportation network to support equitable development by facilitating the efficient movement of people and goods [4]. Importing aggregates from outside the region will increase the production costs of asphalt mixtures because of the distance between the material's quarry and the location of the asphalt mixture's manufacture, which is mostly reliant on the cost of transportation. Researchers need to investigate several options to address the problem of using aggregates from outside the area, such as improving the quality of local aggregates that do not match the requirements or using local aggregates as the most economical solution [5, 6]. Enhancing the quality of locally available aggregates is a more cost-effective solution than importing materials, especially in regions with abundant aggregate reserves. Aggregates that do not meet the required standards for road construction are considered substandard. Key properties, such as specific gravity, flexibility, absorption, and abrasion resistance, affect how well aggregates bond with asphalt in the mixture. Poor-quality aggregates can lead to asphalt peeling, which accelerates deterioration and reduces the road's overall durability and performance [7, 8]. East Kalimantan Province, one of Indonesia's largest provinces, boasts a land area of 127267.52 km^2 and a marine management area of 25656 km^2. The population of East Kalimantan Province is 3300517, distributed across 10 districts and cities [9].

The province of East Kalimantan had 1493.68 km of state roads in 2015, comprising 1357.25 km of paved roads, 63.27 km of rigid pavement roads, and 73.16 km of aggregated or land roads, according to data from the Central Statistics Agency. These data kept growing but did not include district and city-managed roadways [10]. Through laboratory studies, involved in the empirical test group, and Marshall test implementation, some literature on the volumetric properties of asphalt mixes, such as VIM, VMA, and VFB, can be produced. The use of sustainable aggregates and fillers in construction has become a key focus of research to reduce environmental impacts and improve material performance. According to [11], incorporating iron filler waste into warm mix asphalt can enhance performance without compromising quality. Other studies have investigated the use of recycled aggregates and waste materials as alternatives to conventional aggregates, helping reduce the demand for natural resources while also minimizing landfill waste. This approach supports sustainable development by prioritizing material efficiency and reducing environmental impact in the construction industry [1, 12]. Additionally, previous research has extensively analyzed conventional aggregates, such as granite, limestone, and basalt, in asphalt mixtures. Moreover, some other research has focused on incorporating recycled materials, polymers, or industrial by-products to improve the durability and sustainability of asphalt pavements. However, limited studies have specifically investigated the use of local aggregates from under-researched regions, such as SS and MS, in the production of eco-friendly asphalt mixes.

The current study adopts a new approach by evaluating the performance of locally sourced SS and MS in asphalt mixtures, emphasizing the benefits of using local aggregates. The research addresses both the sustainability concerns and economic advantages of reducing dependence on imported or transported materials. Although the interest in eco-friendly construction materials is growing, limited studies have examined the performance of asphalt concrete mixes that incorporate local aggregates, like SS and MS. Existing studies primarily focus on traditional aggregates with established engineering properties but overlook the environmental benefits and unique characteristics of regionally sourced materials. Additionally, the long-term durability, volumetric properties, and mechanical performance of asphalt concrete mixes using SS and MS remain underexplored. This research gap highlights the need to evaluate the viability of these local materials, particularly in terms of their ability to meet structural and environmental standards while contributing to the sustainability goals of the construction industry. This research aims to explore the values of VIM, VMA, and VFB in AC-WC mixtures using SS and MS as aggregates. The study seeks to evaluate how these volumetric properties influence the overall performance and sustainability of the mixture. By linking these parameters with the Life Cycle Assessment (LCA), the research identifies the environmental impact of the materials used. Furthermore, it explores the potential of local aggregates to promote eco-friendly construction practices, emphasizing resource efficiency and reduced carbon footprints.

II. RESEARCH SIGNIFICANCE

This research significance lies in its potential to enhance both environmental sustainability and efficiency in the construction industry. Using locally sourced aggregates, like

SS and MS, in AC-WC mixes provides an eco-friendly alternative to traditional materials while reducing the environmental impact of transporting and extracting non-local aggregates. This approach supports global sustainability goals by lowering the carbon emissions and promoting the use of renewable, locally abundant resources. Additionally, the study contributes to pavement engineering by offering insights into the mechanical and volumetric properties of asphalt mixes incorporating these local aggregates. The findings can help optimize mixed designs for improved strength, durability, and environmental compliance. Ultimately, this research has practical implications for construction practices, encouraging the adoption of sustainable materials in road infrastructure projects.

III. MATERIALS AND METHODS

A. Physical Properties of Aggregate

The characteristics of the fine aggregate, coarse aggregate, and SS ash filler examined in this study are presented in Tables I-III. Based on the test results for stone ash, filler, and coarse aggregate (crushed stone), the aggregates used meet the required standards outlined in [14].

TABLE I. FINE AGGREGATE PROPERTIES

No.	Inspection	Results of inspection
1	Water absorption (%)	2.87
2	Bulk specific gravity	2.48
	Saturated surface dry specific gravity	2.56
	Apparent specific gravity	2.66
3	Sand Equivalent (%)	90.63

TABLE II. FILLER PHYSICAL PROPERTIES

No.	Inspection	Results of inspection
1	Water absorption (%)	2.48
2	Bulk specific gravity	2.64
	Saturated surface dry specific gravity	2.7
	Apparent specific gravity	2.79
3	Sand Equivalent (%)	79.59

TABLE III. COARSE AGGREGATE PROPERTIES

No.	Inspection	Results of Inspection
1	Water absorption (%)	
	Crushed stone 0.5 cm – 1 cm	2.26
	Crushed stone 1 cm - 2 cm	2.28
2	Specific gravity	
	Crushed stone 0.5 cm - 1 cm	
	Bulk specific gravity	2.67
	Saturated surface dry specific gravity	2.69
	Apparent specific gravity	2.80
	Crushed stone 1 cm - 2 cm	
	Bulk specific gravity	2.67
	Saturated surface dry specific gravity	2.69
	Apparent specific gravity	2.8
3	Flatness Index (%)	
	Crushed stone 0.5 cm - 1 cm	22.1
	Crushed stone 1 cm - 2 cm	11.38
4	Abrasion (%)	
	Crushed stone 0.5 cm - 1 cm	20.92
	Crushed stone 1 cm - 2 cm	18.56

B. Physical Properties of Petroleum Bitumen

The findings derived from examining the characteristics of petroleum bitumen grade 60/70 are displayed in Table IV. This bitumen complies with [14].

TABLE IV. PROPERTIES OF PETROLEUM BITUMEN

No.	Inspection	Results of inspection
1	Penetration before weight loss (mm)	77.3
2	Softening point (°C)	56
3	Ductility at 25°C, 5 cm/min (cm)	119
4	Flashpoint (°C)	310
5	Specific gravity	1.14
6	Weight loss (%)	0.2
7	Penetration after weight loss (mm)	89

C. Volumetric of Asphalt Mixture

The volumetric asphalt mixture comprises VIM, VMA, and VFB, according to [14].

1) Void in Mix

Higher VIM values indicate greater porosity in the asphalt mixture, leading to reduced stability and durability [3]. Several factors influence the VIM value, including the percentage of filler, coarse aggregate, and petroleum bitumen in the mixture [14]. Additionally, the physical shape of the material, whether flat or cubic, significantly impacts the results. According to [1], an asphalt mixture containing Ashburton grain type 20/25 recorded a VIM value of 4.5%. The VIM formula investigation [14] demonstrates the following findings:

$$\mathrm{VIM}(\%) = \mathrm{V} - \{\left(\frac{\mathrm{KA}\times 100}{\mathrm{L}}\right) + (\frac{100+\mathrm{AR}+\mathrm{KA}}{\mathrm{G}})\} \quad (1)$$

where AR is the residual content in the mixture (%), G is the bulk specific gravity - the weight of the test object (gr), L is the weight of the test object after having been placed in the oven (gr), and KA is the water content (%).

2) Void Mineral Aggregate

The VMA of the asphalt mixture controls its stiffness; the lower the VIM value is, the stiffer is the asphalt mixture, according to [1]. In the AC asphalt mixture with Ashburton type 5/20, the VMA value was 20.29%, while the VMA value of the AC-WC asphalt mixture containing Lawele Ashburton was 19.2% [13]:

$$\mathrm{VMA} = \left(100 - \frac{\mathrm{Gmb.Ps}}{\mathrm{Gsb}}\right)\cdot \% \quad (2)$$

where VMA is the pore volume between aggregates in solid asphalt, % of the bulk volume of solid asphalt concrete, Gmb is the bulk density of the solid asphalt concrete, Ps is the aggregate content, % by weight with solid asphalt concrete and Gsb is the bulk specific gravity of the aggregate forming solid asphalt concrete.

3) Void Filled Bitumen

In terms of the volume of asphalt in the mixture (VFB), the asphalt content and asphalt film thickness can be represented volumetrically. High durability is also a feature of mixtures including considerable amounts of asphalt. Therefore, a minimum VFB requirement needs to be met to achieve a durable mixture. Except for the asphalt absorbed by the aggregate, VFB is the percentage of voids between the aggregate particles (VMA) filled with asphalt. The VFB equation is:

$$\text{VFB} = 100\ \frac{\text{VMA}-\text{VIM}}{\text{VMA}} \qquad (3)$$

where VFB is the void filled with asphalt, the percent of VMA is the void between mineral aggregates, percent bulk volume, and VIM is voided in the mixture, percentage of the total mixture.

The main purpose of VFB is to set a maximum for both the VMA and asphalt content. The VFB criteria offer a valid VMA, which facilitates mixed planning. The mixture that meets the minimum VMA requirements may also have its allowable void content limited by the VFB. Even if the void content range is reached, the design mix for low traffic will not satisfy the VFB requirements if the void content is relatively large. This change is what the current study plans to do to keep the mixture from deteriorating in light traffic.

IV. RESULTS AND DISCUSSION

A. *Asphalt Concrete Wearing Course Mixed Aggregate Gradation*

Figure 2 shows that the combined aggregate gradation is within the standard specification interval, satisfying the requirements for the surface layer [14] of highways regarding the necessary road materials in Indonesia. This permits the creation of an ideal mix design.

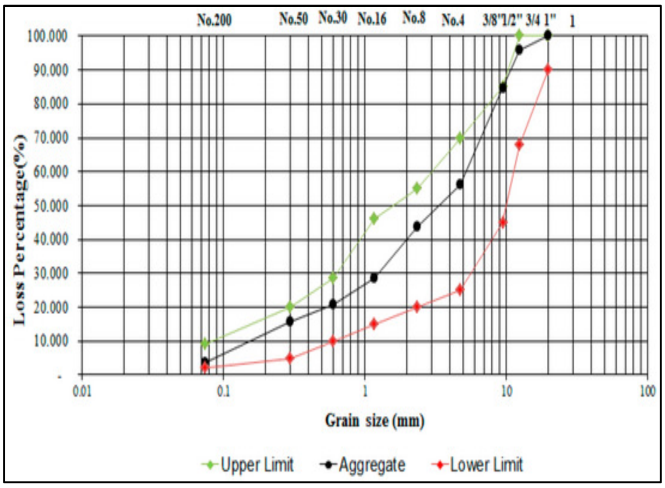

Fig. 1. Combined aggregate gradation.

B. *Mixtures Design of Asphalt Concrete Wearing Course Mixture*

The necessary road materials in Indonesia are included, according to [14], and serve as the basis for the analysis of the AC-WC composition. The mix design was constructed to create specimens with various petroleum bitumen levels of 4.5%, 5%, 5.5%, 6%, and 6.5%, by weight of the mixture, based on earlier analysis results revealing an ideal asphalt percentage of 5.1%. Marshall pounders were used to create the specimens, with 75 collisions on each side. Table V depicts the weight composition of the material based on the percentage of aggregates [14]. There are 1200 g in the specimen

TABLE V. MATERIAL COMPOSITION IN WEIGHT FOR 1200 g OF TEST OBJECT (D MOLD = 10 cm)

Asphalt content (%)	Aggregate (g)				Asphalt (g)	Total (g)
	SS (1 cm^{-2})	SS (0.5 cm^{-1})	MS	Stone ash		
4.5	343.8	458.4	229.2	114.6	54.0	1200
5.0	342.0	456.0	228.0	114.0	60.0	1200
5.5	340.2	453.6	226.8	113.4	66.0	1200
6.0	338.4	451.2	225.6	112.8	72.0	1200
6.5	336.6	448.8	224.4	112.2	78.0	1200

C. *Volumetric Properties of Asphalt Concrete Wearing Course Mixture*

1) *Voids in the Mix*

Based on the volumetric test findings, Figure 3 illustrates the link between the petroleum bitumen content and the VIM value. According to [14], it needs to have a VIM value of 3%–5%. For the petroleum bitumen contents of 4.5%, 5%, 5.5%, 6%, and 6.5%, the corresponding VIM values were 9.26%, 4.51%, 4.33%, 4.17%, and 3.25%. Based on the obtained VIM value, it is evident that the petroleum bitumen content of 5%, 5.5%, 6%, and 6.5% satisfied the condition whereas the petroleum bitumen content of 4.5% did not [14].

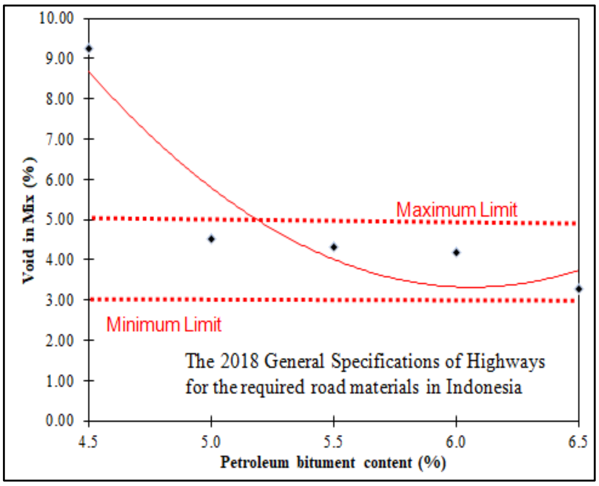

Fig. 2. Petroleum bitumen content with VIM relationship.

VIM is a key parameter in assessing the performance and durability of AC-WC mixtures. It represents the percentage of air voids within the asphalt mix, directly impacting the mechanical properties, moisture resistance, and overall pavement integrity. Optimizing VIM ensures a balance between durability and flexibility, helping to prevent premature issues, such as cracking and rutting. When using local aggregates, like SS and MS, it is crucial to maintain an appropriate VIM to adapt the mixture design to the specific physical and chemical properties of these materials, ensuring compatibility and optimal performance. Integrating LCA into the AC-WC mixture evaluations provides a comprehensive analysis of their environmental impact throughout their lifespan. VIM influences long-term sustainability by affecting material consumption, emissions during production, and maintenance requirements. Local aggregates, such as SS and MS, contribute to environmental benefits by reducing transportation-related emissions and promoting the use of renewable resources. The LCA framework highlights the environmental benefits and trade-offs of these materials, emphasizing the connection between VIM and sustainability metrics. The adoption of eco-friendly materials, like SS and MS, in AC-WC mixtures presents a sustainable solution for pavement construction. These locally sourced aggregates reduce environmental degradation and enhance economic efficiency by decreasing reliance on imported materials. Understanding the influence of VIM on asphalt mix performance is essential for achieving durability and minimizing environmental impact. This study aims to demonstrate how the use of local aggregates can improve the lifecycle performance and sustainability of road infrastructure, aligning with global efforts to lower the carbon footprint of construction activities.

2) Void in Mineral Aggregate

The VMA value in the asphalt mix was at least 15%, which according to [13], is the one needed for road materials. The VMA revealed the existence of voids in between the binding of aggregates. The relationship between the VMA value and the petroleum bitumen concentration is portrayed in Figure 4.

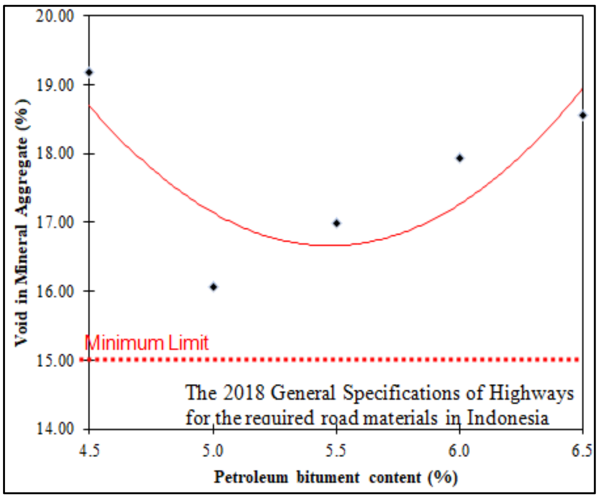

Fig. 3. Petroleum bitumen content with VMA relationship.

The VMA value was 19.18% at a 4.5% petroleum bitumen percentage, a considerable increase from the 16.05% VMA value at a 5% petroleum bitumen level. The VMA values were 18.56%, 17.92%, and 5.5%, respectively, while the petroleum bitumen content was 5.5%, 6%, and 6.5%. All the petroleum bitumen levels utilized in this study satisfied Indonesia's requirements. VMA is a key volumetric property that determines the void space between the aggregates in an asphalt mix, which is subsequently filled with asphalt binder. It is essential for AC-WC mixtures to achieve an optimal VMA to ensure sufficient binder content, and thus provide durability, flexibility, and resistance to moisture-induced damage. Incorporating SS and MS as local aggregates can significantly affect the VMA values due to their unique gradation and shape. Proper optimization of VMA ensures that the asphalt mixture resists deformation and cracking, supporting long-term structural and functional performance. VMA also directly impacts the environmental footprint of asphalt pavements. A well-balanced VMA enhances the mix's performance and reduces the need for frequent repairs and maintenance, leading to lower energy consumption and reduced material usage throughout the pavement's lifecycle. Using eco-friendly materials, like SS and MS, helps reduce environmental impacts, such as transportation emissions and the effects of resource extraction. By exploring the relationship between VMA and LCA metrics, this research highlights the environmental benefits of using local materials for sustainable infrastructure development. However, integrating eco-friendly materials into the AC-WC mixtures requires a thorough understanding of how VMA affects the mix performance and sustainability. SS and MS, as locally sourced aggregates, offer an opportunity to reduce the reliance on non-renewable resources and decrease the carbon footprint associated with asphalt production. By optimizing VMA, these materials can ensure sufficient binder film thickness for enhanced durability while aligning with sustainable construction practices. This research underscores the role of VMA in balancing technical performance and environmental impact, demonstrating the feasibility of adopting local aggregates for greener, more efficient asphalt pavement solutions.

3) Void Filled Bitumen

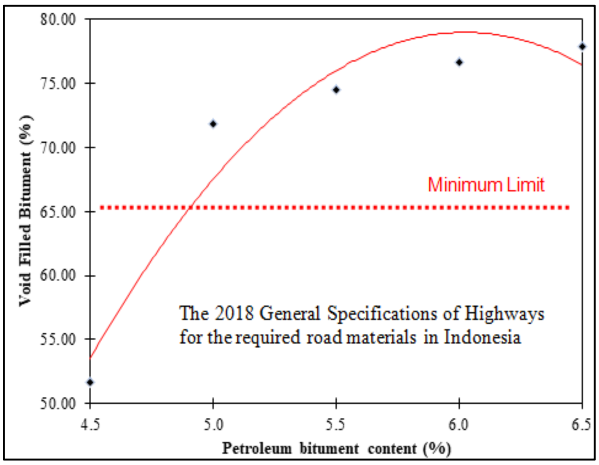

Fig. 4. Petroleum bitumen content with VFB relationship.

Optimizing VFB in AC-WC mixtures using eco-friendly aggregates, such as SS and MS, can align technical performance with sustainability goals. An appropriate VFB ensures that the mix achieves sufficient binder film thickness to protect against environmental degradation while avoiding over-saturation that could compromise structural integrity. By leveraging the unique properties of these local aggregates, the study supports the development of asphalt mixtures that balance performance with environmental considerations. This approach demonstrates the potential to reduce resource dependency and carbon emissions, showcasing the role of VFB as a critical parameter in sustainable pavement engineering.

V. CONCLUSIONS

The asphalt mixture, created using the Asphalt Concrete Wearing Course (AC-WC) gradation, was considered suitable as a hot mix due to the use of local materials from East Kalimantan, including Senoni Stone (SS) and Mahakam Sand (MS) as coarse and fine aggregates. The optimal asphalt content is determined by the volumetric values of Void in Mix (VIM), Void Mineral Aggregate (VMA), and Void Filled Bitumen (VFB) in the mixture. Among these, the VIM value, which represents the air voids in the mixture, had the greatest effect on the asphalt mixture performance. The ideal asphalt content can be determined using both volumetric and stability factors. The interaction between VIM, VMA, and VFB plays a significant role in the Life Cycle Assessment (LCA) and the environmental friendliness of asphalt mixtures using SS and MS. VIM, which determines the air void content, directly affects the mixture's durability and sustainability by influencing water permeability and resistance to aging. Maintaining a balanced VIM ensures the mixture is durable, reduces maintenance needs, and lowers environmental impact over its lifecycle. VMA, which measures the space available within the aggregate structure, influences how much bitumen the mixture can hold, optimizing material usage and minimizing waste. A higher VMA improves the bond between the aggregates and bitumen, strengthening the mixture and extending the pavement's lifespan. VFB, representing the proportion of voids filled with bitumen, is crucial for assessing the mixture's resistance to deformation and cracking. Optimizing VFB reduces the need for frequent repairs, thus decreasing emissions and energy consumption from maintenance activities. By using eco-friendly local materials, like SS and MS, the environmental footprint of these asphalt mixtures is further reduced, lowering transportation emissions and supporting the use of sustainable resources. By combining these volumetric parameters with local aggregates, a sustainable approach to asphalt mixture design is achieved, in line with the LCA principles, fostering the promotion of eco-friendly construction practices.

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