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Utilization of Oil Palm Fiber Agricultural Waste on the Mechanical Characteristics of AC-WC Asphalt Mixtures Using the Dry-Mix Method

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Abstract: Early pavement distress due to permanent deformation and fatigue cracking remains a major challenge for flexible pavement infrastructure in Indonesia, particularly under high traffic loading and tropical climatic conditions. Meanwhile, the Indonesian palm oil industry generates more than 23 million tons annually of Empty Fruit Bunch (EFB), which has not yet been optimally utilized as agro-industrial waste. This study investigates the utilization of EFB fibers treated with NaOH alkali and coated with asphalt emulsion as an additive in Asphalt Concrete Wearing Course (AC-WC) mixtures using the dry-mix method. The experimental variables include two fiber lengths (0.5 cm and 1 cm) and three fiber contents (0.2%, 0.4%, and 0.6%), while maintaining a constant Optimum Asphalt Content (OAC) of 6%. Marshall testing was conducted in accordance with SNI 2489:2018, referring to the Bina Marga General Specifications 2025. The results indicate that fiber incorporation enhances stability up to 1,748.80 kg and increases the Marshall Quotient (MQ) to 530.24 kg/mm, compared to the control mixture with stability of 1,666.16 kg and MQ of 512.33 kg/mm. Volumetric analysis shows a reduction in VIM (4.14-4.32%) and VMA (18.76-18.86%), along with an increase in VFA (77.08-77.92%). The Optimum Fiber Content (OFC) is identified at 0.5 cm fiber length with 0.4% fiber content, yielding stability of 1,748.80 kg, MQ of 530.24 kg/mm, VFA of 77.66%, and an Immersion Residual Strength (IRS) of 90.79%.

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1. Introduction

Indonesia has a national road network exceeding 47,000 km, the majority of which consists of flexible pavements based on asphalt mixtures [1]. Premature distress in the form of permanent deformation (rutting) and fatigue cracking remains a persistent structural issue, primarily triggered by the combined effects of excessive traffic loading and tropical surface temperatures that can reach 60-70°C [2,3]. This condition underscores the urgent need for innovative pavement materials capable of enhancing mechanical performance while maintaining environmental sustainability.

Agricultural waste have been extensively studied as reinforcing additives in asphalt mixtures [4], including those of natural fibers that have advantages over synthetic fibers, including biodegradability, low cost, wide availability and significantly lower environmental impact [5]. As the world’s largest producer of palm oil, Indonesia generates more than 45 million tons of crude palm oil (CPO) annually, which consequently produces a substantial amount of Empty Fruit Bunch (EFB) waste. According to data from Badan Pusat Statistik [6], in 2023 the production of fresh fruit bunches (FFB) reached 134.38 million tons, with EFB estimated at approximately 23% of total FFB, or around 23 million tons per year. To date, most EFB has not been optimally utilized and instead contributes to environmental issues such as soil contamination and methane emissions from decomposition [5,6]. The use of EFB as an asphalt mixture additive therefore offers dual strategic benefits: improving pavement performance while reducing agro-industrial waste burdens.

EFB fibers contain lignocellulosic components consisting of 37.26-63% cellulose, 14.6-37% hemicellulose, and 17-31.7% lignin [5]. The high cellulose content provides potential tensile strength suitable for reinforcement applications. However, the inherently hydrophilic nature of natural fibers such as kenaf, jute, and hamp, due to hydroxyl (-OH) groups poses a major challenge in hydrophobic asphalt systems, resulting in weak interfacial bonding and susceptibility to moisture damage [7]. Previous studies indicate that NaOH alkali treatment effectively removes lignin, hemicellulose, pectin, and surface wax, thereby increasing surface roughness and reactivity, as well as improving cellulose crystallinity from 53% to 62% [8]. Alkali treatment of oil palm EFB fibers has been shown to significantly transform the fiber surface morphology from smooth, wax-coated structures to rough and porous textures, as evidenced by SEM and FTIR analyses, thereby enhancing the effective contact area between fibers and asphalt mixtures [9].

In general, two primary methods are used to incorporate fibers into asphalt mixtures: the wet method and the dry method. In the wet method, fibers are first blended into hot asphalt using a high-speed mixer before being combined with aggregates. In contrast, the dry method involves directly mixing fibers with heated aggregates prior to asphalt addition. Hui et al. [10] reported that basalt fibers incorporated using the dry and combined methods resulted in better fiber dispersion, reduced agglomeration, and did not require specialized mixing equipment. Similarly, Liu et al. [11] highlighted several limitations of the wet method, including the need for high-speed mixers, insignificant improvement in mixture homogeneity, and asphalt absorption by fibers leading to inaccuracies in asphalt content determination. Consequently, the dry method is considered more efficient and practical for field implementation.

Alifuddin et al. [12] investigated untreated oil palm fibers in AC-WC mixtures with an Optimum Asphalt Content (OAC) of 6% and reported a 6% increase in stability and a 14% reduction in VIM at an optimal fiber content of 0.6% with a fiber length of 0.8 cm, achieving a stability value of 1,210.45 kg. However, the VFA values of fiber-reinforced mixtures ranged from 78.26% to 79.31% at optimum conditions, exceeding the 78% limit specified in the Bina Marga General Specifications 2025. Furthermore, Scanning Electron Microscopy (SEM) analysis revealed fiber degradation and breakage due to high mixing temperatures (150°C) and compaction processes, attributed to the absence of surface treatment for fiber protection. These findings highlight the necessity for appropriate treatment of oil palm fibers to control asphalt absorption, enhance fiber-asphalt compatibility, and ensure that volumetric properties, particularly VFA, comply with the Bina Marga specifications.

2. Method

2.1. Material

The Asphalt Concrete Wearing Course (AC-WC) mixture was designed using Type I asphalt with penetration grade 60/70 in accordance with the Bina Marga General Specifications 2025 [13]. The asphalt binder exhibits a penetration value of 66.67 dmm, a softening point of 50°C, and a specific gravity of 1.04 g/cc. The investigated asphalt mixture consists of a coarse-to-fine aggregate proportion of 56%:44% by total aggregate weight, without the addition of filler. The total weight per Marshall specimen was set at 1,200 g. The combined aggregate gradation satisfies the AC-WC gradation requirements specified in the Bina Marga General Specifications 2025.

The oil palm fibers used in this study were derived from Empty Fruit Bunch (EFB) obtained from a palm oil processing plant in East Kalimantan. The fibers incorporated into the Marshall specimens were subjected to alkali treatment, as illustrated in Figure 1(b), aimed at removing lignin, hemicellulose, pectin, and surface wax through immersion in 0.5 N NaOH solution [8]. To modify the fiber surface from hydrophilic to hydrophobic, an asphalt emulsion was applied as a coating, thereby enhancing compatibility with the hot asphalt matrix [14].The treated fibers were subsequently dried and cut into two length variations of 0.5 cm and 1 cm.

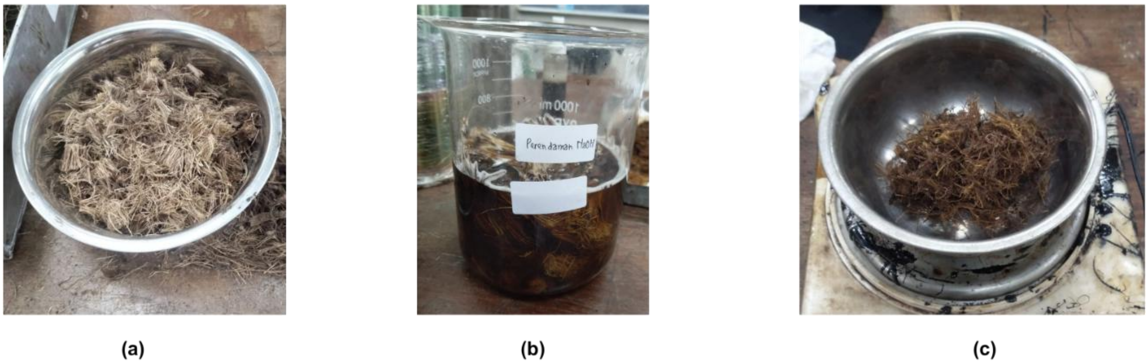


Figure 1 Fibre treatments: (a) EFB fiber cleaned (b) NaOH treatments
(c) asphalt emulsion-coated fibers

2.2. Mixture Design

The preparation of Marshall briquettes as test specimens was conducted through two stages of mix design. The first stage involved determining the Optimum Asphalt Content (OAC) to establish the asphalt content used in fiber-reinforced Marshall specimens. The OAC was determined by varying asphalt content from 4.5% to 6.5% by aggregate weight and selecting the optimum value graphically based on compliance with all Marshall parameters specified in the Bina Marga General Specifications 2025. The second stage involved mixture preparation with variations in fiber content (0%, 0.2%, 0.4%, and 0.6%) and fiber length (0.5 cm and 1 cm) at a fixed OAC of 6%. Fiber weight was calculated as a percentage of total aggregate weight (1,200 g), resulting in fiber quantities per specimen of 2.4 g (0.2%), 4.8 g (0.4%), and 7.2 g (0.6%).

Mixing of aggregates, fibers, and asphalt was carried out using the dry-mix method. The process began with heating the aggregates to 165 °C, followed by uniform incorporation of fibers into the heated aggregates. Hot asphalt (72 g) was then added and thoroughly mixed until a homogeneous blend was achieved. The mixture was compacted using 75 blows per face, as required for AC-WC mixtures [13]. Each variation was represented by two specimens, and the average values were used for analysis.

2.3. Marshall tests

Marshall testing was conducted to obtain key parameters, including Stability, Flow, Marshall Quotient (MQ), Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and density. The theoretical maximum specific gravity (Gmm) was calculated in accordance with SNI 03-6893-2002. Stability values were corrected using specimen volume correlation factors based on SNI 06-2489-1991.

The Index of Retained Strength (IRS) test was conducted through immersion at 60°C for 24 hours, also in accordance with SNI 06-2489-1991. Evaluation criteria referred to the Bina Marga General Specifications 2025 for AC-WC with Type I Pen 60/70 asphalt, which require VIM of 3-5%, VMA ≥ 15%, VFA of 65-78%, Stability ≥ 550 kg, Flow of 2-4 mm, and IRS ≥ 90%. The Marshall Quotient (MQ) is defined as the ratio of stability to flow:

$$MQ = \frac{S}{F} \tag{1}$$

where,
MQ : Marshall Quotient (kg/mm)
S : Stability (kg)
F : Flow (mm)

$$IRS = \frac{S_{24}}{S_{30}} \times 100\% \tag{2}$$

where,
IRS: Index of Retained Stability (%)
S_{24}: Marshall stability after 24-hour immersion at 60°C (kg)
S_{30}: Marshall stability after 30-minute immersion at 60°C (kg)

Figure 2 shows the research procedure flowchart of the EFB fiber modified mixture.

3. Results and discussion

3.1. Material Characteristics

Table 1 Aggregate properties test results

Tests	Results		Specification	
	Coarse aggregate	Fine aggregate	Coarse aggregate	Fine aggregate
Abrasion	34.65%	-	<40%	-
Bulk dry specific gravity	2.72	2.72	<3	<3
SSD specific gravity	2.76	2.74		
Apparent specific gravity	2.82	2.77		

Aggregate characterization tests were conducted to ensure compliance with the requirements specified in the Bina Marga General Specifications 2025. The results in Table 1 indicate that all tested properties satisfy the specified criteria. The abrasion value of 34.65% is below the maximum allowable limit of 40%, indicating good resistance to wear and suitability for asphalt mixtures [13]. The specific gravity values of coarse aggregates are 2.72 (bulk dry), 2.76 (SSD), and 2.82 (apparent), while fine aggregates exhibit values of 2.72, 2.74, and 2.77, respectively. All values are below the maximum limit of 3 and show minimal variation between fractions (<0.2), indicating good aggregate compatibility. Uniformity in specific gravity across aggregate fractions is a critical factor in maintaining consistent volumetric properties in asphalt mixtures [14]. Overall, aggregates meeting specification requirements are expected to yield good mixture performance under various gradation and additive conditions.

Table 2 Standard bitumen tests results

Tests	Results	Specification
Penetration at 25°C	66.67	60/70
Softening point	50	≥48
Specific gravity	1.04	≥1

The standard bitumen test results presented in Table 2 conform to the Bina Marga General Specifications 2025 and classify the binder as Type I Pen. 60/70 asphalt. The penetration value of 66.67 dmm indicates appropriate binder consistency for pavement applications. The softening point of 50°C exceeds the minimum requirement (≥48°C), demonstrating adequate resistance to deformation at elevated temperatures. The specific gravity of 1.04 is used for mixture proportioning and volumetric calculations.

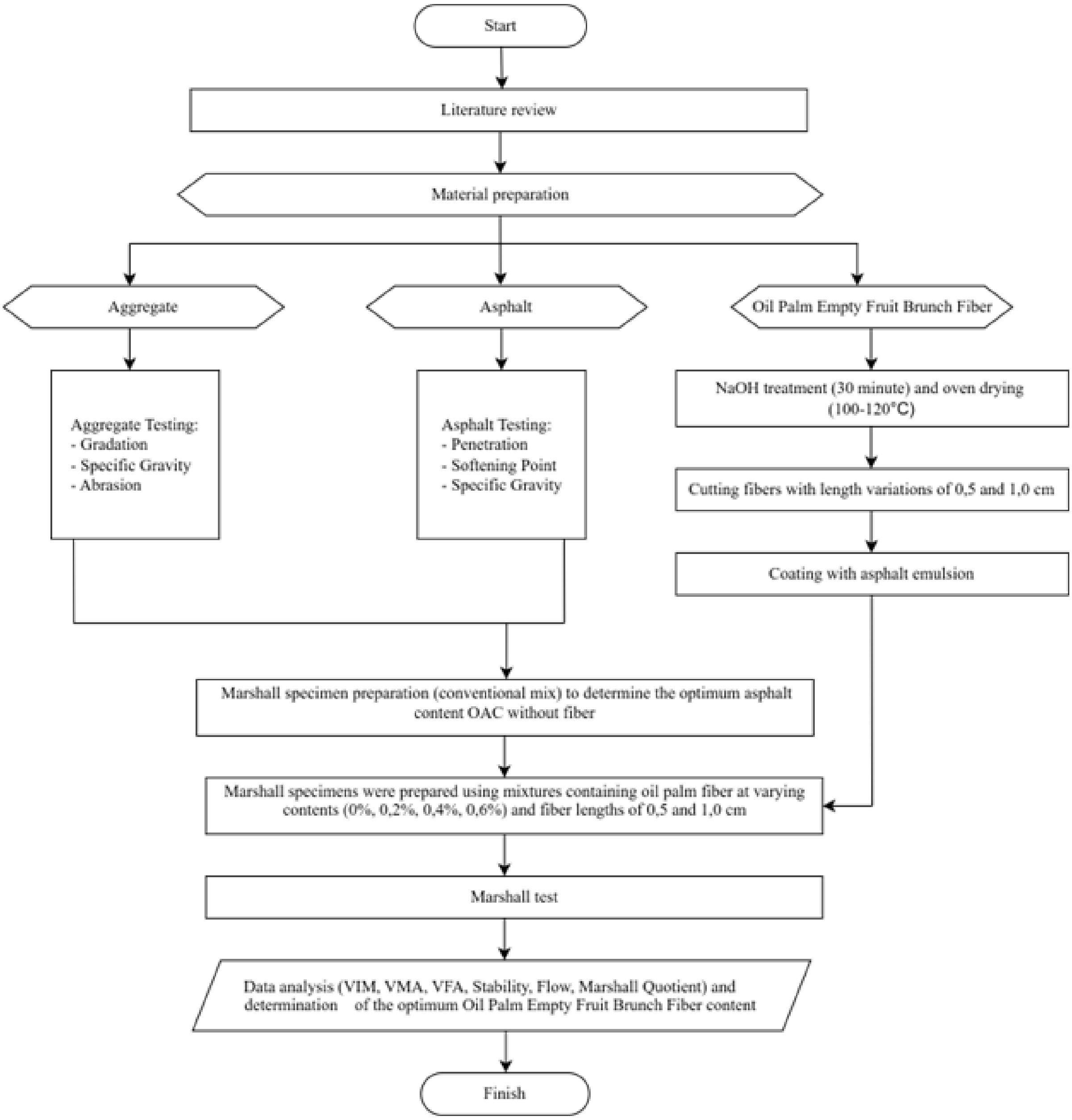


Figure 2 Research procedure of EFB fiber modified mixture

3.2. Optimum Asphalt Content (OAC)

The Optimum Asphalt Content (OAC) was determined through Marshall testing with asphalt content variations ranging from 4.5% to 6.5% by aggregate weight. Graphical evaluation was conducted based on compliance with the requirements of the Bina Marga General Specifications 2025, and the selected OAC satisfies all specified parameters.

Table 3 OAC test result

Bitumen content (%)	Parameter						
	Density (≥2.2 gr/cm3)	VIM (3≥5%)	VMA (≥15%)	VFA (≥65-78%)	Stability (≥1000 kg)	Flow (2≥4 mm)	MQ (≥250 kg/mm)
4.5	2.38	5.91	16.71	64.67	1314.90	2.75	478.54
5	2.41	3.72	15.96	76.69	1262.67	2.84	444.59
5.5	2.38	4.18	17.54	76.18	1314.90	3.05	431.42
6	2.35	4.68	19.13	75.57	1512.67	3.23	469.12
6.5	2.31	5.48	20.85	73.85	1350.19	3.28	406.94

Based on Table 3, an asphalt content of 6% was selected as the OAC, as it meets all specification requirements. The 4.5% asphalt content was rejected due to VFA (64.67%) being below the minimum requirement (65%), while 6.5% was excluded due to excessive VIM (5.48% > 5%). The selected OAC of 6% provides the highest stability (1,512.67 kg) and a flow value of 3.23 mm, resulting in an MQ of 469.12 kg/mm, with all volumetric parameters (VIM, VMA, VFA, density) within acceptable limits.

This OAC value is consistent with previous studies on AC-WC mixtures using Pen. 60/70 asphalt in Indonesia. For example, Idarto et al. reported an MQ of 465.7 kg/mm at an OAC of 6% for heavy traffic conditions [15]. The OAC determined for the control mixture was maintained constant across all fiber-modified mixtures to isolate the effect of fiber addition. Although fiber incorporation may theoretically increase asphalt demand due to absorption [16], maintaining a constant asphalt content enables a clearer evaluation of fiber effects on volumetric and Marshall characteristics.

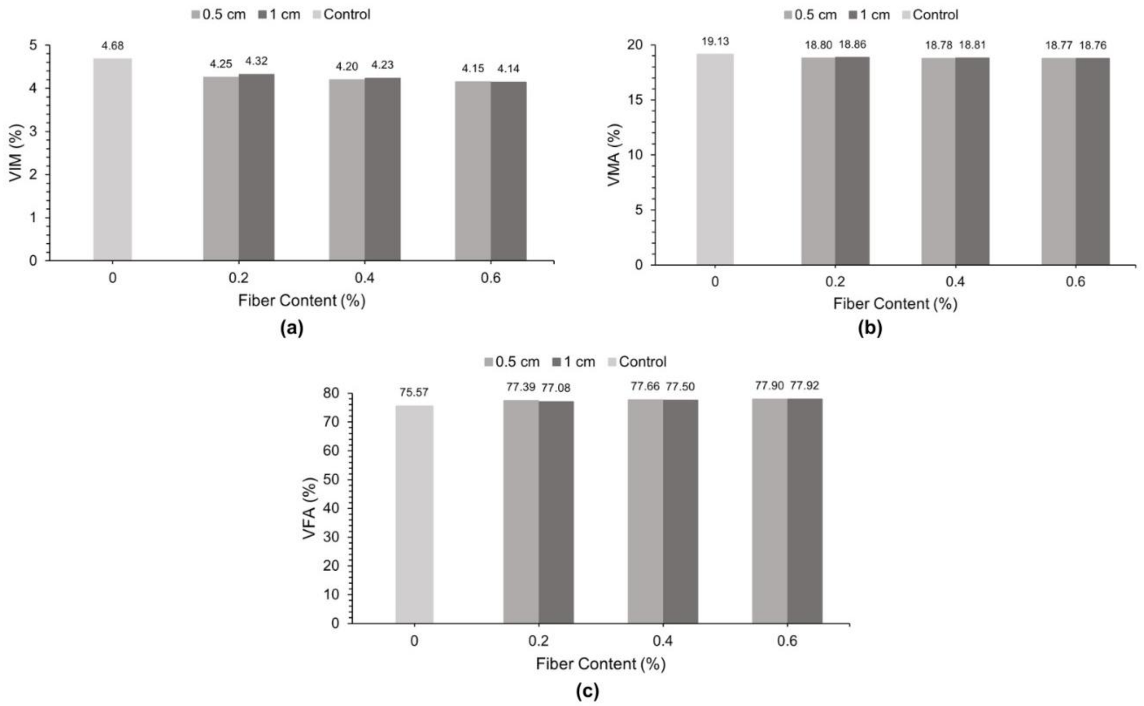
3.3. Effect of Fiber Addition on Volumetric Properties

The volumetric characteristics of asphalt mixtures, particularly density, are influenced by fiber addition. As shown in Table 4, the density of fiber-reinforced mixtures increases slightly compared to the control mixture. This indicates that Empty Fruit Bunch (EFB) fibers act as fillers that reduce void spaces between aggregate particles, resulting in a more compact structure. Fiber treatment through alkali processing and asphalt emulsion coating enhances interaction between fibers, aggregates, and asphalt, leading to more efficient compaction.

Table 4 Volumetric parameter test of the fiber modified asphalt mixture

Parameter	Fiber content (%)	Fiber length (cm)		Specification
		0-5	1	
Density	0	2.35		≥ 2.2 gr/cm3
	0.2	2.36	2.36	
	0.4	2.36	2.36	
	0.6	2.36	2.36	
VIM	0	4.68		3 ≥ 5%
	0.2	4.25	4.32	
	0.4	4.20	4.23	
	0.6	4.15	4.14	
VMA	0	19.13		≥ 15%
	0.2	18.80	18.86	
	0.4	18.78	18.81	
	0.6	18.77	18.76	
VFA	0	75.57		65 ≥ 78 %

Parameter	Fiber content (%)	Fiber length (cm)		Specification
		0-5	1	
	0.2	77.39	77.08	
	0.4	77.66	77.50	
	0.6	77.90	77.92	

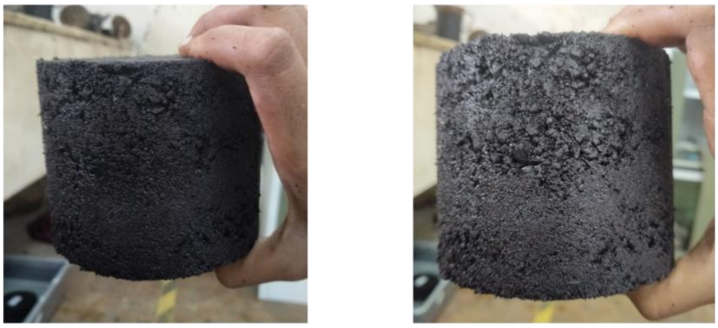


(a) (b) (c)

Figure 3 Volumetric parameters of EFB fiber modified asphalt mixtures: (a) VIM (b) VMA (c) VFA

The reduction in VIM across all fiber variations as shown in **Figure 3a** is attributed to the void-filling effect of EFB fibers. This reduction remains controlled and does not fall below the minimum requirement of 3%. Similar trends were reported by Alifuddin et al. [12], where untreated fibers reduced VIM by 14%. Alkali treatment reduces fiber hydrophilicity, cleans the surface, and decreases moisture absorption [7], while asphalt emulsion coating improves hydrophobicity and limits asphalt absorption during mixing [17]. Shorter fibers (0.5 cm) were more effective in reducing VIM and increasing VFA compared to longer fibers (1 cm), due to better dispersion and more uniform distribution. Longer fibers tend to distribute unevenly, reducing their effectiveness in void filling and potentially increasing the risk of bleeding [12]. Untreated natural fibers with high hydrophilicity can absorb excessive bitumen, reducing binder film thickness and increasing air voids [18]. The combined treatment approach in this study effectively regulates fiber-bitumen interaction, resulting in controlled VIM, VMA, and VFA values.

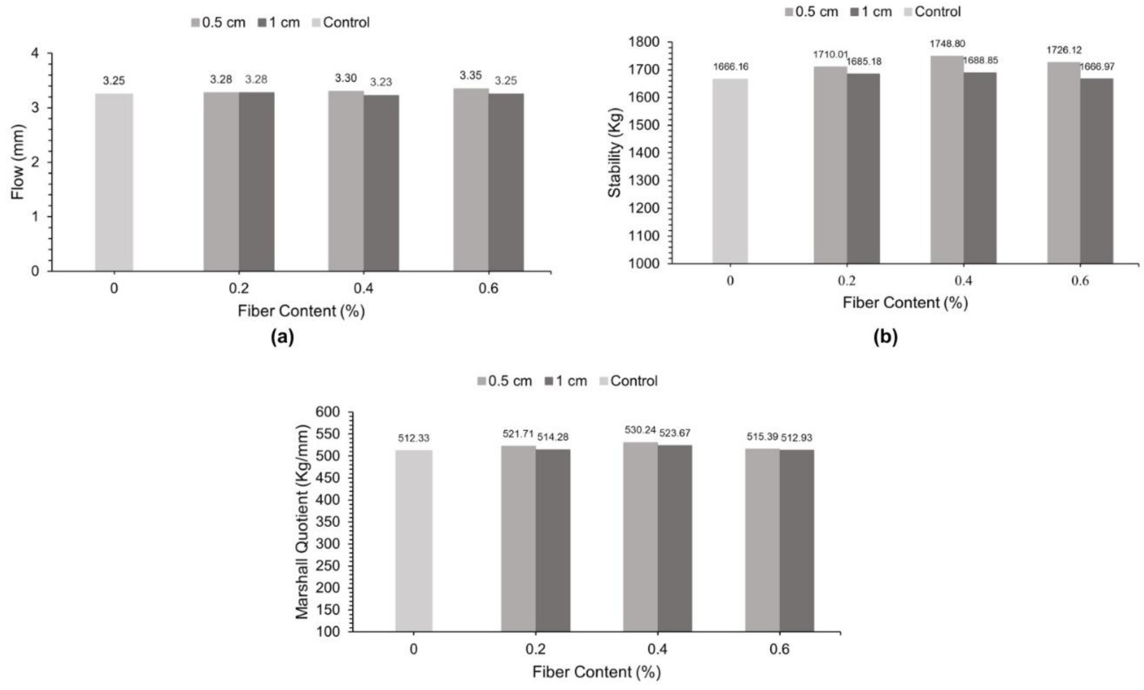
The decrease in VMA (**Figure 3b**) further confirms that EFB fibers fill voids between aggregates, improving adhesion through asphalt emulsion coating. Despite the reduction, VMA values remain within the range of 18.76-18.86%, indicating that sufficient space is still available for asphalt to ensure durability and stability [19]. Visual observations of Marshall specimens (**Figure 4**) reveal that mixtures with 0.5 cm fibers exhibit a more uniform and compact surface, while 1 cm fibers produce a rougher and more porous texture, indicating less uniform distribution and a higher potential for bleeding. These observations are consistent with the volumetric test results.



(a) (b)

Figure 4 Marshall specimens: (a) EFB fiber 0.4%, 0.5 cm (b) EFB fiber 0.4%, 1 cm

3.4. Effect of Fiber Addition on Marshall Characteristics



(a) (b)

(c)

Figure 5 Mixture test results in (a) Stability, (b) Flow, (c) Marshall Quotient

The addition of EFB fiber increases stability across all variations compared to the control mixture, with the highest stability of 1,748.80 kg observed at 0.4% fiber content with 0.5 cm fiber length. This improvement is attributed to the fiber-bridging mechanism, where randomly distributed fibers form a three-dimensional network that connects microcracks and distributes stress more evenly [18].

This mechanism is enhanced by NaOH alkali treatment, which increases fiber surface roughness and crystallinity, and by asphalt emulsion coating, which promotes chemical bonding between fibers and the asphalt matrix [17]. As a result, a multi-level interfacial bonding system (mechanical, physical, and chemical) is established.

Table 5 Marshall test characteristics result of the AC-WC mixes with/out EFB fiber

Parameter	EFB fiber content (%)	Fiber length (cm)		Specification
		0.5	1	
Stability	0	1666.16		≥ 1000 kg
	0.2	1710.01	1685.18	
	0.4	1748.80	1688.85	
	0.6	1726.12	1666.97	
Flow	0	3.25		2 ≥ 4 mm
	0.2	3.28	3.28	
	0.4	3.30	3.23	
	0.6	3.35	3.25	
MQ	0	512.33		≥ 250 kg/mm
	0.2	521.71	514.28	
	0.4	530.24	523.67	
	0.6	515.39	512.93	

Figure 5(a) shows that stability increases up to 0.4% fiber content and decreases at 0.6%, consistent with findings by Guo et al. and Chen et al., where excessive fiber content leads to agglomeration and localized stress concentrations, reducing mixture strength [16,19]. The 0.5 cm fibers consistently outperform 1 cm fibers due to better dispersion in dense-graded mixtures using the dry-mix method.

Flow values (Figure 5b) for all variations remain within the specified range of 2-4 mm, indicating that fiber addition does not adversely affect the elastoplastic behavior of the mixture. The Marshall Quotient (MQ), calculated using Equation (1), serves as an indicator of stiffness. As shown in Figure 5(c), MQ values increase across all fiber variations, with the highest value of 530.24 kg/mm at 0.4% fiber content and 0.5 cm length. Higher MQ values indicate improved resistance to rutting.

The Optimum Fiber Content (OFC) is identified at 0.4% for both fiber lengths, with superior performance observed at 0.5 cm. This finding is consistent with previous studies indicating optimal fiber content in dense-graded mixtures typically ranges from 0.3% to 0.5% [19,20].

3.5. Index of Retained Strength (IRS) at Optimum Fiber Content

The Index of Retained Strength or Stability (IRS) test was conducted at the optimum fiber content (0.4%) to evaluate moisture susceptibility, in accordance with the Bina Marga General Specifications 2025 requirement of IRS ≥ 90% [12]. Marshall specimens were immersed in water at 60°C for 24 hours prior to testing, and IRS was calculated using Equation (2).

Table 6 IRS test result at Optimum Fiber Content

Variation	Standard Stability (kg)	Retained Stability (kg)	IRS (%)
0.4%, 0.5 cm	1748.80	1587.82	90.79
0.4%, 1 cm	1688.85	1514.04	89.65

The results (Table 6) show that the mixture with 0.5 cm fiber length achieves an IRS value of 90.79%, satisfying the specification, while the 1 cm variation yields 89.65%, slightly below the requirement. The higher IRS value for the 0.5 cm fiber is attributed to improved fiber-asphalt-aggregate bonding, which enhances resistance to moisture damage. Previous studies indicate that surface modification of natural fibers improves compatibility with asphalt mixtures and significantly enhances resistance to moistureinduced damage [18,20]. These results confirm that the incorporation of treated EFB fibers at optimum content effectively improves the durability of asphalt mixtures against water-related deterioration.

4. Conclusion

The incorporation of Empty Fruit Bunch (EFB) fibers into AC-WC mixtures using the dry-mix method demonstrates a significant impact on Marshall characteristics, volumetric parameters, and overall mixture performance. Variations in fiber length and content resulted in increased stability and Marshall Quotient (MQ) compared to the control mixture, with stability improving from 1,666.16 kg to 1,748.80 kg at a fiber length of 0.5 cm and content of 0.4%, while MQ increased from 512.33 kg/mm to 530.24 kg/mm. Flow values for all variations ranged from 3.25 to 3.35 mm, remaining within the specified limits.

In terms of volumetric properties, density increased from 2.35 g/cc to 2.36 g/cc, while VIM decreased from 4.68% to 4.15-4.25% and VMA declined from 19.13% to 18.76-18.86%. Conversely, VFA increased from 75.57% to 77.08-77.92%, while still complying with the Bina Marga General Specifications 2025.

The combination of fiber length and content was used to determine the Optimum Fiber Content (OFC) for AC-WC mixtures incorporating EFB fibers. The OFC was identified at a fiber length of 0.5 cm and a fiber content of 0.4%, yielding the best overall performance among all variations, with stability of 1,748.80 kg, MQ of 530.24 kg/mm, flow of 3.30 mm, VIM of 4.20%, VMA of 18.78%, VFA of 77.66%, and an Index of Retained Strength (IRS) of 90.79%, satisfying the minimum requirement of 90% specified in the Bina Marga General Specifications 2025.

The application of alkali treatment and asphalt emulsion coating in conjunction with the dry-mix method proved effective in enhancing interfacial bonding. This resulted in a 45% increase in stability compared to untreated oil palm fibers reported by Alifudiin et al. [12], confirming the effectiveness of fiber surface treatment in improving the performance of AC-WC asphalt mixtures.

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