The Effect Of Coconut Shell Bio-Oil On The Marshall Characteristics Of Asphalt Concrete Wearing Course (AC-WC) Mixtures

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Abstract

The rapid development of road infrastructure has led to a high national dependency on petroleum asphalt, much of which is still imported, thereby necessitating the development of more sustainable alternative materials. Concurrently, the abundant agricultural waste of coconut shells in Indonesia remains underutilized and frequently causes environmental issues. This study aims to determine the technical characteristics of bio-oil derived from coconut shell pyrolysis, analyze the effect of bio-oil percentage variations on the Marshall parameters of Asphalt Concrete - Wearing Course (AC-WC) mixtures, and determine the optimum bio-oil content based on the General Specifications of Bina Marga 2018 Revision 2. This research employed a quantitative approach utilizing a true experimental laboratory design. The bio-oil production was conducted through a pyrolysis process at a temperature range of 400–500°C in a controlled laboratory environment. The investigation began with testing the physical properties of aggregates and penetration 60/70 asphalt to determine the Optimum Asphalt Content (OAC). Once the OAC was established, Marshall test specimens were fabricated by partially substituting the bitumen with coconut shell bio-oil at varied percentages of 0%, 5%, 10%, 15%, and 20% by weight of the binder. Marshall testing was subsequently executed to evaluate the stability, flow, Marshall Quotient (MQ), VIM, VMA, and VFA across all mixture variants. The results indicated that the Optimum Asphalt Content (OAC) was achieved at 6.18%. The substitution of coconut shell bio-oil proved capable of acting as a plasticizer, significantly enhancing the workability of the asphalt mixture. Overall, bio-oil substitution variations up to 15% met all required technical specifications. However, incorporating 20% bio-oil resulted in a VIM value of 5.42%, exceeding the maximum specification limit. The most optimum substitution rate was established at the 10% variation, yielding the highest peak stability of 977,96kg, making it technically feasible as an eco-friendly alternative binder for flexible pavements.

Keywords: *Asphalt concrete-wearing ocurse (AC-WC); Bio-oil; Coconut shell; Modified asphalt; Marshall test*

1. Introduction

One of the most important resources for land transportation is road infrastructure, which promotes both regional connectivity and the expansion of the national economy [1]. The fast growth of road pavement infrastructure in Indonesia is driving up demand for asphalt. In 2022, the country consumed 884,300 tons of asphalt, of which almost 53% was imported [2]. Because of the high greenhouse gas emissions from petroleum processing and the depletion of fossil fuel supplies, this heavy reliance on petroleum-based asphalt presents serious economic and environmental challenges [3]. As a result, pavement engineers now urgently need to develop renewable and ecologically benign alternative binders, or bio-binders [4].

With an annual production of about 2.85 million tons, Indonesia is the world's largest producer of coconuts and has an abundance of biomass waste resources [5]. About 33% of the weight of the entire coconut fruit is made up of the coconut shell [6]. With 36.51% lignin, 33.61% cellulose, and 29.27% hemicellulose, this biomass waste has a high lignocellulosic content [6]. Coconut shells' high lignin content prevents them from breaking down naturally, which leads to trash buildup that pollutes the environment [7]. By transforming this solid biomass waste into liquid bio-oil in an oxygen-free environment, thermochemical conversion via the pyrolysis process offers a novel option [8].Guaiacol, phenolic compounds, and heavy hydrocarbons from the breakdown of lignin make up the majority of the organic chemicals found in coconut shell bio-oil, which has viscosity and viscoelastic qualities similar to those of traditional asphalt binders [9], [10].

The use of bio-oil or pyrolysis tar made from several biomass feedstocks, such as sugarcane bagasse, sawdust, and coffee husks, as partial replacements for petroleum asphalt has been studied in the past [11]–[13]. However, there are still few quantitative studies that precisely assess the mechanical and volumetric interactions of unrefined coconut shell bio-oil added to dense-graded Asphalt Concrete-Wearing Course (AC-WC) mixtures. Since AC-WC is the surface layer of flexible pavement, it must be extremely stable and resistant to both permanent deformation and traffic loading [14]. Therefore, the purpose of this work is to assess the performance characteristics of AC-WC mixtures that include coconut shell bio-oil generated from pyrolysis as a partial bitumen alternative. This study specifically aims to identify the ideal bio-oil composition that can meet the technical standards outlined in the 2018 General Specifications for Highways (Bina Marga), Revision 2, which are currently in use in Indonesia, while also offering the highest Marshall stability.

2. Materials and Methods

2.1 Materials

The study's control binder was 60/70 penetration grade petroleum asphalt (Type I), which met the Indonesian National Standard (SNI) with a penetration value of 64.5 dmm, a softening point of 49.2 °C, and a specific gravity of 1.04 g/cm³. PT. Riau Mas Bersaudara, located in Riau, Indonesia, provided the coarse aggregates (crushed stone sizes 10–20 mm and 20–30 mm), medium aggregate, fine aggregate (stone dust), and natural sand. The asphalt mixture contained mineral filler that passed the No. 200 sieve.In order to meet the AC-WC gradation envelope outlined in the 2018 Bina Marga General Specifications, a combined aggregate gradation of 12.23% coarse aggregate, 41.28% medium aggregate, 37.28% stone dust, and 9.21% sand was created utilizing the matrix method. The bulk specific gravity (Gsb) of the blended aggregate was 2.639.

To guarantee even heating, coconut shells were washed to get rid of contaminants, oven-dried at 105 °C, and then broken into smaller pieces. The Renewable Energy Engineering Laboratory at Universitas Malikussaleh conducted fast pyrolysis in a closed reactor at temperatures between 400 and 500 °C. A water-cooling system was used to condense the volatile compounds produced during thermal breakdown, resulting in dark brown to black bio-oil with an acidic pH of 2.5 to 3.0 and a density of 1.05–1.13 g/mL.

2.2 Experimental Procedure

In order to determine the Optimum Asphalt Content (OAC) for the control combination without bio-oil (0%), 15 Marshall specimens with asphalt contents of 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% by total mixture weight were prepared. The chosen OAC was 6.18% based on the assessment of mechanical and volumetric factors. The 60/70 penetration asphalt was heated to about 140 °C prior to mixing for the modified combinations. Next, at substitution levels of 0%, 5%, 10%, 15%, and 20% by total binder weight, coconut shell bio-oil was added to the control binder. Before blending with aggregates that had been heated to about 110 °C until every aggregate particle was evenly covered, the modified binder was manually blended to guarantee homogeneity.

Marshall specimens were compressed in cylindrical molds that were 101.6 mm in diameter and 63.5 mm in height using an automatic Marshall compactor that applied 75 blows to each face. For every bio-oil content, three duplicate specimens were made, for a total of fifteen specimens. Following a 24-hour curing period, the specimens were submerged in a water bath at 60 °C for 30 minutes prior to Marshall testing to assess flow and stability. The volumetric and mechanical parameters of the experimental data were then calculated using standard Marshall equations and given in tabular and graphical form for debate.

The Marshall parameters evaluated in this study include:Stabilitas

1. Marshall Stability – the maximum load sustained by the asphalt mixture before failure at 60 °C, representing its resistance to permanent deformation under traffic loading.
2. Flow – the vertical deformation of the specimen at maximum load, indicating the flexibility of the asphalt mixture. The test was conducted at a loading rate of 50.8 mm/min
3. Void In The Mix (VIM)

$$VIM = (100\ x\ \frac{Gmm - Gmb}{Gmm})\ \%\ \text{from the bulk volume of asphalt concrete} \qquad (1)$$

Where:

Gmb = Bulk specific gravity of dense asphalt concrete

Gmm = Maximum specific gravity of uncompacted asphalt concrete

4. Void In The Mineral Agregat (VMA)

$$VMA = (100 - \frac{Gmb.Ps}{Gsb})\ \%\ \text{from the bulk volume of asphalt concrete} \quad (2)$$

Where:

Gmb = Bulk specific gravity of dense asphalt concrete

Ps = Aggregate content, % by weight of compacted asphalt concrete

Gsb = Bulk specific gravity of aggregates forming dense asphalt concrete

5. *Void Filled with Aspalt (VFA)*

$$VFA = \frac{100\ x\ (VMA - VIM)}{VMA} \quad (3)$$

Where:

VMA = Voids in Mineral Aggregate

VIM = Voids in Mix

3. Results and Discussion

3.1 Aggregate Sieve Analysis Results

The aggregate particle size distribution and aggregate proportions utilized in the Asphalt Concrete – Wearing Course (AC-WC) mixture were ascertained using sieve analysis. Stone dust (fine aggregate), natural sand, medium aggregate, and 10–20 mm crushed coarse aggregate made up the aggregates.

Table 1. Aggregate Passing Percentage (%)

Sieve No.	**% Aggregate Passing**			
	CA	**MA**	**FA**	**FS**
1″	100.00	100.00	100.00	100.00
3/4″	100.00	100.00	100.00	100.00
1/2″	34.58	100.00	100.00	100.00
3/8″	9.30	89.62	100.00	100.00
No.4	0.84	24.07	99.37	100.00
No.8	0.64	4.30	74.71	79.20
No.16	0.60	1.42	50.35	58.41
No.30	0.50	1.14	41.11	38.97
No.50	0.44	1.03	28.67	28.97
No.100	0.22	0.70	17.56	8.35
No.200	0.03	0.38	12.25	2.97

3.2 Combined Aggregate Gradation of the AC-WC Mixtur

The matrix approach was used to calculate the percentage of each aggregate component in the mixture. 12.23% Coarse Aggregate (CA), 41.28% Medium Aggregate (MA), 37.28% Fine Aggregate (FA, stone dust), and 9.21% Fine Sand (FS) made up the final mixture. The combined gradation produced by this aggregate composition satisfies the requirements of the 2018 Bina Marga General Specifications (Revision 2) for Asphalt Concrete– Wearing Course (AC-WC) mixtures.

Table 2. Combined Aggregate Gradation of the AC-WC Mixture

Sieve No.	Material Composition (%)				Combined Gradation	Spec. % Passing
	CA	MA	FA	FS		
(Composition)	12.23	41.28	37.28	9.21	–	–
1″	12.23	41.28	37.28	9.21	100.000	100
3/4″	12.23	41.28	37.28	9.21	100.000	100–100
1/2″	4.23	41.28	37.28	9.21	92.000	90–100
3/8″	1.14	37.00	37.28	9.21	84.625	77–90
No.4	0.10	9.94	37.05	9.21	56.296	53–69
No.8	0.08	1.78	27.85	7.29	37.000	33–53
No.16	0.07	0.58	18.77	5.38	24.808	21–40
No.30	0.06	0.47	15.33	3.59	19.448	14–30
No.50	0.05	0.43	10.69	2.67	13.836	9.0–22
No.100	0.03	0.29	6.55	0.77	7.630	6.0–15
No.200	0.00	0.16	4.57	0.27	5.000	4.0–9

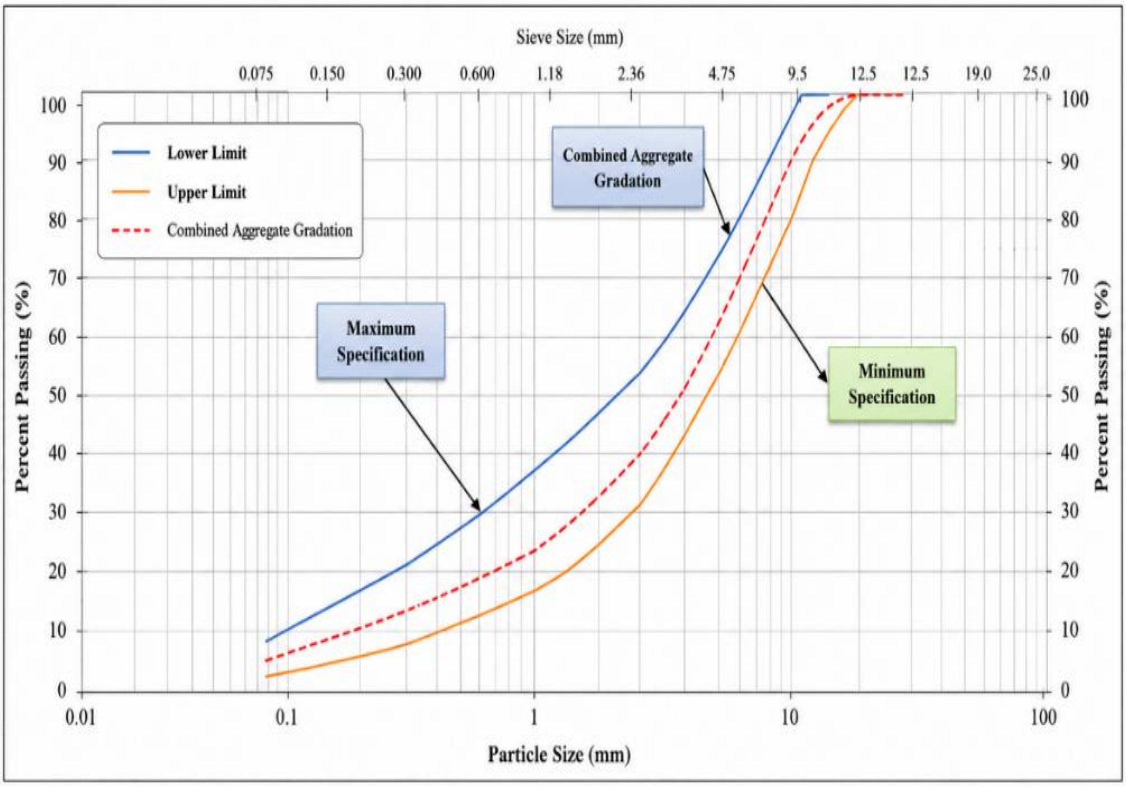

Figure 1. WC Combined Aggregate Gradation Curve for AC-WC Mixture

Based on the figure above, the combined aggregate gradation curve lies within the minimum and maximum specification limits specified in the 2018 Bina Marga General Specifications (Revision 2). This indicates that the selected aggregate gradation satisfies the requirements for Asphalt Concrete–Wearing Course (AC-WC) mixtures.

3.3 Specific Gravity Test Results of Aggregates

a. Fine Aggregate

Table 3. Specific Gravity Test Results of Fine Aggregate

Aggregate Property			Result
S	SSD condition test specimen weight	gr	441
A	Dry sample weight	gr	436,5
B	SSD sample weight	gr	649,5
C	Sample weight in water (SSD)	gr	916,5
Dry specific gravity		gr/cc	2,516
SSD specific gravity		gr/cc	2,542
Apparent specific gravity		gr/cc	2,583
Absorption		gr/cc	1,031

b. Coarse Aggregate

Table 4. Specific Gravity Test Results of Coarse Aggregate

No	Aggregate Property		Result
A	Dry sample weight	gr	1975
B	SSD sample weight	gr	1992
C	Sample weight in water (SSD)	gr	1280
Dry specific gravity		gr/cc	2,7739
SSD specific gravity		gr/cc	2,7978
Apparent specific gravity		gr/cc	2,8417
Absorption		gr/cc	0,8608

The test results indicate that all aggregates have a specific gravity greater than 2.5, while their water absorption values comply with the specification requirements. Therefore, the aggregates are considered suitable for use in asphalt pavement mixtures

3.4 . Determination of the Optimum Asphalt Content (OAC)

Marshall testing was subsequently conducted using asphalt contents of 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% to determine the Optimum Asphalt Content (OAC).

Table 5. Marshall test results for the AC-WC mixture

No	**Parameter**	**Asphalt Content (%)**					**Bina Marga Specification (2018)**
		4,5	5	5,5	6	6,5	
1	VMA(%)	17,213	16,296	17,118	16,816	16,576	Min.15
2	VIM (%)	8,590	6,407	6,155	4,625	3,146	3,0 – 5,0
3	VFA (%)	50,096	60,686	64,044	72,499	81,020	Min. 65
4	Stability (kg)	1006,73	1146,48	923,92	1076,46	1119,07	Min. 800
5	*Flow* (mm)	2,55	2,91	2,80	2,95	3,16	2-4

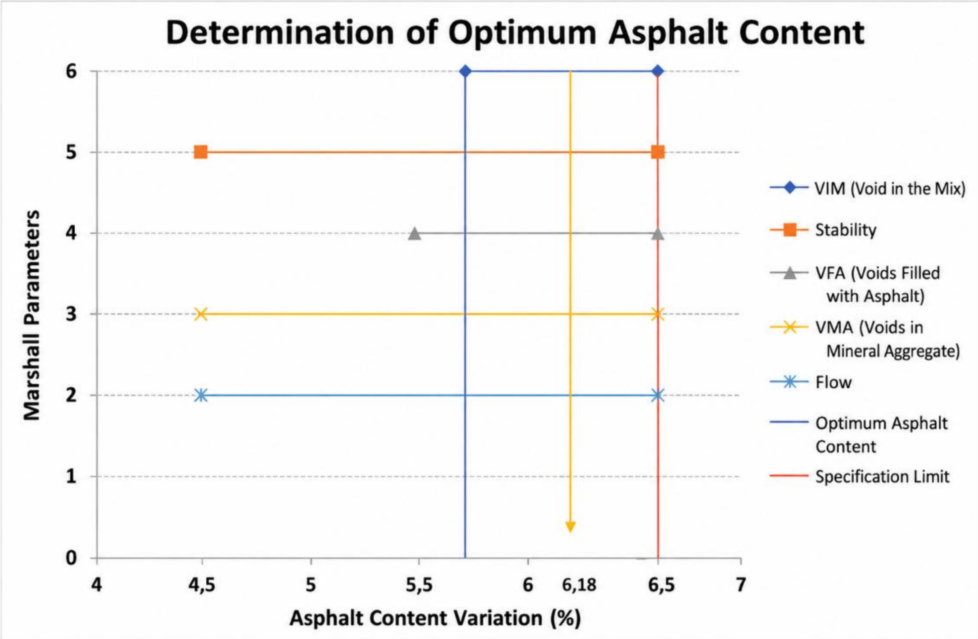

Figure 2. Determination of the Optimum Asphalt Content (OAC)

Based on Figure 2, the Optimum Asphalt Content (OAC) was determined in accordance with the 2018 Bina Marga General Specifications (Revision 2) by evaluating the Marshall parameters, including Stability, Flow, Void in the Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). The intersection of the curves that satisfied all specification requirements indicated an optimum asphalt content of 6.18%The selected OAC represents the optimum balance between mixture stability, flexibility, and volumetric properties, ensuring satisfactory pavement performance under traffic loading while complying with all technical requirements. Therefore, the 6.18% OAC was adopted as the control asphalt content for the subsequent Marshall tests with 0%, 5%, 10%, 15%, and 20% bio-oil substitution levels.

3.5 . Marshall Test Results with Bio-Oil Variation

The Optimum Asphalt Content (OAC) of 6.18% and bio-oil substitution levels of 0%, 5%, 10%, 15%, and 20% by weight of the asphalt binder were used in Marshall testing. For every variation, three specimens were made, for a total of fifteen specimens. The Marshall test was performed on each specimen following its preparation.Stability, Flow, Void in the Mix (VIM), Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), and Marshall Quotient (MQ) were the Marshall parameters that were assessed in order to determine how coconut shell bio-oil affected the AC-WC mixture's performance.

Table 6. Marshall test results of AC-WC mixtures with bio-oil variation

No	Parameter	Coconut Shell Bio-oil Content (%)					Bina Marga Specification (2018)
		0	5	10	15	20	
1	VMA(%)	17,153	17,374	17,393	17,745	17,885	Min.15
2	VIM (%)	4,57	4,83	4,85	5,25	5,42	3,0 – 5,0
3	VFA (%)	73,343	72,213	72,120	70,389	69,717	Min. 65
4	Stability (kg)	875,98	871,62	977,96	943,97	875,98	Min. 800
5	*Flow* (mm)	2,95	3,06	3,23	3,26	3,33	2-4

The volumetric and mechanical

characteristics of the AC-WC mixtures usually met the requirements of the 2018 Bina Marga General Specifications (Revision 2), according to Table 6's Marshall test findings. For the majority of bio-oil substitution levels, the examined parameters—Void in Mineral Aggregate (VMA), Void in the Mix (VIM), Void Filled with Asphalt (VFA), Stability, Flow, and Marshall Quotient (MQ)—met the specification limitations. However, the VIM value marginally surpassed the designated maximum limit for the 15 and 20% bio-oil substitution levels. The Marshall test findings are then displayed as graphs showing the link between the bio-oil replacement level and each Marshall parameter for a clearer understanding of the impact of bio-oil content on the asphalt mixture's performance.

a. Effect of Bio-Oil Content on Marshall Stability

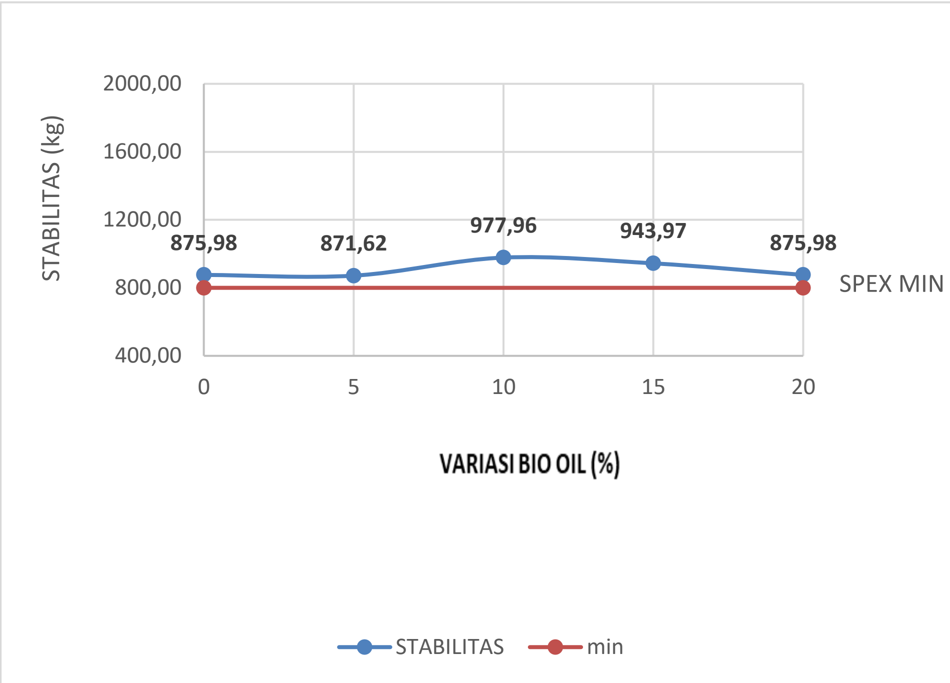

Figure 3. Effect of Bio-Oil Content on Marshall Stability

The stability value exhibited a fluctuating trend with increasing bio-oil content, reaching the highest value of 977,96 kg at 10% bio-oil. All mixtures satisfied the minimum stability requirement of 800 kg specified in the 2018 Bina Marga General Specifications (Revision 2), indicating that the AC-WC mixtures maintained adequate resistance to traffic loading.

b. Effect of Bio-Oil Content on Marshall Flow

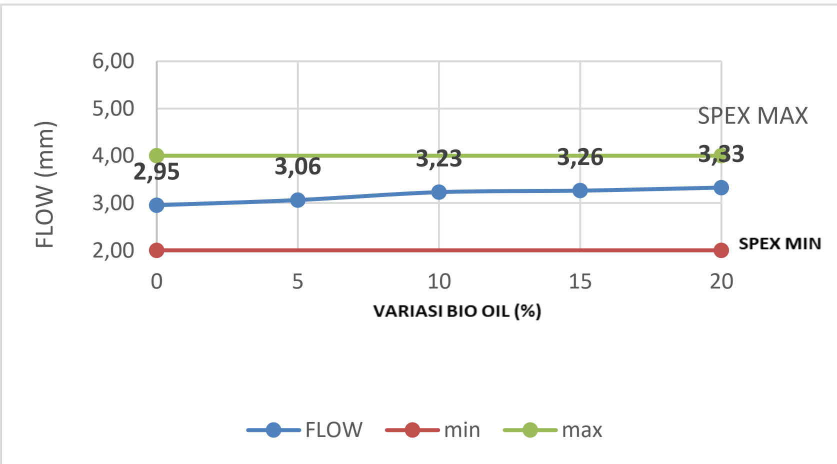

Figure 4. Effect of Bio-Oil Content on Marshall Flow

The flow value increased from 2.95 mm to 3.33 mm with increasing bio-oil content. All values remained within the specification range of 2–4 mm, indicating that the mixtures became more flexible while still satisfying the requirements of the 2018 Bina Marga General Specifications (Revision 2).

c. Effect of Bio-Oil Content on Void in Mineral Aggregate (VMA)

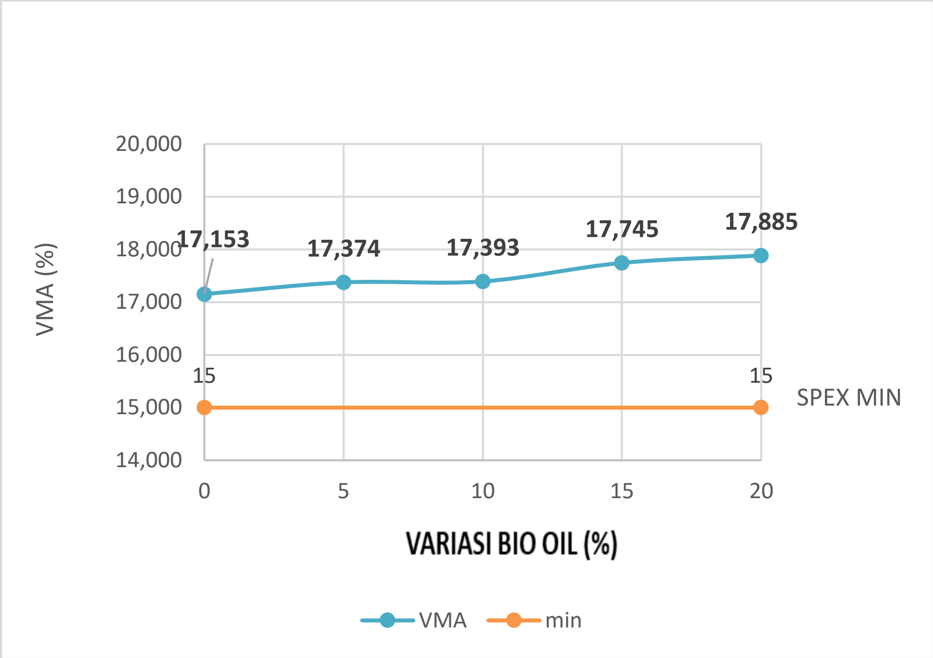

Figure 5. Effect of Bio-Oil Content on Void in Mineral Aggregate (VMA)

The VMA value increased from 17,153% to 17,885% as the bio-oil content increased. All values remained above the minimum specification limit of 15%, indicating that the mixtures satisfied the requirements of the 2018 Bina Marga General Specifications (Revision 2).

d. Effect of Bio-Oil Content on Void in the Mix (VIM)

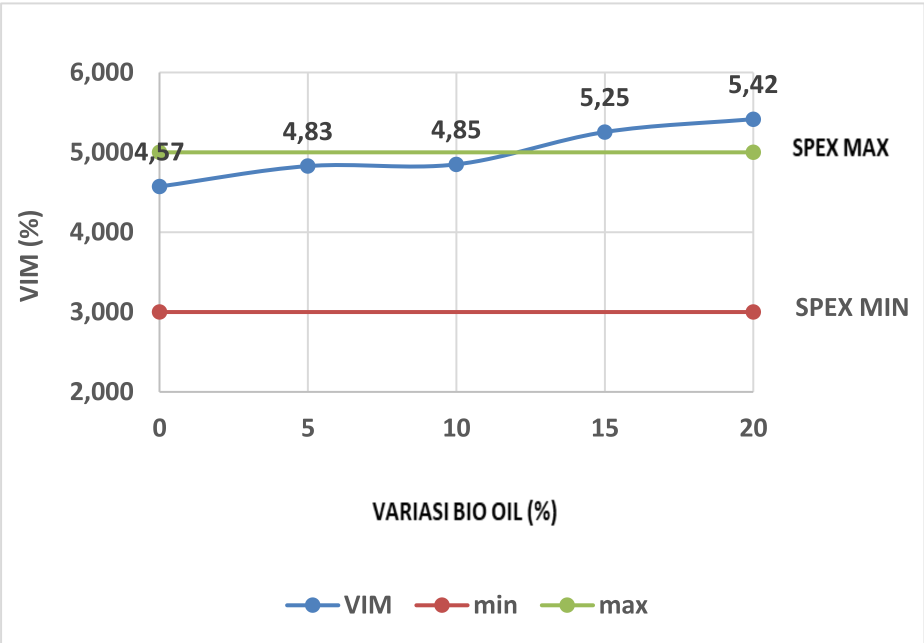

Figure 6. Effect of Bio-Oil Content on Void in the Mix (VIM)

As the amount of bio-oil grew, the VIM value rose from 4.57% to 4.85%. While mixtures with 15% and 20% bio-oil marginally above the maximum permitted amount, mixtures with up to 10% bio-oil met the specified range of 3–5%. 3–5%,

e. Effect of Bio-Oil Content on Void Filled with Asphalt (VFA)

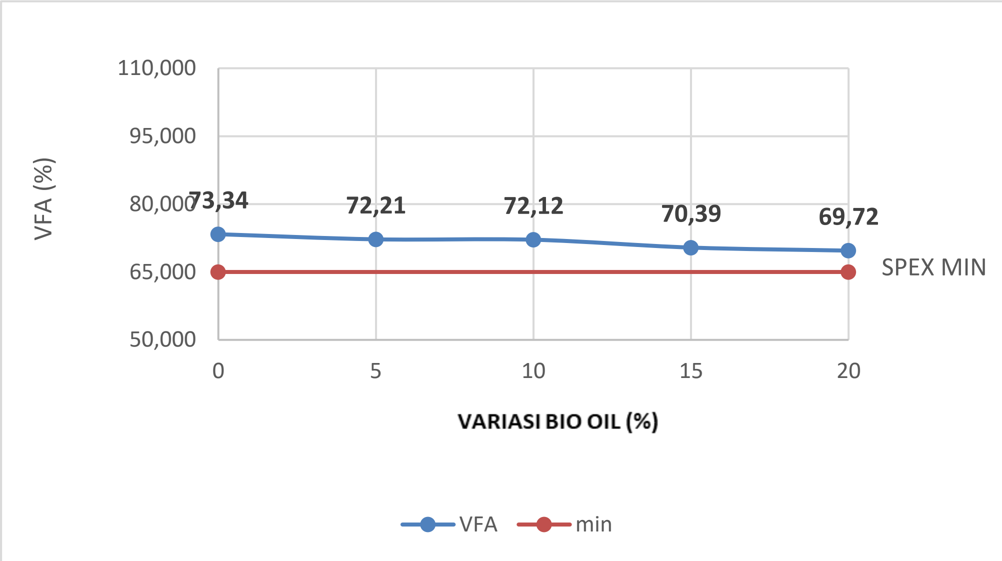

Figure 7. Effect of Bio-Oil Content on Void Filled with Asphalt (VFA)

As the amount of bio-oil increased, the VFA values varied between 73,34% and 69,72%. All combinations, however, continued to be over the 65% minimum specification level, demonstrating conformity with the 2018 Bina Marga General Specifications (Revision 2).

4. Conclusion

The Marshall properties of Asphalt Concrete–Wearing Course (AC-WC) mixtures were affected by the addition of coconut shell bio-oil produced by pyrolysis as a partial replacement for conventional asphalt, according to laboratory research and Marshall test analysis. Because bio-oil has a lower viscosity than 60/70 penetration asphalt, it made the mixtures easier to deal with. The flow, VIM, and VMA values all generally increased as the bio-oil concentration rose, while the VFA value trended downward. With the exception of the 20% bio-oil mixture, which generated a VIM value marginally above the maximum permitted level, all mixtures met the requirements of the 2018 Bina Marga General Specifications (Revision 2).

It was discovered that 10% of bio-oil produced the best Marshall performance, with a stability of 977.96 kg. All Marshall metrics, including VMA (17,393%), VIM (4.85%), VFA (72,12%), and flow (3.23 mm), met the 2018 Bina Marga General Specifications (Revision 2) at this substitution level. These results show that, with an ideal substitution level of 10%, coconut shell bio-oil has significant promise as a sustainable partial asphalt substitute in AC-WC combinations.

Authors' Contributions

R.M. conceived the study, conducted the experiments, analyzed the data, and drafted the manuscript. J.A. supervised the research, contributed to the methodology, and reviewed the manuscript. M.D.Y. contributed to data analysis, validation, and manuscript revision. F.M. supervised the project and reviewed the manuscript. All authors read and approved the final manuscript.

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