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An Experimental Study on the Use of Teak Wood Ash and Bengawan Solo Sand as Filler Additives in Asphalt Concrete – Wearing Course (AC-WC)

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Abstract

Asphalt Concrete–Wearing Course (AC-WC) is the surface layer of flexible pavement that directly receives traffic loads and is exposed to environmental conditions. This study investigated Bengawan Solo sand as a partial aggregate substitution and teak wood sawdust ash as a filler in AC-WC mixtures. The study aimed to evaluate their effects on Marshall characteristics and determine the optimum combination based on the 2025 Bina Marga General Specifications. An experimental laboratory method was employed using 60/70 penetration grade asphalt, aggregates conforming to the specifications, Bengawan Solo sand substitution levels of 0%, 1%, 2%, and 3%, and teak wood sawdust ash contents of 0%, 0.4%, 0.8%, and 1.2%. Marshall testing was conducted to determine stability, flow, Marshall Quotient (MQ), Void in the Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). The results showed that the 2% Bengawan Solo sand substitution group consistently satisfied the specified Marshall requirements. The optimum mixture was P2A0.4, consisting of 2% Bengawan Solo sand substitution and 0.4% teak wood sawdust ash, with VIM of 4.42%, VMA of 22.26%, VFA of 80.14%, stability of 850.80 kg, flow of 2.62 mm, and MQ of 323.50 kg/mm. The highest stability value of 965.34 kg was obtained from P2A1.2, while the lowest value of 818.08 kg occurred at P3A0.4, with both values remaining above the minimum stability requirement of 800 kg. These results indicate that Bengawan Solo sand substitution and teak wood sawdust ash addition can provide favorable Marshall characteristics when their proportions are appropriately controlled, with P2A0.4 demonstrating the most balanced overall performance among the investigated mixtures.

Keywords: *Asphalt Concrete–Wearing Course (AC-WC), Bengawan Solo Sand, Filler, Marshall Test, Teak Wood Sawdust Ash.*

INTRODUCTION

Road infrastructure is a vital component of economic development because it supports the movement of people, the distribution of goods and services, and the connectivity of production and consumption activities. The quality of pavement construction directly influences travel safety, riding comfort, structural performance, and service life, making material selection and mixture design fundamental concerns in pavement engineering. Flexible pavement incorporating asphalt concrete remains widely applied because its aggregate–binder system is capable of accommodating repeated traffic loading while providing adequate structural and functional performance (Roberts et al., 1996). In Indonesia, asphalt concrete pavement generally consists of the Asphalt Concrete–Wearing Course (AC-WC), Asphalt Concrete–Binder Course (AC-BC), and Asphalt Concrete–Base (AC-Base), which collectively contribute to load distribution and pavement durability (Hardiyatmo, 2015). The AC-WC layer has a particularly strategic role because it constitutes the pavement surface that directly interacts with traffic and environmental exposure, requiring an appropriate balance between stability, volumetric characteristics, deformation resistance, and durability (Direktorat Jenderal Bina Marga, 2025). Contemporary asphalt-material research has increasingly explored the incorporation of industrial, agricultural, and biomass-derived residues into asphalt mixtures as part of a broader transition toward resource-efficient and environmentally responsible infrastructure. This development has created an important research direction in which waste materials are not merely treated as disposal problems but are investigated as functional constituents capable of modifying the physicochemical and mechanical behavior of asphalt mixtures.

Within asphalt mixture design, filler represents a critical fine-grained component because its interaction with asphalt binder produces a mastic that influences aggregate packing, stiffness, cohesion, and the overall volumetric structure of the mixture. Conventional fillers such as stone dust, Portland cement, and limestone remain widely used, yet their continued consumption raises questions regarding material availability, cost efficiency, and the environmental burden associated with extraction and processing. The role of fine particles is also closely related to mixture density and void characteristics, which are fundamental parameters in evaluating asphalt concrete performance (Sukirman, 2013). Experimental studies have demonstrated that biomass-derived ash can modify Marshall characteristics and mixture performance, although the magnitude and direction of these effects depend strongly on ash composition, particle size, replacement level, and interaction with the asphalt binder (Tahami et al., 2018). Research on wood ash has shown that its mineralogical and physical characteristics can allow it to function as an alternative filler, indicating that biomass combustion residues may possess engineering value beyond their conventional disposal function (Moura et al., 2022). Similar evidence has emerged from rice husk ash research, where the incorporation of ash into AC-WC mixtures has been associated with measurable changes in mixture characteristics and has reinforced the feasibility of agricultural waste as a functional asphalt-material component (Intari et al., 2019). These findings indicate that the performance of alternative fillers should not be assessed solely from their waste-reduction potential but through their capacity to satisfy the mechanical and volumetric requirements of the asphalt mixture.

Recent Indonesian studies further indicate that alternative ash materials can produce meaningful changes in AC-WC performance, although the reported responses are not necessarily consistent across different waste sources and mixture configurations. Rice husk ash, for instance, has been investigated as a filler in asphalt mixtures for coastal pavement applications, demonstrating the relevance of biomass ash in environments where conventional materials may face additional durability challenges (Farida & Juniayanti, 2024). Other research has reported that palm oil fuel ash can be incorporated into PG 70 asphalt mixtures for AC Mod-WC, reinforcing the broader applicability of locally available biomass residues as alternative filler materials (Oktaviani et al., 2024). More recent work has positioned bio-based rice husk ash as an environmentally oriented filler for latex-modified asphalt concrete wearing course mixtures, illustrating how waste-derived materials can be integrated with modified asphalt systems rather than being restricted to conventional mixtures (Ramadhani et al., 2025). Wood ash has attracted particular attention because its mineral fraction can contribute to filler–binder interaction, while its effectiveness remains dependent on physical characteristics and chemical composition (Dimter et al., 2021). A recent assessment of wood ash as an asphalt filler likewise identified its potential for incorporation into asphalt mixtures while emphasizing the need to evaluate its suitability through mixture-level performance indicators rather than assuming equivalence with conventional mineral fillers (Mior Sani et al., 2024). The emerging literature therefore supports the technological potential of biomass ash, but it also reveals that the behavior of one ash source cannot automatically be generalized to another because differences in combustion conditions, biomass species, fineness, mineral composition, and dosage may substantially alter mixture response. This variability becomes particularly important when the material originates from a specific local biomass resource, such as teak wood, for which experimentally validated evidence in AC-WC mixtures remains comparatively limited.

The use of teak wood ash presents a particularly relevant research opportunity in regions where teak-processing activities generate substantial quantities of wood residues that are not always converted into higher-value applications. From an engineering perspective, the fine particle characteristics of wood ash provide a reasonable basis for investigating its function as a filler, while its mineral constituents may influence the stiffness and internal structure of asphalt mastic. Existing studies on wood ash have established the general feasibility of biomass combustion ash as an asphalt filler, but their findings cannot be directly transferred to teak wood ash because the characteristics of ash are strongly influenced by the biological origin and combustion process of the source material (Moura et al., 2022). The Indonesian context also provides an opportunity to combine waste-derived filler with locally available aggregate resources, thereby addressing both material sustainability and regional resource utilization. Bengawan Solo sand is particularly relevant because its fine particles may contribute to aggregate gradation and void filling, potentially altering the packing structure and volumetric properties of the AC-WC mixture. The engineering significance of fine aggregate characteristics is reflected in the requirement to evaluate properties such as specific gravity, water absorption, and cleanliness before their incorporation into asphalt mixtures (Badan Standardisasi Nasional, 2016). The proportion of material passing the 75-µm sieve is likewise an important consideration because excessive or insufficient fine material can alter the aggregate–mastic relationship and consequently affect mixture behavior (Badan Standardisasi Nasional, 2012). Consequently, the combination of teak wood ash and Bengawan Solo sand should be considered as an integrated material system rather than as two independent substitutions, because changes in the fine aggregate and filler fractions can interact to modify aggregate packing, asphalt absorption, mastic volume, and the resulting Marshall characteristics.

The central gap in the existing literature lies in the limited empirical understanding of how teak wood ash interacts with a locally sourced fine aggregate such as Bengawan Solo sand when introduced into an AC-WC mixture, particularly when the objective is to evaluate both mechanical and volumetric responses under Indonesian pavement specifications. Previous studies have predominantly examined individual biomass ashes, including rice husk ash, palm oil fuel ash, and wood ash, while comparatively little attention has been directed toward teak-derived ash combined with a specific local sand source (Ridwan & Nadia, 2024). Research on alternative asphalt additives has also demonstrated that modifications capable of improving one Marshall parameter may simultaneously alter other properties, indicating that material substitution should be evaluated through a multidimensional mixture-performance framework rather than through stability alone (Amelia et al., 2023). Similar variability has been reported in studies involving latex-modified AC-WC mixtures, where changes in additive composition and dosage can produce different responses in stability, flow, and volumetric properties (Perwenda & Ayu, 2023). The use of alternative fillers therefore requires systematic experimental control because improvements in one characteristic do not necessarily indicate an overall improvement in mixture quality. Indonesian pavement specifications and established Marshall procedures provide an essential technical basis for determining whether alternative materials remain within the required performance limits (Standar Nasional Indonesia, 1991). The absence of a sufficiently specific experimental framework for teak wood ash and Bengawan Solo sand leaves an empirical gap concerning their appropriate utilization level, their influence on mixture characteristics, and the extent to which their combination can serve as a technically viable alternative to conventional filler materials. Addressing this gap is scientifically relevant because it can clarify whether the observed performance of biomass ash reported in other material systems is transferable to teak-derived ash and a locally sourced sand under AC-WC mixture conditions.

Against this background, the present study positions itself at the intersection of sustainable pavement-material development, local-resource utilization, and experimental asphalt-mixture engineering. The study specifically investigates teak wood ash as a filler additive and Bengawan Solo sand as a supplementary fine material in AC-WC mixtures, with emphasis on their effects on mechanical and volumetric characteristics. The experimental approach is designed to establish whether the proposed material combination can produce a mixture that remains technically acceptable while reducing dependence on conventional mineral filler. The analysis considers the interrelationship among mixture stability, flow, void characteristics, and asphalt content so that material performance can be interpreted as an integrated response rather than as an isolated Marshall value. Particular attention is directed toward identifying the mixture condition that provides the most favorable balance between structural performance and volumetric requirements. The research is also intended to provide an evidence-based assessment of whether locally generated teak wood ash and Bengawan Solo sand can be transformed from low-value residual materials into functional resources for pavement construction. Through this approach, the study contributes theoretically by extending the understanding of biomass-derived filler behavior within an AC-WC material system and contributes methodologically by establishing an experimental basis for evaluating the combined utilization of teak wood ash and locally sourced sand.

RESEARCH METHODS

Penelitian ini merupakan empirical experimental study conducted under laboratory conditions to investigate the effect of teak wood ash and Bengawan Solo sand as filler additives in Asphalt Concrete–Wearing Course (AC-WC) mixtures. The experimental architecture comprises material characterization, mixture proportioning, specimen fabrication, and Marshall testing, with the constituent materials consisting of coarse aggregate, fine aggregate, asphalt binder, teak wood ash, and

Bengawan Solo sand. The aggregate materials are initially characterized through specific gravity and water absorption tests, while the fineness and cleanliness of the filler and fine material are evaluated to establish their suitability for asphalt mixture production (Badan Standardisasi Nasional, 2016). The asphalt binder is characterized through its specific gravity and relevant physical properties before incorporation into the mixture to ensure that the binder satisfies the applicable requirements for asphalt pavement materials (Badan Standardisasi Nasional, 2011). Teak wood ash is prepared as a fine filler material, whereas Bengawan Solo sand is incorporated as an additional fine aggregate component, with the selected proportions forming the experimental variations investigated in the AC-WC mixture. Each mixture variation is proportioned according to the aggregate gradation and asphalt-content requirements specified for asphalt pavement construction, while the mixture design follows the technical provisions established in the General Specifications for Bina Marga pavement works (Direktorat Jenderal Bina Marga, 2025). The prepared materials are heated, proportioned, mixed, compacted into Marshall specimens, and conditioned under controlled laboratory procedures so that differences in measured performance can be attributed to the material variations rather than inconsistencies in specimen preparation.

The experimental evaluation is conducted using the Marshall method to quantify the mechanical and volumetric characteristics of each AC-WC mixture variation, with the test procedure referring to the Indonesian Marshall testing standard (Standar Nasional Indonesia, 1991). For each specimen, the measured parameters include bulk density, Marshall stability, flow, Void in Mineral Aggregate (VMA), Void in the Mix (VIM), Void Filled with Bitumen (VFB), and Marshall Quotient (MQ), which collectively represent the load-bearing capacity, deformation response, internal void structure, and stiffness characteristics of the asphalt mixture. The volumetric calculations are supported by measurements of aggregate and asphalt specific gravity and are used to determine the relationship between aggregate structure, binder content, and air-void characteristics within the compacted mixture. The experimental results for each treatment are compared with the applicable AC-WC specification limits to validate whether the incorporation of teak wood ash and Bengawan Solo sand produces mixtures that remain technically acceptable for pavement applications (Direktorat Jenderal Bina Marga, 2025). The performance of each variation is evaluated by comparing its stability, flow, VMA, VIM, VFB, MQ, and density values against the control mixture, allowing the direction and magnitude of material-induced changes to be identified quantitatively. The filler fraction is also evaluated based on its passing percentage through the 75-μm sieve because the quantity of very fine material can affect aggregate packing and the formation of asphalt mastic within the mixture (Badan Standardisasi Nasional, 2012). The optimum-performing variation is determined from the combination of mechanical and volumetric compliance, with the selected mixture representing the most balanced response between stability, deformation characteristics, internal void structure, and the requirements for an acceptable AC-WC mixture.

RESULTS AND DISCUSSION

Characterization of Asphalt and Aggregate Materials

The experimental study began with the preparation and characterization of the constituent materials for the Asphalt Concrete–Wearing Course (AC-WC) mixture. Coarse aggregate, medium aggregate, stone dust, and 60/70 penetration asphalt were obtained from the Asphalt Mixing Plant (AMP) of PT. Semarang Multi Cons in Kaliwungu, Kendal, while teak wood powder ash and Bengawan Solo River sand were obtained from Blora Regency. Before specimen preparation, the materials were oven-dried at a temperature of (110 ± 5)∘ C to remove moisture that could interfere with subsequent testing. Initial material characterization was conducted to determine the physical and mechanical properties of each constituent and to assess their compliance with the applicable Bina Marga requirements. The characterization included asphalt penetration, softening point, ductility, flash point, and specific gravity, as well as sieve analysis, water absorption, specific gravity, and abrasion resistance for the aggregates. The results of these examinations provided the material-quality basis for preparing the AC-WC mixture and conducting the subsequent Marshall evaluation.

The asphalt binder used in this study was 60/70 penetration asphalt produced by Pertamina, which served as the binding material in the AC-WC mixture. Its characteristics were evaluated through penetration, softening point, and specific gravity tests, with the results compared with the requirements specified in the General Specifications of Bina Marga 2025 (Revision 2). As presented in Table 1, the penetration value was 65 (0.1 mm), the softening point was 50.5∘C, and the specific gravity was 1.034, with each parameter reported as satisfying the applicable specification.

Table 1. Physical and Mechanical Properties of 60/70 Penetration Asphalt

No.	Type of Examination	Unit	Specification Min	Specification Max	Test Result	Specification	Remark
1	Penetration at 25ºC, 100 g, 5 seconds	0.1 mm	60	70	65	SNI 2456:2011	Complies
2	Softening Point 5ºC (Ring and Ball Test)	ºC	48	58	50.5	SNI 2434:2011	Complies
3	Specific Gravity	%	1	-	1.034	SNI 2441:2011	Complies

Source: Research Results, 2026

The penetration value indicates that the binder falls within the specified 60–70 range, while its softening point also remains between the required limits of 48–58°C. These results indicate that the binder possessed the required physical characteristics for incorporation into the experimental mixture. The compliance of the asphalt binder is important because binder consistency affects the interaction between asphalt and aggregate during mixing and compaction. A binder that satisfies the specified range provides a controlled condition for assessing the effects of the experimental additives. Accordingly, the asphalt characterization results support the use of 60/70 penetration asphalt in the subsequent AC-WC mixture preparation.

Aggregate gradation was subsequently examined because the distribution of particle sizes determines the internal structure and packing characteristics of the asphalt mixture. A well-distributed gradation promotes particle interlocking and contributes to a denser and more mechanically stable mixture, whereas an inappropriate gradation may produce an unfavorable void structure. The study therefore used gradation testing as a basis for assessing aggregate suitability and determining the proportions required for the mixture design. Figure 1 presents the aggregate gradation testing process used in the study. The resulting gradation data were then compared with the applicable Bina Marga specification to establish whether the aggregate materials could be incorporated into the AC-WC mixture.

Figure 1. Aggregate Gradation Testing Process

The physical and mechanical characteristics of the aggregate materials are presented in Table 2, covering both coarse and fine aggregate fractions. The coarse aggregate passing the No. 200 sieve was 0.64% for the ½-inch coarse aggregate and 0.60% for the ¾-inch medium aggregate, both below the maximum requirement of 1%. Water absorption values were 1.610% and 2.090%, respectively, while the reported bulk specific gravities were 2.620 and 2.610. For the fine aggregate, the stone dust and sand showed No. 200 sieve passing values of 3.45% and 12.36%, water absorption values of 2.39% and 2.79%, and bulk specific gravities of 2.51 and 2.51, respectively. The reported results indicate that the aggregate materials complied with the specified requirements and were considered suitable for use in the AC-WC mixture.

Table 2. Physical and Mechanical Properties of Aggregate

No.	Type of Examination	Method	Requirement	Result	Remark
A	**Coarse Aggregate**				
1a	Coarse Aggregate ½" passing No. 200 sieve	SNI ASTM C117:2012	Max. 1%	0.64%	Complies
1b	Medium Aggregate ¾" passing No. 200 sieve	SNI ASTM C117:2012	Max. 1%	0.60%	Complies
2a	Water Absorption of Coarse Aggregate ½"	SNI 1969:2016	Max. 3%	1.610%	Complies
2b	Water Absorption of Medium Aggregate ¾"	SNI 1969:2016	Max. 3%	2.090%	Complies
3a	Bulk Specific Gravity of Coarse Aggregate ½"	SNI 1969:2016	Max. 2.5%	2.620%	Complies
3b	Bulk Specific Gravity of Medium Aggregate ¾"	SNI 1969:2016	Max. 2.5%	2.610%	Complies
B	**Fine Aggregate**				
1a	Stone Dust passing No. 200 sieve	SNI 03-4142-1996	Max. 15%	3.45%	Complies
1b	Sand passing No. 200 sieve	SNI 03-4142-1996	Max. 15%	12.36%	Complies
2a	Water Absorption of Stone Dust	SNI 1970:2016	Max. 3%	2.39%	Complies
2b	Water Absorption of Sand	SNI 1970:2016	Max. 3%	2.79%	Complies
3a	Bulk Specific Gravity of Stone Dust	SNI 1970:2016	Min. 2.5%	2.51%	Complies
3b	Bulk Specific Gravity of Sand	SNI 1970:2016	Min. 2.5%	2.51%	Complies

Source: Research Results, 2026

The Bengawan Solo River sand was then examined separately because it functioned as one of the experimental fine-aggregate materials. The gradation analysis showed that 100% of the sand passed the No. 30 sieve and was retained beginning at the No. 50 sieve, with 38.20% reported as passing the No. 50 sieve. The material passing the No. 100 sieve was 10.40%, while the material passing the No. 200 sieve was 8.70%. These particle-size characteristics indicate that the sand occupied the fine portion of the aggregate gradation and could be incorporated as the specified substitution material. The reported gradation was considered to comply with SNI ASTM C136:2012 and provided the particle-size basis for evaluating the effect of Bengawan Solo River sand on the AC-WC mixture.

Table 3. Particle-Size Distribution Analysis of Bengawan Solo Sand

Material Type: Sand									
Sieve Size		Cumulative			Average (%)	Cumulative			Average (%)
		Retained		Passing		Retained		Passing	
inch	mm	gr	%	%		gr	%	%	
1½"	37.5	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
1"	25.0	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00

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3/4"	19.0	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
1/2"	12.5	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
3/8"	9.5	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
#4	4.75	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
#8	2.36	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
#16	1.15	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
#30	0.60	0.00	0.00	100.00	100.00	0.00	0.00	100.00	100.00
#50	0.30	320.0	64.00	36.00	38.20	298.0	59.60	40.40	38.20
#100	0.15	453.0	90.60	9.40	10.40	443.0	88.60	11.40	10.40
#200	0.075	448.0	89.60	10.40	8.70	465.0	93.00	7.00	8.70
Sample Weight		**500.0**				**500.0**			

Material Type: Sand

Source: Research Results, 2026

The teak wood powder ash was characterized as a fine material intended to replace part of the stone dust fraction in the experimental mixture. The material was processed to obtain the required particle-size distribution and was reported as passing the No. 100 sieve and being retained at the No. 200 sieve. Table 4 shows that the average passing value at the No. 100 sieve was 35.50%, while the average passing value at the No. 200 sieve was 95.38%. The high proportion of fine particles indicates that the teak wood powder ash occupied the finer portion of the mixture and could influence the packing characteristics of the aggregate-filler system. Its incorporation was therefore relevant to evaluating changes in the volumetric and Marshall characteristics of the AC-WC mixture at the specified additive levels.

Table 4. Test Results of Teak Wood Powder Ash

Material Type: Teak Wood Powder Ash								
Sieve Size		**Trial I**			**Trial II**			**Average**
		Retained		**Passing**	**Retained**		**Passing**	
inch	**mm**	**gr**	**%**	**%**	**gr**	**%**	**%**	
1½"	37.5							
1"	25.0							
3/4"	19.0							
1/2"	12.5							
3/8"	9.5							
#4	4.75							
#8	2.36	-	-	100.00	-	-	100.00	100.00
#16	1.15	-	-	100.00	-	-	100.00	100.00
#30	0.60	-	-	100.00	-	-	100.00	100.00
#50	0.30	-	-	100.00	-	-	100.00	100.00
#100	0.15	120.0	60.00	40.00	138.0	69.00	31.00	35.50
#200	0.075	8.7	4.35	95.65	9.8	4.90	95.10	95.38
Sample Weight (gr)		**200.00**			**200.0**			

Source: Research Results, 2026

Cement was used as the filler material in the AC-WC mixture and was characterized through particle-size distribution analysis. The material was reported to pass the No. 8 through No. 100 sieves and to be retained at the No. 200 sieve in accordance with the stated testing procedure. As shown in Table 5, the average passing percentage at the No. 200 sieve reached 98.20%, indicating that the cement consisted predominantly of very fine particles. Such a particle-size distribution provides the fine fraction required for the filler component of the asphalt mixture. The combination of the characterized asphalt, aggregate, Bengawan Solo River sand, teak wood powder ash, and cement filler established the material conditions used in the subsequent mixture proportioning and Marshall testing stages.

Table 5. Particle-Size Distribution Analysis of Filler (Cement)

Material Type: Filler (Cement)									
Sieve Size		Trial I			Trial II			Average
		Retained		Passing	Retained		Passing	
inch	mm	gr	%	%	gr	%	%	
1½"	37.5							
1"	25.0							
3/4"	19.0							
1/2"	12.5							
3/8"	9.5							
#4	4.75							
#8	2.36	-	-	100.00	-	-	100.00	100.00
#16	1.15	-	-	100.00	-	-	100.00	100.00
#30	0.60	-	-	100.00	-	-	100.00	100.00
#50	0.30	-	-	100.00	-	-	100.00	100.00
#100	0.15	-	-	100.00	-	-	100.00	100.00
#200	0.075	2.5	2.50	97.50	1.1	1.10	98.90	98.20
Sample Weight (gr)		**100.00**			**100.0**			

Source: Research Results, 2026

Aggregate Combination and AC-WC Mixture Composition

The aggregate combination stage was conducted to establish a continuous particle-size distribution suitable for the AC-WC mixture. Each aggregate fraction was combined according to its proportion so that the resulting gradation could satisfy the specified limits from the 3/4-inch sieve through the No. 200 sieve. The combination included 1/2-inch coarse aggregate, 3/8-inch medium aggregate, stone dust, Bengawan Solo River sand, teak wood powder ash, and cement filler. The calculation of each fraction was based on the percentage passing obtained from the material characterization tests presented in the preceding section. This approach was necessary because the gradation of the combined aggregate determines the packing arrangement and contributes to the volumetric characteristics of the compacted mixture.

The calculated aggregate combination is presented in Table 6, which shows the percentage passing at each sieve size and the contribution of the individual aggregate fractions. The selected proportions consisted of 70.0% of one aggregate fraction, 12.0%, 40.0%, 42.0%, 3.0%, 1.0%, and 2.0% for the respective material components recorded in the original calculation. The combined gradation produced passing percentages of 93.75% at the 1/2-inch sieve, 74.55% at the 3/8-inch sieve, 55.88% at the No. 4 sieve, and 5.34% at the No. 200 sieve. These values demonstrate a progressive reduction in the percentage passing as the sieve opening decreases, indicating that the aggregate system contains both coarse and fine fractions. The resulting gradation was subsequently evaluated against the specified lower and upper limits before the mixture proportions were finalized.

Table 6. Aggregate Combination Calculation

Sieve Size	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
mm	25	19	12.7	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Aggregate Fraction 1	100.00	100.00	47.95	5.10	1.23	0.22	1.14	1.12	0.58	0.48	0.09
Aggregate Fraction 2	100.00	100.00	100.00	64.84	19.34	6.60	6.94	6.90	6.54	6.27	2.27
Aggregate Fraction 3	100.00	100.00	100.00	100.00	100.00	75.10	49.10	24.20	20.20	10.80	3.30
Sand	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	38.20	10.40	4.70
Cement Filler	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.20
Teak Wood Powder Ash	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	35.50	95.38
Composition	70.0%	70.00	60.11	43.53	31.87	22.67	15.18	10.54	8.29	7.28	3.19
Composition	12.0%	12.00	5.75	0.61	0.15	0.03	0.14	0.13	0.07	0.06	0.01
Composition	40.0%	40.00	40.00	25.94	7.74	2.64	2.78	2.76	2.62	2.51	0.91
Composition	42.0%	42.00	42.00	42.00	42.00	31.54	20.62	10.16	8.48	4.54	1.39
Composition	3.0%	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.15	0.31	0.14
Composition	1.0%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98
Composition	2.0%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.71	1.91

Source: Research Results, 2026

The combined gradation was then compared with the AC-WC specification limits, as summarized in Table 7. The combined material produced 5.34% passing the No. 200 sieve against a specified range of 3–7%, while the No. 100 and No. 50 sieve values were 9.12% and 15.32%, respectively. At the No. 30, No. 16, No. 8, and No. 4 sieves, the combined passing percentages were 19.06%, 29.53%, 40.21%, and 55.88%, respectively, and each remained within the corresponding specification range. The coarser fractions also complied, with 74.55% passing the 3/8-inch sieve, 93.75% passing the 1/2-inch sieve, and 100% passing the 3/4-inch and 1-inch sieves. The agreement between the calculated values and the specified limits indicates that the selected aggregate proportions generated an acceptable gradation for AC-WC mixture preparation.

Table 7. Specification of Combined Aggregate Passing Limits

Sieve No.	Combined Passing (%)	Lower Limit	Upper Limit
#200	5.34	3	7
#100	9.12	5	12
#50	15.32	8	18
#30	19.06	12	25
#16	29.53	23	35
#8	40.21	33	48
#4	55.88	50	65
3/8"	74.55	70	80
1/2"	93.75	85	95
3/4"	100.00	100	100
1"	100.00	100	100

Source: Research Results, 2026

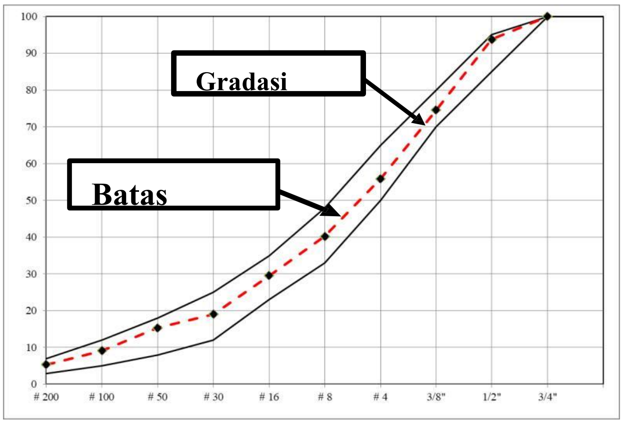

Figure 2. Combined Aggregate Gradation
Source: Research Results, 2026

The gradation curve in Figure 2 confirms that the combined aggregate distribution remained between the upper and lower specification boundaries over the evaluated sieve sizes. This position indicates that the mixture contained a balanced distribution of coarse, intermediate, and fine particles rather than concentrating excessively in a single particle-size range. The No. 200 sieve value of 5.34% is particularly relevant because it remains close to the lower-middle portion of the specified 3–7% range, indicating controlled fine-particle content. The continuous gradation also provides an appropriate structural basis for achieving aggregate interlocking while retaining sufficient spaces for asphalt binder and filler. The selected gradation therefore became the basis for calculating the material quantities required for the AC-WC specimens.

Following the gradation calculation, the material quantities for specimen preparation were determined according to the mold capacity. The mixture design used an asphalt content of 5.8% with a mold capacity of 1,200 g, resulting in 69.6 g of asphalt and 1,130.4 g of total aggregate. The aggregate components consisted of 300 g of coarse aggregate, 300 g of medium aggregate, 480 g of sand, 36 g of stone dust, and 14.4 g of filler, producing a total aggregate mass of 1,130.4 g. These calculated quantities are summarized in Table 8, which establishes the material composition used for the AC-WC mixture. The calculation also confirms that the selected 5.8% asphalt content was treated as the optimum asphalt content in the original experimental design.

Table 8. AC-WC Material Composition

No.	Type of Material	Composition	Weight (g)	Cumulative Weight (g)
1	Medium Aggregate ¾”	25.0%	300.0	300.0
2	Coarse Aggregate ½”	25.0%	300.0	600.0
3	Stone Dust	40.0%	480.0	1080.0
4	Sand	3.0%	36.0	1116.0
5	Filler	1.2%	14.4	1130.4
6	Asphalt	5.8%	69.6	1200.0

Source: Research Results, 2026

The composition presented in Table 8 establishes the reference mixture before the experimental substitutions of Bengawan Solo River sand and teak wood powder ash are evaluated. The 5.8% asphalt content corresponds to an asphalt mass of 69.6 g for the 1,200 g mold capacity, while the remaining 1,130.4 g consists of aggregate and filler components. This proportional arrangement maintains the total specimen mass at 1,200 g and provides a consistent basis for comparing the subsequent mixture variations. The combination of an acceptable gradation and controlled material mass is important because differences in Marshall performance should be interpreted in relation to the designed material proportions. The resulting mixture composition therefore serves as the reference framework for the volumetric and mechanical testing presented in the following section.

Marshall Test and Maximum Specific Gravity (GMM) Results

The Marshall testing process was conducted after each specimen had been measured in terms of height, diameter, and weight under dry, 24-hour immersion, and Saturated Surface-Dry (SSD) conditions. The specimens were then tested using a Marshall apparatus to obtain stability and flow values, while the volumetric characteristics were determined from the measured properties of the compacted mixture. In addition to the Marshall parameters, the Maximum Specific Gravity (GMM) test was conducted to determine the maximum specific gravity of the asphalt mixture for each combination of Bengawan Solo River sand substitution and teak wood powder ash. The mixtures consisted of 0%, 1%, 2%, and 3% Bengawan Solo River sand substitution combined with teak wood powder ash contents of 0%, 0.4%, 0.8%, and 1.2%. The GMM results were subsequently used as one of the supporting parameters in determining the volumetric characteristics of the asphalt mixture, particularly VIM, VMA, and VFA. The results for each sand-substitution group are presented in Tables 9–12, while the subsequent Marshall results are discussed based on the corresponding mixture variations.

Table 9. Examination of Specific Gravity Data on a Mixture of Bengawan Solo River Sand Additives 0% and Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)

No.	Substitution of Bengawan Solo sand (0%) + Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)			Testing of Asphalt Mixture Specific Gravity (GMM)							
	Specimen No.			1	2	1	2	1	2	1	2
1	Weight of Bottle + Specimen		Grm	1.366	1.366	1.366	1.366	1.366	1.366	1.366	1.366
2	Weight of Bottle		Grm	766	766	766	766	766	766	766	766
3	Weight of Specimen	(1 – 2)	Grm	600	600	600	600	600	600	600	600
4	Weight of Bottle + Specimen + Water (Calibration Limit)		Grm	2.245	2.229	2.249	2.229	2.231	2.233	2.225	2.243
5	Weight of Bottle + Water (Calibration Limit)		Grm	1.892	1.892	1.892	1.892	1.892	1.892	1.892	1.892
6	Weight of Water	(4 – 5)	Grm	353	337	357	337	339	341	333	351
7	Specimen Volume	(3 – 6)	Grm	247	263	243	263	261	259	267	249
8	Maximum Specific Gravity (GMM)	(3 : 7)	Grm/cc	2,429	2,281	2,469	2,281	2,299	2,317	2,247	2,410
9	Water Temperature (T)		Grm	25	25	25	25	25	25	25	25
10	Temperature Correction		Grm	1	1	1	1	1	1	1	1
11	Maximum Specific Gravity (GMM)	(8 × 10)	Grm/cc	2,429	2,281	2,469	2,281	2,299	2,317	2,247	2,410
Average GMM					**2,355**		**2,375**		**2,308**		**2,328**
				0%		**0,4%**		**0,8%**		**1,2%**	

The GMM test for the mixture without Bengawan Solo River sand substitution produced average values of 2.355, 2.375, 2.308, and 2.328 g/cm³ for teak wood powder ash contents of 0%, 0.4%, 0.8%, and 1.2%, respectively. The highest average GMM value was obtained at 0.4% teak wood powder ash, while the lowest value occurred at 0.8% ash content. The individual specimen results also showed differences within each ash-content variation, reflecting variations in the measured specimen volume during the GMM testing process. The GMM values provide the maximum specific gravity reference required for calculating the volumetric properties of the compacted asphalt mixture. The decrease in average GMM from 2.375 g/cm³ at 0.4% ash to 2.308 g/cm³ at 0.8% ash indicates that the addition of the ash did not produce a linear change in mixture specific gravity. At 1.2% ash, the average GMM increased slightly to 2.328 g/cm³, although it remained below the value obtained at 0.4%. These results demonstrate that the GMM characteristics of the P0 mixture varied with the proportion of teak wood powder ash.

Table 10. Examination of Specific Gravity Data on a Mixture of Bengawan Solo River Sand Additives 1% and Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)

No.	Substitution of Bengawan Solo sand (1%) + Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)			Testing of Asphalt Mixture Specific Gravity (GMM)							
	Specimen No.			1	2	1	2	1	2	1	2
1	Weight of Bottle + Specimen		Grm	1.366	1.366	1.366	1.366	1.366	1.366	1.366	1.366
2	Weight of Bottle		Grm	766	766	766	766	766	766	766	766
3	Weight of Specimen	(1 − 2)	Grm	600	600	600	600	600	600	600	600
4	Weight of Bottle + Specimen + Water (Calibration Limit)		Grm	2.244	2.219	2.238	2.254	2.248	2.220	2.224	2.223
5	Weight of Bottle + Water (Calibration Limit)		Grm	1.892	1.892	1.892	1.892	1.892	1.892	1.892	1.892
6	Weight of Water	(4 − 5)	Grm	352	327	346	362	356	328	332	331
7	Specimen Volume	(3 − 6)	Grm	248	273	254	238	244	272	268	269
8	Maximum Specific Gravity (GMM)	(3 : 7)	Grm/cc	2,419	2,198	2,362	2,521	2,459	2,206	2,239	2,230
9	Water Temperature (T)		Grm	25	25	25	25	25	25	25	25
10	Temperature Correction		Grm	1	1	1	1	1	1	1	1
11	Maximum Specific Gravity (GMM)	(8 × 10)	Grm/cc	2,419	2,198	2,362	2,521	2,459	2,206	2,239	2,230
	Average GMM				**2,309**		**2,442**		**2,332**		**2,235**
				0%		**0,4%**		**0,8%**		**1,2%**	

The GMM results for the 1% Bengawan Solo River sand substitution show average values of 2.309, 2.442, 2.332, and 2.235 g/cm³ for 0%, 0.4%, 0.8%, and 1.2% teak wood powder ash, respectively. The highest average GMM was obtained at 0.4% ash, reaching 2.442 g/cm³, while the lowest value occurred at 1.2% ash with 2.235 g/cm³. The individual measurements also show relatively large differences between specimens, particularly in the 0.4% and 0.8% ash variations. These differences are reflected in the specimen volume values, which ranged from 238 to 273 g based on the reported calculation. The variation in GMM indicates that the addition of teak wood powder ash influenced the maximum specific gravity of the mixture when combined with 1% river-sand substitution. The reduction from 2.442 g/cm³ at 0.4% ash to 2.235 g/cm³ at 1.2% ash suggests a change in the composition and density characteristics of the mixture. The GMM values obtained from this group were subsequently used in the volumetric analysis of the corresponding P1 mixtures.

Table 11. Examination of Specific Gravity Data on a Mixture of Bengawan Solo River Sand Additives 2% and Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)

No.	Substitution of Bengawan Solo sand (2%) + Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)			Testing of Asphalt Mixture Specific Gravity (GMM)							
	Specimen No.			1	2	1	2	1	2	1	2
1	Weight of Bottle + Specimen		Grm	1.366	1.366	1.366	1.366	1.366	1.366	1.366	1.366
2	Weight of Bottle		Grm	766	766	766	766	766	766	766	766
3	Weight of Specimen	(1 − 2)	Grm	600	600	600	600	600	600	600	600
4	Weight of Bottle + Specimen + Water (Calibration Limit)		Grm	2.246	2.228	2.225	2.252	2.240	2.228	2.253	2.240
5	Weight of Bottle + Water (Calibration Limit)		Grm	1.892	1.892	1.892	1.892	1.892	1.892	1.892	1.892
6	Weight of Water	(4 − 5)	Grm	354	336	333	360	348	336	361	348
7	Specimen Volume	(3 − 6)	Grm	246	264	267	240	252	264	239	252
8	Maximum Specific Gravity (GMM)	(3 : 7)	Grm/cc	2,439	2,273	2,247	2,500	2,381	2,273	2,510	2,381
9	Water Temperature (T)		Grm	25	25	25	25	25	25	25	25
10	Temperature Correction		Grm	1	1	1	1	1	1	1	1
11	Maximum Specific Gravity (GMM)	(8 × 10)	Grm/cc	2,439	2,273	2,247	2,500	2,381	2,273	2,510	2,381
	Average GMM				**2,356**		**2,374**		**2,327**		**2,446**
				0%		**0,4%**		**0,8%**		**1,2%**	

For the 2% Bengawan Solo River sand substitution, the average GMM values were 2.356, 2.374, 2.327, and 2.446 g/cm³ for teak wood powder ash contents of 0%, 0.4%, 0.8%, and 1.2%, respectively. Unlike the P0 and P1 groups, the highest GMM value in this group occurred at the highest ash content of 1.2%, reaching 2.446 g/cm³. The lowest average value was recorded at 0.8% ash, with a GMM of 2.327 g/cm³. The individual GMM results also varied between specimens, with the highest individual value of 2.510 g/cm³ occurring in the P2A1.2 variation. The relatively high GMM at 1.2% ash indicates that the combination of 2% river-sand substitution and the higher ash content produced a mixture with comparatively high maximum specific gravity. Nevertheless, the GMM value itself does not directly determine the optimum mixture because it must be evaluated together with the resulting VIM, VMA, VFA, stability, flow, and MQ values. The P2 GMM results therefore provide an important basis for the subsequent Marshall analysis and comparison of the four P2 variations.

Table 12. Examination of Specific Gravity Data on a Mixture of Bengawan Solo River Sand Additives 3% and Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)

No.	Substitution of Bengawan Solo sand (3%) + Teak Sawdust Ash (0%, 0.4%, 0.8%, 1.2%)			Testing of Asphalt Mixture Specific Gravity (GMM)							
	Specimen No.			1	2	1	2	1	2	1	2
1	Weight of Bottle + Specimen		Grm	1.366	1.366	1.366	1.366	1.366	1.366	1.366	1.366
2	Weight of Bottle		Grm	766	766	766	766	766	766	766	766
3	Weight of Specimen	(1 – 2)	Grm	600	600	600	600	600	600	600	600
4	Weight of Bottle + Specimen + Water (Calibration Limit)		Grm	2.242	2.234	2.213	2.241	2.225	2.247	2.241	2.222
5	Weight of Bottle + Water (Calibration Limit)		Grm	1.892	1.892	1.892	1.892	1.892	1.892	1.892	1.892
6	Weight of Water	(4 – 5)	Grm	350	342	321	349	333	355	349	330
7	Specimen Volume	(3 – 6)	Grm	250	258	279	251	267	245	251	270
8	Maximum Specific Gravity (GMM)	(3 : 7)	Grm/cc	2,400	2,326	2,151	2,390	2,247	2,449	2,390	2,222
9	Water Temperature (T)		Grm	25	25	25	25	25	25	25	25
10	Temperature Correction		Grm	1	1	1	1	1	1	1	1
11	Maximum Specific Gravity (GMM)	(8 × 10)	Grm/cc	2,400	2,326	2,151	2,390	2,247	2,449	2,390	2,222
	Average GMM				**2,363**		**2,270**		**2,348**		**2,306**
				0%		**0,4%**		**0,8%**		**1,2%**	

The GMM results for the 3% Bengawan Solo River sand substitution produced average values of 2.363, 2.270, 2.348, and 2.306 g/cm³ for the four teak wood powder ash contents. The highest average GMM was obtained for P3A0 at 2.363 g/cm³, while the lowest was recorded for P3A0.4 at 2.270 g/cm³. The individual results show substantial variation, particularly for P3A0.4, where the GMM values were 2.151 and 2.390 g/cm³. At 0.8% ash, the individual values increased to 2.247 and 2.449 g/cm³, resulting in an average of 2.348 g/cm³. The 1.2% ash variation produced an average GMM of 2.306 g/cm³, which was slightly lower than the P3A0 and P3A0.8 variations. These results indicate that the relationship between teak wood powder ash content and GMM was not linear at the 3% river-sand substitution level. The GMM data from P3 were subsequently used as the basis for calculating the volumetric characteristics and evaluating the Marshall performance of the corresponding mixtures.

Overall, the GMM results demonstrate that changes in Bengawan Solo River sand substitution and teak wood powder ash content produced different maximum specific gravity characteristics across the tested mixtures. The average GMM values for the P0 group ranged from 2.308 to 2.375 g/cm³, while those for P1 ranged from 2.235 to 2.442 g/cm³. The P2 group showed average values ranging from 2.327 to 2.446 g/cm³, whereas the P3 group ranged from 2.270 to 2.363 g/cm³. These variations confirm that the maximum specific gravity was affected by the combination of aggregate substitution and additional fine material. However, GMM should not be interpreted independently because its principal role in this study is to support the calculation and interpretation of the volumetric characteristics of the asphalt mixture. Therefore, the GMM results in Tables 9–12 are used as the foundation for evaluating the subsequent Marshall parameters, including VIM, VMA, VFA, stability, flow, and MQ.

Evaluation of Marshall Test Results and Determination of the Optimum Mixture

The Marshall test results were evaluated to determine the effect of Bengawan Solo River sand substitution and teak wood powder ash addition on the performance of the AC-WC mixture. The evaluation covered the volumetric parameters of Void in the Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFB), as well as the mechanical parameters of stability, flow, and Marshall Quotient (MQ). The test results were compared with the requirements of the 2025 Bina

Marga Specification to determine the level of compliance of each mixture variation. Four levels of Bengawan Solo River sand substitution were investigated, namely 0%, 1%, 2%, and 3%, while the teak wood powder ash contents were 0%, 0.4%, 0.8%, and 1.2%. The evaluation was conducted both on the average Marshall characteristics of each variation and on the fulfillment of the specified requirements for each mixture. The results for the 3% Bengawan Solo River sand substitution group are specifically summarized in Table 13, while the complete recapitulation of all mixture variations is presented in Table 14.

Table 13. Recapitulation of Average Marshall Test Results for 3% Bengawan Solo River Sand Substitution with 0%, 0.4%, 0.8%, and 1.2% Teak Wood Powder Ash

Test Parameter	Test Specimen Variations				Specification
	P3A0	P3A0.4	P3A0.8	P3A1.2	
Void in the Mix (VIM)	3.39	0.90	4.63	3.92	3.0–5.0%
Void in Mineral Aggregate (VMA)	21.78	22.89	23.26	24.07	Min. 15%
Void Filled with Asphalt (VFA)	84.59	96.11	80.09	83.72	Min. 65%
Stability	831.17	818.08	821.35	824.62	Min. 800 kg
Flow	4.13	3.90	3.10	3.43	2.0–4.0 mm
Marshall Quotient (MQ)	201.51	210.71	279.71	245.19	Min. 250 kg/mm

Source: Research Results, 2026

Table 13 indicates that the 3% Bengawan Solo River sand substitution group exhibited different responses to the addition of teak wood powder ash across the investigated contents. The P3A0 variation produced VIM of 3.39%, VMA of 21.78%, VFA of 84.59%, and stability of 831.17 kg, but its flow of 4.13 mm and MQ of 201.51 kg/mm did not satisfy the specified requirements. The P3A0.4 variation showed an even more pronounced reduction in VIM, reaching only 0.90%, although its VMA and VFA remained relatively high at 22.89% and 96.11%, respectively. The P3A0.8 variation provided the most favorable result within the P3 group, with VIM of 4.63%, VMA of 23.26%, VFA of 80.09%, stability of 821.35 kg, flow of 3.10 mm, and MQ of 279.71 kg/mm. Meanwhile, P3A1.2 maintained acceptable volumetric characteristics and flow, but its MQ of 245.19 kg/mm remained below the minimum requirement of 250 kg/mm. These results demonstrate that the 3% sand substitution level did not provide consistent compliance across all Marshall parameters, even though several individual parameters remained within the required limits.

The overall comparison in Table 14 provides a more comprehensive assessment because it evaluates every combination of Bengawan Solo River sand substitution and teak wood powder ash content against the applicable specification. At the 0% substitution level, P0A0 and P0A0.4 satisfied the volumetric and stability requirements but failed in flow and MQ, whereas P0A0.8 and P0A1.2 satisfied all evaluated parameters. At the 1% substitution level, several mixtures still experienced deficiencies, particularly in MQ, while P1A1.2 showed a VIM value of only 1.22% despite satisfying its other listed parameters. The 2% substitution group was different because P2A0, P2A0.4, P2A0.8, and P2A1.2 all satisfied the requirements for VIM, VMA, VFB, stability, flow, and MQ. In contrast, the 3% substitution group again showed several failures, including the excessive flow and insufficient MQ of P3A0, the low VIM and MQ of P3A0.4, and the insufficient MQ of P3A1.2. Therefore, Table 14 confirms that the 2% Bengawan Solo River sand substitution group provided the most consistent compliance among all investigated substitution levels.

Table 12. Determination of the Optimum Mixture Based on Marshall Characteristics

Description	Bengawan Solo Sand Content	Teak Wood Sawdust Ash Content	Specification	Laboratory Test Results	Remarks
Bengawan Solo Sand 0% + Teak Wood Powder Ash 0%					

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Voids in the Mix (VIM)	0%	0%	3.0% - 5.0%	3.00 %	Comply
Voids in Mineral Aggregate (VMA)	0%	0%	Min 15%	27.71 %	Comply
Voids Filled with Bitumen (VFB)	0%	0%	Min 65%	86.27 %	Comply
Stability	0%	0%	Min 800 Kg	906.43 kg	Comply
Plastic Flow / *Flow*	0%	0%	2.0mm – 4.0mm	4.23 mm	Not Comply
Marshall Quotient	0%	0%	Min 250 Kg/mm	214.29 kg/mm	Not Comply
Bengawan Solo Sand 0% + Teak Wood Powder Ash 0.4%					
Voids in the Mix (VIM)	0%	0.4%	3.0% - 5.0%	3.57 %	Comply
Voids in Mineral Aggregate (VMA)	0%	0.4%	Min 15%	21.51 %	Comply
Voids Filled with Bitumen (VFB)	0%	0.4%	Min 65%	83.61 %	Comply
Stability	0%	0.4%	Min 800 Kg	876.98 kg	Comply
Plastic Flow / *Flow*	0%	0.4%	2.0mm – 4.0mm	4.56 mm	Not Comply
Marshall Quotient	0%	0.4%	Min 250 Kg/mm	192.32 kg/mm	Not Comply
Bengawan Solo Sand 0% + Teak Wood Powder Ash 0.8%					
Voids in the Mix (VIM)	0%	0.8%	3.0% - 5.0%	3.67 %	Comply
Voids in Mineral Aggregate (VMA)	0%	0.8%	Min 15%	23.82 %	Comply
Voids Filled with Bitumen (VFB)	0%	0.8%	Min 65%	84.61 %	Comply
Stability	0%	0.8%	Min 800 Kg	912.98 kg	Comply
Plastic Flow / *Flow*	0%	0.8%	2.0mm – 4.0mm	3.56 mm	Comply
Marshall Quotient	0%	0.8%	Min 250 Kg/mm	256.46 kg/mm	Comply
Bengawan Solo Sand 0% + Teak Wood Powder Ash 1.2%					
Voids in the Mix (VIM)	0%	1.2%	3.0% - 5.0%	3.74 %	Comply
Voids in Mineral Aggregate (VMA)	0%	1.2%	Min 15%	23.20 %	Comply
Voids Filled with Bitumen (VFB)	0%	1.2%	Min 65%	83.87 %	Comply
Stability	0%	1.2%	Min 800 Kg	873.73 kg	Comply
Plastic Flow / *Flow*	0%	1.2%	2.0mm – 4.0mm	2.86 mm	Comply
Marshall Quotient	0%	1.2%	Min 250 Kg/mm	305.49 kg/mm	Comply
Bengawan Solo Sand 1% + Teak Wood Powder Ash 0%					
Voids in the Mix (VIM)	1%	0%	3,0% - 5,0%	3.19 %	Comply
Voids in Mineral Aggregate (VMA)	1%	0%	Min 15%	23.41 %	Comply
Voids Filled with Bitumen (VFB)	1%	0%	Min 65%	86.50 %	Comply
Stability	1%	0%	Min 800 Kg	870.44 kg	Comply
Plastic Flow / *Flow*	1%	0%	2,0mm – 4,0mm	3.50 mm	Comply
Marshall Quotient	1%	0%	Min 250 Kg/mm	248.70 kg/mm	Not Comply
Bengawan Solo Sand 1% + Teak Wood Powder Ash 0.4%					
Voids in the Mix (VIM)	1%	0.4%	3,0% - 5,0%	2.90 %	Comply
Voids in Mineral Aggregate (VMA)	1%	0.4%	Min 15%	18.76 %	Comply

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Voids Filled with Bitumen (VFB)	1%	0.4%	Min 65%	84.58 %	Comply
Stability	1%	0.4%	Min 800 Kg	870.44 kg	Comply
Plastic Flow / *Flow*	1%	0.4%	2,0mm – 4,0mm	3.83 mm	Comply
Marshall Quotient	1%	0.4%	Min 250 Kg/mm	227.27 kg/mm	Not Comply
Bengawan Solo Sand 1% + Teak Wood Powder Ash 0.8%					
Voids in the Mix (VIM)	1%	0.8%	3,0% - 5,0%	4.98 %	Comply
Voids in Mineral Aggregate (VMA)	1%	0.8%	Min 15%	24.06 %	Comply
Voids Filled with Bitumen (VFB)	1%	0.8%	Min 65%	79.43 %	Comply
Stability	1%	0.8%	Min 800 Kg	880.25 kg	Comply
Plastic Flow / *Flow*	1%	0.8%	2,0mm – 4,0mm	3.60 mm	Comply
Marshall Quotient	1%	0.8%	Min 250 Kg/mm	244.51 kg/mm	Not Comply
Bengawan Solo Sand 1% + Teak Wood Powder Ash 1.2%					
Voids in the Mix (VIM)	1%	1.2%	3,0% - 5,0%	1.22 %	Not Comply
Voids in Mineral Aggregate (VMA)	1%	1.2%	Min 15%	24.60 %	Comply
Voids Filled with Bitumen (VFB)	1%	1.2%	Min 65%	94.99 %	Comply
Stability	1%	1.2%	Min 800 Kg	880.25 kg	Comply
Plastic Flow / *Flow*	1%	1.2%	2,0mm – 4,0mm	3.26 mm	Comply
Marshall Quotient	1%	1.2%	Min 250 Kg/mm	270.02 kg/mm	Comply
Bengawan Solo Sand 2% + Teak Wood Powder Ash 0%					
Voids in the Mix (VIM)	2%	0%	3,0% - 5,0%	3.86 %	Comply
Voids in Mineral Aggregate (VMA)	2%	0%	Min 15%	22.39 %	Comply
Voids Filled with Bitumen (VFB)	2%	0%	Min 65%	82.74 %	Comply
Stability	2%	0%	Min 800 Kg	854.08 %	Comply
Plastic Flow / *Flow*	2%	0%	2,0mm – 4,0mm	3.30 mm	Comply
Marshall Quotient	2%	0%	Min 250 Kg/mm	258.51 kg/mm	Comply
Bengawan Solo Sand 2% + Teak Wood Powder Ash 0.4%					
Voids in the Mix (VIM)	2%	0.4%	3,0% - 5,0%	4.42 %	Comply
Voids in Mineral Aggregate (VMA)	2%	0.4%	Min 15%	22.26 %	Comply
Voids Filled with Bitumen (VFB)	2%	0.4%	Min 65%	80.14%	Comply
Stability	2%	0.4%	Min 800 Kg	850.80 kg	Comply
Plastic Flow / *Flow*	2%	0.4%	2,0mm – 4,0mm	2.62 mm	Comply
Marshall Quotient	2%	0.4%	Min 250 Kg/mm	323.50 kg/mm	Comply
Bengawan Solo Sand 2% + Teak Wood Powder Ash 0.8%					
Voids in the Mix (VIM)	2%	0.8%	3,0% - 5,0%	4.48 %	Comply
Voids in Mineral Aggregate (VMA)	2%	0.8%	Min 15%	23.84 %	Comply
Voids Filled with Bitumen (VFB)	2%	0.8%	Min 65%	81.19 %	Comply
Stability	2%	0.8%	Min 800 Kg	931.61 kg	Comply
Plastic Flow / *Flow*	2%	0.8%	2,0mm – 4,0mm	3.23 mm	Comply

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Marshall Quotient	2%	0.8%	Min 250 Kg/mm	288.73 kg/mm	Comply
Bengawan Solo Sand 2% + Teak Wood Powder Ash 1.2%					
Voids in the Mix (VIM)	2%	1.2%	3,0% - 5,0%	4.19 %	Comply
Voids in Mineral Aggregate (VMA)	2%	1.2%	Min 15%	19.70 %	Comply
Voids Filled with Bitumen (VFB)	2%	1.2%	Min 65%	78.80 %	Comply
Stability	2%	1.2%	Min 800 Kg	965.34 kg	Comply
Plastic Flow / *Flow*	2%	1.2%	2,0mm – 4,0mm	3.36 mm	Comply
Marshall Quotient	2%	1.2%	Min 250 Kg/mm	287.30 kg/mm	Comply
Bengawan Solo Sand 3% + Teak Wood Powder Ash 0%					
Voids in the Mix (VIM)	3%	0%	3,0% - 5,0%	3.39 %	Comply
Voids in Mineral Aggregate (VMA)	3%	0%	Min 15%	21.78 %	Comply
Voids Filled with Bitumen (VFB)	3%	0%	Min 65%	84.59 %	Comply
Stability	3%	0%	Min 800 Kg	831.17 kg	Comply
Plastic Flow / *Flow*	3%	0%	2,0mm – 4,0mm	4.13 mm	Not Comply
Marshall Quotient	3%	0%	Min 250 Kg/mm	201.25 kg/mm	Not Comply
Bengawan Solo Sand 3% + Teak Wood Powder Ash 0.4%					
Voids in the Mix (VIM)	3%	0.4%	3,0% - 5,0%	0.90 %	Not Comply
Voids in Mineral Aggregate (VMA)	3%	0.4%	Min 15%	22.89 %	Comply
Voids Filled with Bitumen (VFB)	3%	0.4%	Min 65%	96.11 %	Comply
Stability	3%	0.4%	Min 800 Kg	818.08 %	Comply
Plastic Flow / *Flow*	3%	0.4%	2,0mm – 4,0mm	3.90 mm	Comply
Marshall Quotient	3%	0.4%	Min 250 Kg/mm	209.76 kg/mm	Not Comply
Bengawan Solo Sand 3% + Teak Wood Powder Ash 0.8%					
Voids in the Mix (VIM)	3%	0.8%	3,0% - 5,0%	4.63 %	Comply
Voids in Mineral Aggregate (VMA)	3%	0.8%	Min 15%	23.26 %	Comply
Voids Filled with Bitumen (VFB)	3%	0.8%	Min 65%	80.09 %	Comply
Stability	3%	0.8%	Min 800 Kg	821.35 kg	Comply
Plastic Flow / *Flow*	3%	0.8%	2,0mm – 4,0mm	3.10 mm	Comply
Marshall Quotient	3%	0.8%	Min 250 Kg/mm	264.95 kg/mm	Comply
Bengawan Solo Sand 3% + Teak Wood Powder Ash 1.2%					
Voids in the Mix (VIM)	3%	1.2%	3,0% - 5,0%	3.92 %	Comply
Voids in Mineral Aggregate (VMA)	3%	1.2%	Min 15%	24.07 %	Comply
Voids Filled with Bitumen (VFB)	3%	1.2%	Min 65%	83.72 %	Comply
Stability	3%	1.2%	Min 800 Kg	824.62 kg	Comply
Plastic Flow / *Flow*	3%	1.2%	2,0mm – 4,0mm	3.43 mm	Comply
Marshall Quotient	3%	1.2%	Min 250 Kg/mm	240.41 kg/mm	Not Comply

Source: Research Results, 2026

The comparison in Table 14 further shows that the 0% and 1% substitution groups still contained variations that failed to satisfy one or more Marshall requirements. For P0, the addition of 0.8% and 1.2% teak wood powder ash resulted in complete compliance, whereas the 0% and 0.4% ash variations were limited by excessive flow and insufficient MQ. For P1, the MQ values of P1A0, P1A0.4, and P1A0.8 remained below the minimum requirement, while P1A1.2 achieved the required MQ but had a VIM value of only 1.22%, which was outside the specified range. These results indicate that increasing the ash content does not necessarily improve all Marshall characteristics simultaneously because changes in filler content also influence the internal void structure and deformation behavior of the mixture. The P3 group presented a similar inconsistency, with P3A0 failing in flow and MQ, P3A0.4 failing in VIM and MQ, and P3A1.2 failing in MQ despite its acceptable VIM, VMA, VFB, stability, and flow values. Thus, the comparison demonstrates that the performance of the mixture depends on the combined proportion of sand substitution and teak wood powder ash rather than on either material individually.

The 2% Bengawan Solo River sand substitution group provided the most consistent overall performance among the four substitution levels evaluated in this study. P2A0 satisfied all requirements with VIM of 3.86%, VMA of 22.39%, VFB of 82.74%, stability of 854.08 kg, flow of 3.30 mm, and MQ of 258.51 kg/mm. P2A0.4 also satisfied all requirements and produced VIM of 4.42%, VMA of 22.26%, VFB of 80.14%, stability of 850.80 kg, flow of 2.62 mm, and MQ of 323.50 kg/mm. P2A0.8 and P2A1.2 likewise remained within the specified limits, with P2A1.2 providing the highest stability of 965.34 kg while maintaining a flow of 3.36 mm and MQ of 287.30 kg/mm. The complete compliance of all four P2 variations demonstrates that a 2% substitution level provides a more stable balance between aggregate structure, air voids, asphalt filling, strength, and deformation characteristics. Among these variations, P2A0.4 produced the highest MQ value of 323.50 kg/mm, indicating the highest stiffness according to the laboratory recapitulation. Therefore, the P2 group, particularly P2A0.4, provides the most favorable overall Marshall performance among the tested combinations.

Based on the complete evaluation of Tables 13 and 14, the optimum mixture is determined as P2A0.4, consisting of 2% Bengawan Solo River sand substitution and 0.4% teak wood powder ash. This variation satisfies all evaluated Marshall requirements, with VIM of 4.42%, VMA of 22.26%, VFB of 80.14%, stability of 850.80 kg, flow of 2.62 mm, and MQ of 323.50 kg/mm. The combination provides a relatively low flow value while maintaining stability above the minimum requirement, resulting in a high Marshall Quotient that indicates a favorable stiffness-to-deformation relationship. Although P2A1.2 produces a higher stability value of 965.34 kg, its MQ of 287.30 kg/mm is lower than the value obtained by P2A0.4, while P2A0.8 also produces a lower MQ of 288.73 kg/mm. The P2A0.4 variation therefore offers the most balanced performance when all volumetric and mechanical parameters are considered simultaneously rather than selecting the mixture solely according to its highest stability. The findings also confirm that the 2% Bengawan Solo River sand substitution level is more consistent than the 0%, 1%, and 3% levels because all four P2 variations satisfy the specified Marshall criteria. Accordingly, P2A0.4 is selected as the optimum mixture for the AC-WC mixture investigated in this study.

CONCLUSION

Based on the analysis of the research data, the modified Asphalt Concrete–Wearing Course (AC-WC) mixture using Bengawan Solo River sand substitution and teak wood powder ash addition produced different Marshall characteristics depending on the combination of substitution and ash content. Based on the overall comparison of the Marshall parameters and the 2025 Bina Marga Specification, the most consistent performance was obtained from the 2% Bengawan Solo River sand substitution group (P2), in which all variations from 0% to 1.2% teak wood powder ash satisfied the specified volumetric and mechanical requirements. Among these variations, P2A0.4, consisting of 2% Bengawan Solo River sand substitution and 0.4% teak wood powder ash, showed the highest overall Marshall Quotient, reaching approximately 323.56 kg/mm, while maintaining VIM, VMA, VFA, stability, and flow within the required limits. The P2A0.4 mixture recorded VIM of 4.42%, VMA of 22.26%, VFA of 80.14%, stability of 850.80 kg, and flow of approximately 2.63 mm, indicating a balanced relationship between volumetric characteristics, strength, and deformation. The consistency of the P2 group was also reflected by its VIM range of 3.86–4.48%, VMA of 19.70–23.84%, VFA of 78.80–82.74%, stability of 850.80–965.34 kg, flow of 2.63–3.36 mm, and MQ of 262.92–323.56

kg/mm, all of which remained within the specified limits. Therefore, based on the complete Marshall evaluation, P2A0.4 is considered the optimum mixture and has the potential to be applied as an AC-WC pavement mixture because it provides the most balanced performance among the tested combinations.

The use of Bengawan Solo River sand substitution and teak wood powder ash also influenced the stability and mechanical behavior of the modified AC-WC mixture, although the response varied according to the proportion of each material. The lowest average stability among the tested combinations occurred in P3A0.4, with a value of 818.08 kg, which nevertheless remained above the minimum stability requirement of 800 kg, while the highest stability was obtained from P2A1.2, reaching 965.34 kg. The results show that increasing the sand substitution level did not continuously increase mixture stability because the 3% substitution group generally produced lower mechanical performance and several MQ values below the required 250 kg/mm. In contrast, the 2% substitution group demonstrated the most consistent mechanical performance, with stability values ranging from 850.80 to 965.34 kg and Marshall Quotient values remaining within the specification. The 3% substitution group also showed problems in several parameters, including P3A0 with flow of 4.13 mm and MQ of 201.51 kg/mm, P3A0.4 with VIM of only 0.90% and MQ of 210.71 kg/mm, and P3A1.2 with MQ of 245.19 kg/mm. These findings indicate that the combination of Bengawan Solo River sand and teak wood powder ash can modify the internal structure, stiffness, and deformation characteristics of the AC-WC mixture, but the proportion must be controlled to maintain compliance with the required specifications. Thus, the research results support the selection of 2% Bengawan Solo River sand substitution with 0.4% teak wood powder ash (P2A0.4) as the most favorable combination for the modified AC-WC mixture based on the overall Marshall performance.

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