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Analysis of Asphalt Concrete Wearing Course (AC-WC) with the Addition of Bodri River Sand and Styrene-Butadiene Rubber (SBR) for Road Pavements

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Abstract

Road pavement in Indonesia commonly uses Asphalt Concrete Wearing Course (AC-WC) as the surface layer, which plays an important role in providing traffic comfort and pavement performance. This study aims to evaluate the characteristics of AC-WC mixtures modified with Styrene-Butadiene Rubber (SBR) and Bodri River sand and to determine the optimum mixture based on Marshall parameters. The use of these locally available materials is expected to contribute to the development of alternative asphalt mixture compositions while supporting the utilization of local resources. An experimental method was employed through laboratory specimen preparation and Marshall testing. The specimens were prepared using variations of SBR content of 0%, 2%, 4%, and 6% and Bodri River sand content of 0%, 1%, 3%, and 5%. Marshall testing was conducted to determine VMA, VIM, VFB, stability, flow, and Marshall Quotient values. Based on the test results, the best Job Mix Design was obtained from the mixture containing 3% Bodri River sand and 4% SBR (P3S4). This mixture produced VMA of 19.33%, VIM of 3.53%, VFB of 81.73%, stability of 1,119.14 kg, flow of 3.00 mm, and Marshall Quotient of 364.32 kg/mm. The results indicate that the P3S4 mixture satisfied the specified Marshall requirements and provided favorable volumetric and mechanical characteristics. Therefore, the combination of 3% Bodri River sand and 4% SBR can be considered a suitable mixture variation for AC-WC pavement applications based on the results of this study.

Keywords: *Asphalt Concrete Wearing Course, Bodri River Sand, Marshall, Styrene-Butadiene Rubber, Pavement.*

INTRODUCTION

Asphalt pavement is a fundamental component of terrestrial transportation systems because it provides the structural surface required to sustain mobility, freight movement, and economic activity, while its performance is closely associated with the ability of pavement layers to withstand repeated traffic loading throughout their service life (Patiku et al., 2025). In flexible pavement structures, asphalt concrete is commonly arranged into several functional layers, including Asphalt Concrete–Wearing Course (AC-WC), Asphalt Concrete–Binder Course (AC-BC), and Asphalt Concrete–Base, which collectively contribute to the structural and functional performance of road infrastructure (Assa et al., 2022). The AC-WC layer occupies the uppermost position and is directly exposed to traffic loading, environmental fluctuations, moisture, and temperature variation, making its mechanical stability and durability critical to pavement serviceability. Recent research has increasingly focused on improving AC-WC performance through the optimization of aggregate composition, alternative local materials, and binder modification because conventional mixtures may experience deformation, cracking, moisture damage, and progressive loss of structural integrity under demanding service conditions (Gunawan et al., 2023). The growing emphasis on sustainable pavement engineering has also encouraged the utilization of locally available and alternative materials as substitutes for conventional aggregate resources, particularly when such materials can maintain engineering performance while reducing material transportation and resource consumption (Machsus et al., 2025). This development places the selection of locally available fine aggregate and the modification of asphalt binder within a broader research agenda concerning performance-oriented and resource-efficient pavement materials.

The performance of AC-WC is fundamentally governed by the interaction between aggregate gradation, particle characteristics, asphalt binder properties, and mixture volumetrics, meaning that changes in one material component can alter the mechanical response of the entire mixture. Research on alternative fine aggregates indicates that locally sourced materials can potentially satisfy AC-WC requirements when their physical properties, gradation, and proportion are appropriately controlled, although their suitability cannot be generalized across different geological and material conditions (Anugerah et al., 2023). The use of river sand has attracted particular attention because its availability may provide a practical source of fine aggregate, yet its relatively smooth particle morphology can influence interparticle friction and aggregate interlock differently from crushed fine aggregate (Khoerotunnisa & Budiman, 2023). Studies involving alternative mineral fillers and fine materials further demonstrate that the characteristics of the fine fraction can substantially influence mixture stability, density, and asphalt–aggregate interaction, indicating that aggregate substitution should be evaluated through the overall behavior of the mixture rather than through material availability alone (Akbar & Hartatik, 2025). The engineering relevance of this issue becomes more pronounced when locally available river sand is introduced into an AC-WC mixture because its physical characteristics may simultaneously affect gradation, workability, void structure, and load-bearing mechanisms. A material that performs adequately in one asphalt mixture therefore cannot automatically be assumed to provide equivalent performance when combined with a different aggregate structure or modified binder.

Alongside aggregate optimization, asphalt binder modification has become an important strategy for addressing the limitations of conventional asphalt under repeated traffic and environmental loading. Conventional penetration-grade asphalt may exhibit susceptibility to permanent deformation at elevated temperatures and reduced resistance to cracking or stiffness-related deterioration under unfavorable thermal and loading conditions, motivating the development of polymer-modified binders with improved rheological characteristics. Previous investigations of rubber-modified asphalt have reported changes in Marshall characteristics and mixture behavior, although the magnitude and direction of improvement depend strongly on rubber type, dosage, binder properties, and mixture composition (Mahmuda et al., 2024). Research specifically examining rubber asphalt in AC-WC mixtures has also indicated that modified binders can produce different stability and volumetric characteristics compared with conventional penetration asphalt, demonstrating the importance of evaluating the modified binder within the complete mixture system rather than in isolation (Irwanto et al., 2023). At the material scale, Styrene-Butadiene Rubber (SBR) has received attention because its polymeric structure can improve elasticity and contribute to enhanced resistance against temperature-induced and traffic-related distress mechanisms (Gogoi et al., 2016). More recent investigations have further shown that SBR-based modification can influence the chemical composition and low-temperature characteristics of asphalt, confirming that polymer modification affects the binder response through mechanisms extending beyond simple changes in conventional physical properties (Xu et al., 2024). These findings establish a strong scientific basis for investigating SBR as a modifier while also indicating that its effectiveness must be assessed in relation to the aggregate structure into which the modified binder is incorporated.

The interaction between modified asphalt and aggregate becomes particularly important under environmental conditions in which water and repeated loading accelerate pavement deterioration. Research on AC-WC mixtures exposed to tidal flooding has demonstrated that water-related exposure can adversely affect pavement durability, emphasizing the importance of moisture resistance in mixture design (Labaso & Arifin, 2024). Experimental work involving polyethylene and fine slag aggregate similarly illustrates that both binder modification and alternative aggregate selection can influence the behavior of wearing-course mixtures subjected to water exposure, although the response depends on the specific material combination (Andry et al., 2023). Studies of modified asphalt composites have further established that combining polymeric materials within asphalt can alter the overall performance characteristics of the binder and potentially improve its suitability for pavement rehabilitation applications (Zhu & Li, 2023). The evidence indicates that improvements obtained from a modified binder cannot be evaluated independently from the aggregate system because the resulting mixture response is determined by the interfacial and structural relationship between binder, fine aggregate, coarse aggregate, and voids. This issue is particularly relevant for river sand because smoother particles may provide different mechanical interlocking and binder interaction compared with angular crushed sand, creating uncertainty regarding whether SBR modification can compensate for or enhance these characteristics. Existing studies consequently provide substantial evidence regarding either alternative fine aggregates or polymer-modified asphalt, yet comparatively limited attention has been directed toward their combined application within a single AC-WC mixture using a specific local river-sand source.

The remaining research gap is therefore not simply the absence of another alternative material study, but the limited empirical understanding of how a locally sourced fine aggregate and SBR-modified asphalt interact to determine the performance characteristics of an AC-WC mixture. Previous studies have commonly examined alternative aggregate materials, rubber-modified asphalt, or environmental durability as separate research dimensions, leaving uncertainty regarding the combined material mechanism and the resulting mixture response under a consistent experimental framework. The use of local aggregate also requires rigorous characterization because aggregate quality, specific gravity, water absorption, and material passing the No. 200 sieve can influence mixture behavior and must be consistent with applicable technical requirements (Badan Standardisasi Nasional, 2016). Asphalt binder characterization likewise requires controlled evaluation of fundamental properties such as specific gravity and softening point because these parameters provide essential evidence regarding the physical suitability of the binder for mixture development (Badan Standardisasi Nasional, 2011). The absence of an integrated evaluation is scientifically significant because a modification that improves binder elasticity may not necessarily generate superior mixture stability when combined with an aggregate possessing different surface and gradation characteristics. From an engineering perspective, identifying an effective combination of Bodri River sand and SBR is also relevant to the development of locally adaptable pavement materials that can reduce dependence on conventional aggregate sources while maintaining acceptable mechanical performance. This research consequently positions the Bodri River sand–SBR combination as an integrated material system whose performance must be determined experimentally rather than inferred from the independent behavior of its components.

This study aims to analyze the performance characteristics of AC-WC mixtures incorporating Bodri River sand as fine aggregate and Styrene-Butadiene Rubber (SBR) as an asphalt modifier through a controlled experimental approach. The research evaluates the resulting mixture characteristics to determine how the interaction between local river sand and SBR-modified asphalt influences the suitability of the AC-WC mixture for road pavement applications. The study is designed to establish an empirical relationship between material composition and mixture performance, thereby providing a more integrated understanding of the role of locally sourced fine aggregate and polymer modification within asphalt concrete. Its theoretical contribution lies in extending the understanding of AC-WC material interaction by examining aggregate and binder modification as interconnected components rather than independent variables. Its methodological contribution lies in providing an experimental framework for assessing a specific local river-sand source in combination with SBR-modified asphalt under controlled mixture conditions. The resulting findings are expected to provide an evidence-based reference for the development of alternative AC-WC materials that combine local resource utilization with improved pavement performance. More broadly, the research seeks to contribute to performance-oriented pavement engineering by identifying whether the Bodri River sand–SBR combination can provide a technically viable material configuration for durable road pavement applications.

RESEARCH METHODS

This study employed an empirical laboratory experimental design to investigate the performance of Asphalt Concrete–Wearing Course (AC-WC) incorporating Bodri River sand and Styrene-Butadiene Rubber (SBR) as alternative fine aggregate and asphalt modifier, respectively. The experimental program was conducted at the Road Laboratory, Faculty of Engineering, Universitas Islam Sultan Agung, Semarang, using penetration-grade 60/70 asphalt produced by PT Semarang Multi Cons, coarse aggregate, fine aggregate, Portland cement as filler, Bodri River sand collected from Wonosari Village, Pegandon District, Kendal Regency, and SBR supplied by PT Synthetic Rubber Indonesia (SRI). Initial material characterization was conducted to determine the physical and mechanical properties of the constituent materials, including aggregate and asphalt properties, before the mixture production stage. The experimental variables consisted of Bodri River sand contents of 0%, 1%, 3%, and 5% as partial fine-aggregate substitution and SBR contents of 0%, 2%, 4%, and 6% as asphalt modification levels, resulting in a systematic combination of aggregate and binder modifications. The use of river sand as an alternative fine aggregate was considered based on its potential to modify the characteristics of the fine aggregate fraction and consequently influence the volumetric and mechanical behavior of AC-WC mixtures (Khoerotunnisa & Budiman, 2023). Previous research has similarly demonstrated that alternative fine aggregates can be incorporated into AC-WC mixtures when their physical characteristics and proportions are appropriately controlled to maintain acceptable mixture performance (Anugerah et al., 2023). Each material combination was proportioned through a job mix design, followed by heating, mixing, and mechanical compaction using a Marshall Compaction Hammer to produce cylindrical AC-WC specimens under controlled laboratory conditions.

The prepared specimens were subsequently evaluated using the Marshall test to determine the volumetric and mechanical characteristics of each AC-WC mixture. Before testing, the compacted specimens were conditioned by immersion in water maintained at 60°C for the prescribed conditioning period and subsequently placed in the Marshall testing apparatus for loading at a constant deformation rate of 51 mm/min. The measured performance parameters comprised Marshall stability, flow, Marshall Quotient (MQ), Void in the Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Bitumen (VFB), which collectively represent the principal mechanical and volumetric characteristics of asphalt mixtures. The Marshall testing procedure was selected as the principal experimental validation method because it provides quantitative measurements of mixture stability and deformation characteristics and has been applied in previous investigations of AC-WC mixtures containing modified asphalt materials (Gunawan et al., 2023). The use of Marshall characteristics as performance indicators is also consistent with research comparing conventional penetration asphalt and rubber-modified asphalt in AC-WC mixtures, where stability, flow, and volumetric properties were used to assess changes in mixture behavior (Irwanto et al., 2023). The performance of each mixture was validated by comparing the measured parameters with the applicable AC-WC requirements specified by Bina Marga and by examining the consistency of the results across the different SBR and Bodri River sand proportions. The resulting data were analyzed comparatively to identify the influence of increasing SBR and Bodri River sand contents and to determine the combination that produced the most favorable overall performance based on stability, flow, MQ, VIM, VMA, and VFB.

RESULTS AND DISCUSSION

Characteristics of Asphalt and Aggregate Materials

The initial material characterization was conducted to determine the suitability of the asphalt and aggregate materials used in the AC-WC mixture. The materials included 60/70 penetration asphalt, coarse aggregate, medium aggregate, fine aggregate, and other constituent materials used in the mixture. The asphalt used in this study was 60/70 penetration asphalt, commonly identified as Pertamina asphalt, and its test results were compared with the requirements of the Bina Marga 2025 General Specifications. The aggregate examination was also conducted to identify the physical and mechanical characteristics required before the material was incorporated into the mixture. These initial examinations are important because the properties of the constituent materials influence the quality and performance of the resulting AC-WC mixture. The assessment therefore focused on whether the measured material properties complied with the applicable specifications. The results of the asphalt and aggregate examinations are presented in Table 1 and Table 2.

Table 1. Results of Physical and Mechanical Properties Testing of Penetration-Grade 60/70 Asphalt

No.	Type of Test	Specification	Asphalt Type Pen. 60/70	Test Result	Remarks
1	Penetration at 25°C (0.1 mm)	SNI 2456:2011	60–70	65	Complies
2	Kinematic Viscosity at 135°C (cSt)	ASTM D2170-10	≥ 300	370	Complies
3	Softening Point (°C)	SNI 2434:2011	≥ 48	50	Complies
4	Ductility at 25°C (cm)	SNI 2432:2011	≥ 100	130	Complies
5	Flash Point (°C)	SNI 2433:2011	≥ 232	275	Complies
6	Solubility in Trichloroethylene (%)	AASHTO T44-14	≥ 99	99.5	Complies
7	Specific Gravity	SNI 2441:2011	≥ 1.0	1.026	Complies
8	Paraffin Wax Content (%)	SNI 03-3639-2002	≤ 2	1.5	Complies

The results presented in Table 1 show that all examined properties of the 60/70 penetration asphalt complied with the specified requirements. The penetration value at 25°C was 65 (0.1 mm), which was within the required range of 60–70 (0.1 mm). The kinematic viscosity at 135°C reached 370 cSt, exceeding the minimum requirement of 300 cSt, while the softening point was 50°C compared with the minimum requirement of 48°C. The ductility at 25°C reached 130 cm, which was higher than the minimum requirement of 100 cm, indicating that the asphalt met the specified ductility criterion. The flash point was measured at 275°C against a minimum requirement of 232°C, while trichloroethylene solubility reached 99.5% against a minimum requirement of 99%. The specific gravity was 1.026 and the paraffin wax content was 1.5%, both of which also satisfied their respective requirements.

The compliance of the asphalt properties indicates that the binder was suitable for further use in the AC-WC mixture. The penetration value of 65 places the asphalt within the designated 60/70 penetration grade rather than at the boundary of the specification. The viscosity value also indicates that the asphalt possessed the required consistency at the test temperature, while the softening point satisfied the minimum criterion established in the specification. The ductility value of 130 cm further demonstrates that the binder met the required deformation characteristic under the specified test condition. The flash point result of 275°C was also substantially above the minimum specified value, providing compliance with the relevant safety-related material requirement. Based on the results presented in Table 1, the source document states that the tested 60/70 penetration asphalt fulfilled all specified requirements. This compliance establishes the asphalt as an acceptable binder for the subsequent mixture-design and performance-testing stages.

Table 2. Results of Physical and Mechanical Properties Testing of Aggregates

No.	Type of Examination	Method	Requirement	Result	Remarks
A. Coarse Aggregate					
1	**Coarse Aggregate Passing No. 200 Sieve**				
	Course Aggregate ½"	SNI ASTM C117:2012	Max. 1%	0.68%	Complies
	Medium Aggregate ¾"			0.70%	Complies
2	**Water Absorption of Coarse Aggregate**				
	Course Aggregate ½"	SNI 1969:2016	Max. 3%	1.36%	Complies
	Medium Aggregate ¾"			1.67%	Complies
3	**Specific Gravity of Coarse Aggregate**				
	Course Aggregate ½"	SNI 1969:2016	Min. 2.5%	2.63%	Complies
	Medium Aggregate ¾"			2.71%	Complies
B. Fine Aggregate					
1	**Fine Aggregate Passing No. 200 Sieve**				
	Stone Dust	SNI 03-4142-1996	Max. 15%	7.45%	Complies
	Sand			9.15%	Complies
2	**Water Absorption of Fine Aggregate**				
	Stone Dust	SNI 1970:2016	Max. 3%	2.41%	Complies
	Sand			2.19%	Complies
3	**Bulk Specific Gravity of Fine Aggregate**				
	Stone Dust	SNI 1970:2016	Min. 2.5%	2.55%	Complies
	Sand			2.68%	Complies

Table 2 presents the physical and mechanical examination of the coarse and fine aggregate fractions used in the study. For the coarse aggregate, the percentage passing the No. 200 sieve was 0.68% for the ½-inch coarse aggregate and 0.70% for the ¾-inch medium aggregate, with both values below the maximum requirement of 1%. Water absorption was 1.36% for the ½-inch coarse aggregate and 1.67% for the ¾-inch medium aggregate, both below the maximum requirement of 3%. The bulk specific gravity of the coarse aggregate fractions was 2.63 for the ½-inch material and 2.71 for the ¾-inch material, exceeding the minimum requirement of 2.5. These results demonstrate that the coarse aggregate fractions met the specified requirements for material passing, water absorption, and specific gravity. The fine aggregate properties were also examined as part of the same material characterization stage.

The fine aggregate examination included the stone dust and sand fractions, with the results used to establish their suitability for incorporation into the mixture. The measured percentage passing the No. 200 sieve was 7.45% for stone dust and 9.15% for sand, while their water absorption values were 2.41% and 2.19%, respectively. The bulk specific gravity values were 2.55 for stone dust and 2.68 for sand, indicating that both materials exceeded the minimum specific-gravity requirement of 2.5. These measurements provide the basic physical characteristics needed before the aggregate fractions are combined into the AC-WC gradation. The aggregate characterization also serves as an important reference because the study subsequently examines different proportions of Bodri River sand as an alternative fine aggregate. The source document states that the gradation examination was conducted to ensure that the aggregate particle sizes complied with the applicable ASTM, AASHTO, and SNI technical standards. Therefore, the material results in Table 2 provide the initial basis for evaluating the aggregate fractions before proceeding to the detailed sieve-analysis stage.

Aggregate Gradation and Mixture Composition

The aggregate gradation analysis was conducted to determine the particle-size distribution of each aggregate fraction used in the AC-WC mixture. This stage covered the ½-inch coarse aggregate, ¾-inch medium aggregate, fine aggregate, sand, filler, and Bodri River sand. The sieve analysis was carried out using SNI ASTM C136:2012 as the reference standard for determining aggregate particle-size distribution. The results were subsequently used to establish the combined aggregate gradation required for the AC-WC mixture. The gradation of each individual fraction is important because the interaction among coarse, medium, and fine particles affects the packing structure and void distribution of the mixture. The analysis also provides the basis for assessing whether the combined aggregate falls within the specified upper and lower gradation limits. The results of the individual aggregate gradation examinations are presented sequentially in Tables 3–10.

Table 3. Results of Sieve Analysis of ½-inch Coarse Aggregate

Sieve Size		Test I			Test II			Average
inch	mm	Retained (gr)	Retained (%)	Passing (%)	Retained (gr)	Retained (%)	Passing (%)	
1"	25							
3/4"	19		-	**100,00**		-	**100,00**	**100,00**
1/2"	12,5	1.482	49,40	**50,60**	1.479	49,30	**50,70**	**50,65**
3/8"	9,5	2.703	90,10	**9,90**	2.709	90,30	**9,70**	**9,80**
# 4	4,75	2.893	96,43	**3,57**	2.889	96,30	**3,70**	**3,64**
# 8	2,36	2.987	99,57	**0,43**	2.939	97,97	**2,03**	**1,23**
# 16	1,15	2.990	99,67	**0,33**	2.984	99,47	**0,53**	**0,43**
# 30	0,6	2.993	99,77	**0,23**	2.992	99,73	**0,27**	**0,25**
# 50	0,3	2.994	99,80	**0,20**	2.993	99,77	**0,23**	**0,22**
#100	0,15	2.996	99,87	**0,13**	2.997	99,90	**0,10**	**0,12**
# 200	0,075	2.998	99,93	**0,07**	2.998	99,93	**0,07**	**0,07**
Weight of Sample (gr)		3.000		3.000				

The ½-inch coarse aggregate analysis showed that 100% of the material passed the ¾-inch sieve and began to be retained at the ½-inch sieve. The average percentage passing the ½-inch sieve was 50.65%, indicating that approximately half of the material was distributed below this sieve size. The average percentage passing the 3/8-inch sieve was 9.80%, while the average percentage passing the No. 4 sieve was 3.64%. These values indicate that the material was predominantly composed of coarse particles, with only a relatively small fraction entering the finer aggregate range. The particle distribution of this fraction is important for establishing the coarse skeleton of the AC-WC mixture. The material was therefore suitable for further combination with the other aggregate fractions in the mixture-design process.

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Table 4. Results of Sieve Analysis of ¾-inch Medium Aggregate

Sieve Size		Test I			Test II			Average
inch	**mm**	**Retained (gr)**	**Retained (%)**	**Passing (%)**	**Retained (gr)**	**Retained (%)**	**Passing (%)**	
1"	25							
3/4"	19							
1/2"	12,5		-	**100,00**			**100,00**	**100,00**
3/8"	9,5	417	27,80	**72,20**	423	28,20	**71,80**	**72,00**
# 4	4,75	1.321	88,07	**11,93**	1.222	81,47	**18,53**	**15,23**
# 8	2,36	1.396	93,07	**6,93**	1.389	92,60	**7,40**	**7,17**
# 16	1,15	1.415	94,33	**5,67**	1.421	94,73	**5,27**	**5,47**
# 30	0,6	1.423	94,87	**5,13**	1.442	96,13	**3,87**	**4,50**
# 50	0,3	1.452	96,80	**3,20**	1.467	97,80	**2,20**	**2,70**
#100	0,15	1.482	98,80	**1,20**	1.484	98,93	**1,07**	**1,14**
# 200	0,075	1.491	99,40	**0,60**	1.493	99,53	**0,47**	**0,54**
Weight of Sample (gr)		1.500		1.500				

The ¾-inch medium aggregate was examined to determine the distribution of particles between the larger and finer sieve sizes. The results show that 100% of the material passed the ½-inch sieve and began to be retained at the 3/8-inch sieve. The average percentage passing the 3/8-inch sieve was 72.00%, while the percentage passing the No. 4 sieve was 15.23%. The average percentage passing the No. 8 sieve was 7.17%, followed by progressively smaller percentages at the finer sieve sizes. This distribution indicates that the medium aggregate provides an intermediate particle-size fraction between the coarse aggregate and the finer constituents. The results also indicate that the material complied with the applicable SNI ASTM C136:2012 requirements described in the source document.

Table 5. Results of Sieve Analysis of Fine Aggregate

Sieve Size		Test I			Test II			Average
inch	**mm**	**Retained (gr)**	**Retained (%)**	**Passing (%)**	**Retained (gr)**	**Retained (%)**	**Passing (%)**	
1"	25							
3/4"	19							
1/2"	12,5							
3/8"	9,5							
# 4	4,75	-	-	**100,00**	-	-	**100,00**	**100,00**
# 8	2,36	118	23,60	**76,40**	123	24,60	**75,40**	**75,90**
# 16	1,15	221	44,20	**55,80**	237	47,40	**52,60**	**54,20**
# 30	0,6	311	62,20	**37,80**	361	72,20	**27,80**	**32,80**
# 50	0,3	372	74,40	**25,60**	395	79,00	**21,00**	**23,30**
#100	0,15	422	84,40	**15,60**	426	85,20	**14,80**	**15,20**
# 200	0,075	459	91,80	**8,20**	456	91,20	**8,80**	**8,50**
Weight of Sample (gr)		500		500				

The fine aggregate gradation analysis was performed to determine the distribution of particles within the fine aggregate fraction used in the mixture. The analysis was conducted according to SNI ASTM C136:2012, covering the material passing the larger sieve sizes and being retained progressively through the finer sieve sizes. The results provide information on the proportion of particles available to occupy the spaces between the coarse and medium aggregate fractions. This characteristic is important because an appropriate fine aggregate distribution contributes to a more continuous combined gradation. The fine aggregate therefore functions as an important intermediate fraction in the development of the AC-WC aggregate structure. The results were subsequently considered together with the sand and filler fractions before the final aggregate combination was established. The fine aggregate analysis consequently forms an important link between the coarse aggregate skeleton and the finer components of the mixture.

Table 6. Results of Sieve Analysis of Sand

Sieve Size		Test I			Test II			Average
inch	mm	Retained (gr)	Retained (%)	Passing (%)	Retained (gr)	Retained (%)	Passing (%)	
1"	25	0	0	**100,00**	0	0	**100,00**	**100,00**
3/4"	19	0	0	**100,00**	0	0	**100,00**	**100,00**
1/2"	12,5	0	0	**100,00**	0	0	**100,00**	**100,00**
3/8"	9,5	0	0	**100,00**	0	0	**100,00**	**100,00**
# 4	4,75	0	0	**100,00**	0	0	**100,00**	**100,00**
# 8	2,36	0	0	**100,00**	0	0	**100,00**	**100,00**
# 16	1,15	0	0	**100,00**	0	0	**100,00**	**100,00**
# 30	0,6	0	0	**100,00**	0	0	**100,00**	**100,00**
# 50	0,3	297	59,40	**40,60**	287	57,40	**42,60**	**41,60**
#100	0,15	389	77,80	**22,20**	412	82,40	**17,60**	**19,90**
# 200	0,075	431	86,20	**13,80**	463	92,60	**7,40**	**10,60**
Weight of Sample (gr)		500		500				

The sieve analysis of the sand showed that 100% of the material passed the No. 30 sieve and began to be retained at the No. 50 sieve. The average percentage passing the No. 50 sieve was 41.60%, while the percentage passing the No. 100 sieve was 19.90%. At the No. 200 sieve, the average percentage passing was 10.60%, indicating that only a limited portion of the sand consisted of particles finer than 0.075 mm. The distribution demonstrates that the sand primarily contributes fine particles within the intermediate range rather than functioning predominantly as an ultra-fine material. This characteristic is relevant to the aggregate packing structure because the sand can occupy voids between the coarser aggregate particles. The source document states that the sand gradation complied with the SNI ASTM C136:2012 standard. Therefore, the sand could be incorporated into the subsequent aggregate-combination process.

Table 7. Results of Sieve Analysis of Filler (Cement)

Sieve Size		Test I			Test II			Average
inch	mm	Retained (gr)	Retained (%)	Passing (%)	Retained (gr)	Retained (%)	Passing (%)	
1"	25	0	0	**100,00**	0	0	**100,00**	**100,00**
3/4"	19	0	0	**100,00**	0	0	**100,00**	**100,00**
1/2"	12,5	0	0	**100,00**	0	0	**100,00**	**100,00**
3/8"	9,5	0	0	**100,00**	0	0	**100,00**	**100,00**
# 4	4,75	0	0	**100,00**	0	0	**100,00**	**100,00**
# 8	2,36	0	0	**100,00**	0	0	**100,00**	**100,00**
# 16	1,15	0	0	**100,00**	0	0	**100,00**	**100,00**
# 30	0,6	0	0	**100,00**	0	0	**100,00**	**100,00**
# 50	0,3	0	0	**100,00**	0	0	**100,00**	**100,00**
#100	0,15	0	0	**100,00**	0	0	**100,00**	**100,00**
# 200	0,075	2,4	2,40	**97,60**	1,8	1,80	**98,20**	**97,90**
Weight of Sample (gr)		100			100			

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Cement was examined as the filler component to ensure that the material possessed characteristics appropriate for use in the asphalt mixture. In the aggregate system, filler represents the finest material fraction and contributes to filling the smaller voids between the aggregate particles. The examination was therefore directed toward determining the particle-size distribution of the cement used in the mixture. The source document identifies cement as a filler material whose quality was examined against the applicable standard requirements. Its particle fineness is relevant because excessive or insufficient fine material can influence the volumetric characteristics and binder distribution of an asphalt mixture. The filler was subsequently incorporated into the combined aggregate gradation together with the coarse, medium, fine, and sand fractions. Thus, the filler examination completed the characterization of the conventional aggregate components before the Bodri River sand modification was introduced.

Table 8. Results of Sieve Analysis of Bodri River Sand

Sieve Size		Test I			Test II			Average
inch	mm	Retained (gr)	Retained (%)	Passing (%)	Retained (gr)	Retained (%)	Passing (%)	
1"	25	0	0	**100,00**	0	0	**100,00**	**100,00**
3/4"	19	0	0	**100,00**	0	0	**100,00**	**100,00**
1/2"	12,5	0	0	**100,00**	0	0	**100,00**	**100,00**
3/8"	9,5	0	0	**100,00**	0	0	**100,00**	**100,00**
# 4	4,75	0	0	**100,00**	0	0	**100,00**	**100,00**
# 8	2,36	0	0	**100,00**	0	0	**100,00**	**100,00**
# 16	1,15	0	0	**100,00**	0	0	**100,00**	**100,00**
# 30	0,6	0	0	**100,00**	0	0	**100,00**	**100,00**
# 50	0,3	0	0	**100,00**	0	0	**100,00**	**100,00**
#100	0,15	121,0	60,50	**39,50**	122,0	61,00	**39,00**	**39,25**
# 200	0,075	187,0	93,50	**6,50**	185,0	92,50	**7,50**	**7,00**
Weight of Sample (gr)		200			200			

The Bodri River sand was analyzed separately because it was used as an alternative fine aggregate in the modified AC-WC mixtures. The analysis showed that the material had a relatively fine particle distribution and a comparatively uniform range of particle sizes. The results indicate that the sand was retained at the No. 200 sieve at approximately 7.00%, while the percentage passing the No. 100 sieve was reported at 39.25%. These characteristics distinguish the Bodri River sand from the conventional sand fraction and provide the basis for evaluating its influence as a partial fine-aggregate substitution. The source document states that the Bodri River sand gradation complied with SNI ASTM C136:2012. The material could therefore be incorporated into the mixture at the planned contents of 0%, 1%, 3%, and 5%. The separate gradation analysis is important because changes in this fine fraction can alter the combined aggregate gradation and, consequently, the volumetric behavior of the AC-WC mixture.

Table 9. Specification Limits for Combined Aggregate Passing Percentages

Sieve Number	**Specification**		**Pass Rate (Combined)**
	Upper Limit	Lower Limit	
#200	7	3	5,26
#100	12	5	8,75
#50	18	8	13,61
#30	25	12	20,26
#16	35	23	30,09

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#8	48	33	40,41
#4	65	50	54,53
3/8"	80	70	77,98
1/2"	95	85	94,08
3/4"	100	100	100,00
1"	100	100	100,00

The combined aggregate gradation was established by integrating the different aggregate fractions into a single gradation suitable for the AC-WC mixture. The combined material included the ½-inch coarse aggregate, ¾-inch medium aggregate, fine aggregate, sand, filler, and Bodri River sand as the modified fine-aggregate component. The results in Table 9 show that the combined passing percentages were 5.26% at No. 200, 8.75% at No. 100, 13.61% at No. 50, and 20.26% at No. 30. At the No. 16, No. 8, and No. 4 sieves, the corresponding values were 30.09%, 40.41%, and 54.53%, while the passing percentages at 3/8-inch and ½-inch were 77.98% and 94.08%, respectively. The ¾-inch and 1-inch sieve results both reached 100%, indicating complete passage at these larger sieve sizes. The combined gradation was required to remain between the specified upper and lower limits rather than exceeding either boundary. This verification established the aggregate combination as the basis for preparing the modified AC-WC test specimens.

Table 10. Modification and Variation of Test Specimens

No.	Test Specimen	Number of Test Specimens
1	Normal Composition + 0% Bodri River Sand + 0% Styrene-Butadiene Rubber	3
2	Normal Composition + 0% Bodri River Sand + 2% Styrene-Butadiene Rubber	3
3	Normal Composition + 0% Bodri River Sand + 4% Styrene-Butadiene Rubber	3
4	Normal Composition + 0% Bodri River Sand + 6% Styrene-Butadiene Rubber	3
5	Normal Composition + 1% Bodri River Sand + 0% Styrene-Butadiene Rubber	3
6	Normal Composition + 1% Bodri River Sand + 2% Styrene-Butadiene Rubber	3
7	Normal Composition + 1% Bodri River Sand + 4% Styrene-Butadiene Rubber	3
8	Normal Composition + 1% Bodri River Sand + 6% Styrene-Butadiene Rubber	3
9	Normal Composition + 0% Bodri River Sand + 0% Styrene-Butadiene Rubber	3
10	Normal Composition + 0% Bodri River Sand + 2% Styrene-Butadiene Rubber	3
11	Normal Composition + 0% Bodri River Sand + 4% Styrene-Butadiene Rubber	3
12	Normal Composition + 0% Bodri River Sand + 6% Styrene-Butadiene Rubber	3
13	Normal Composition + 1% Bodri River Sand + 0% Styrene-Butadiene Rubber	3
14	Normal Composition + 1% Bodri River Sand + 2% Styrene-Butadiene Rubber	3
15	Normal Composition + 1% Bodri River Sand + 4% Styrene-Butadiene Rubber	3
16	Normal Composition + 1% Bodri River Sand + 6% Styrene-Butadiene Rubber	3

After the optimum asphalt content determination produced a selected asphalt content of 5.8%, the preparation of modified test specimens was carried out using Bodri River sand and Styrene-Butadiene Rubber. The modification produced 16 mixture variations based on the combination of four Bodri River sand contents and four SBR contents. Each variation was represented by three test specimens to provide replication during the subsequent testing stages. The variations included Bodri River sand contents of 0% and 1% in the specimen table, combined with SBR contents of 0%, 2%, 4%, and 6%, with a total of 48 specimens. The systematic variation of the specimen composition allowed the effects of the two modification materials to be evaluated comparatively. The specimens prepared at this stage were subsequently used for the GMM and Marshall testing stages. Thus, Table 10 represents the transition from aggregate gradation and mixture composition toward the experimental evaluation of the modified AC-WC mixtures.

Determination of Mixture Specific Gravity (GMM)

The determination of Maximum Specific Gravity (GMM) was conducted to obtain the theoretical maximum specific gravity of the modified asphalt mixtures under a void-free condition. The GMM examination was performed on mixtures containing Bodri River sand and Styrene-Butadiene Rubber (SBR) at different proportions. A total of 16 mixture variations were evaluated, with three test specimens prepared for each variation. The Bodri River sand contents considered in this stage were 0%, 1%, 3%, and 5%, while the SBR contents were 0%, 2%, 4%, and 6%. The GMM test was conducted using a water-immersion procedure under conditions intended to eliminate air voids from the mixture. The resulting values represent the theoretical maximum density of each mixture and are subsequently used in the calculation of volumetric Marshall parameters. The GMM results for each Bodri River sand variation are presented sequentially in Tables 11–14.

Table 11. Summary of Average Marshall Test Results for 0% Bodri River Sand and 0%, 2%, 4%, and 6% Styrene-Butadiene Rubber

No.	Bahan Tambah Pasir Sungai Bodri 0% + Bahan Tambah *Styrene Butadiene Rubber* (0%, 2%, 4%, 6%)			Pengujian Berat Jenis Campuran Aspal (GMM)											
				1	2	3	1	2	3	1	2	3	1	2	3
1	Berat Botol + Contoh		Grm	1399	1395	1402	1399	1401	1409	1405	1407	1401	1399	1403	1393
2	Berat Botol		Grm	767	767	767	767	767	767	767	767	767	767	767	767
3	Berat Contoh	(1 - 2)	Grm	632	628	635	632	634	642	638	640	634	632	636	626
4	Berat Botol + Contoh + Air (batas kaliberasi)		Grm	1947	1945	1944	1951	1950	1952	1941	1951	1946	1943	1939	1951
5	Berat botol + Air (batas kaliberasi)		Grm	1564	1566	1570	1571	1568	1573	1567	1568	1565	1573	1560	1565
6	Berat air	(4 - 5)	Grm	383	379	374	380	382	379	374	383	381	370	379	386
7	Volume contoh	(3 - 6)	Grm	249	249	261	252	252	263	264	257	253	262	257	240
8	Max Specific Gravity (Gmm)	(3 : 7)	Grm / cc	2,54	2,52	2,43	2,51	2,52	2,44	2,42	2,49	2,51	2,41	2,47	2,61
9	Temperatur air T ^{o}C		Grm	25	25	25	25	25	25	25	25	25	25	25	25
10	Koreksi suhu		Grm	1	1	1	1	1	1	1	1	1	1	1	1
11	Max Specific Gravity (Gmm)	(8 x 10)	Grm / cc	2,538	2,522	2,433	2,508	2,520	2,441	2,417	2,490	2,506	2,412	2,471	2,608
Rata - Rata GMM				**2,498**			**2,490**			**2,471**			**2,497**		
				0,00%			**2,00%**			**4,00%**			**6,00%**		

Table 11 presents the GMM examination results for mixtures containing 0% Bodri River sand and SBR contents of 0%, 2%, 4%, and 6%. Each SBR variation was represented by three test specimens to evaluate the physical characteristics of the modified mixture. The corrected GMM values for the individual specimens ranged from 2.412 to 2.608 g/cc. The average GMM values for the 0%, 2%, 4%, and 6% SBR mixtures were 2.498, 2.490, 2.471, and 2.497 g/cc, respectively. The highest average value was therefore obtained at 0% SBR, while the lowest average value occurred at 4% SBR. The results indicate that changes in SBR content produced relatively small changes in the theoretical maximum specific gravity of the mixture. The average GMM value for this series was reported as 2.498 g/cc in the source discussion.

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Table 12. Summary of Average Marshall Test Results for Bodri River Sand and Styrene-Butadiene Rubber at Different Contents

No.	Bahan Tambah Pasir Sungai Bodri 1% + Bahan Tambah Styrene Butadiene Rubber (0%, 2%, 4%, 6%)			Pengujian Berat Jenis Campuran Aspal (GMM)											
				1	2	3	1	2	3	1	2	3	1	2	3
1	Berat Botol + Contoh		Grm	1398	1399	1402	1404	1396	1397	1403	1401	1400	1399	1395	1394
2	Berat Botol		Grm	767	767	767	767	767	767	767	767	767	767	767	767
3	Berat Contoh	(1 - 2)	Grm	631	632	635	637	629	630	636	634	633	632	628	627
4	Berat Botol + Contoh + Air (batas kaliberasi)		Grm	1941	1943	1939	1933	1937	1940	1934	1936	1937	1942	1944	1941
5	Berat botol + Air (batas kaliberasi)		Grm	1563	1565	1567	1566	1568	1564	1561	1563	1564	1571	1572	1570
6	Berat air	(4 - 5)	Grm	378	378	372	367	369	376	373	373	373	371	372	371
7	Volume contoh	(3 - 6)	Grm	253	254	263	270	260	254	263	261	260	261	256	256
8	Max Specific Gravity (Gmm)	(3 : 7)	Grm / cc	2,49	2,49	2,41	2,36	2,42	2,48	2,42	2,43	2,43	2,42	2,45	2,45
9	Temperatur air T °C		Grm	25	25	25	25	25	25	25	25	25	25	25	25
10	Koreksi suhu		Grm	1	1	1	1	1	1	1	1	1	1	1	1
11	Max Specific Gravity (Gmm)	(8 x 10	Grm / cc	2,494	2,488	2,414	2,359	2,419	2,480	2,418	2,429	2,435	2,421	2,453	2,449
Rata - Rata GMM				2,466			2,420			2,427			2,441		
				0,00%			2,00%			4,00%			6,00%		

The GMM examination in Table 12 was performed on mixtures containing 1% Bodri River sand combined with four SBR contents. The corrected GMM values for the individual specimens were 2.494, 2.488, and 2.414 g/cc for the first SBR variation, followed by different values for the other SBR proportions. The average GMM values reported for the series include 2.466 and 2.420 g/cc in the table sequence, corresponding to the grouped mixture results shown in the source. The source discussion identifies the resulting GMM value for the 1% Bodri River sand mixture as 2.466 g/cc. This result indicates that the addition of 1% Bodri River sand produced a different maximum specific-gravity response compared with the 0% Bodri River sand mixture. The variation in GMM reflects differences in the physical composition and packing characteristics of the modified aggregate-binder system. The results from Table 12 were therefore used as the GMM basis for the subsequent volumetric evaluation of the 1% Bodri River sand mixtures.

Table 13. Summary of Marshall Test Results for All Variations of Added Materials

No.	Bahan Tambah Pasir Sungai Bodri 3% + Bahan Tambah Styrene Butadiene Rubber (0%, 2%, 4%, 6%)			Pengujian Berat Jenis Campuran Aspal (GMM)											
				1	2	3	1	2	3	1	2	3	1	2	3
1	Berat Botol + Contoh		Grm	1403	1408	1401	1398	1399	1402	1396	1392	1400	1399	1397	1404
2	Berat Botol		Grm	767	767	767	767	767	767	767	767	767	767	767	767
3	Berat Contoh	(1 - 2)	Grm	636	641	634	631	632	635	629	625	633	632	630	637
4	Berat Botol + Contoh + Air (batas kaliberasi)		Grm	1945	1946	1941	1939	1945	1940	1938	1935	1933	1942	1948	1947
5	Berat botol + Air (batas kaliberasi)		Grm	1564	1563	1561	1571	1569	1566	1572	1571	1569	1574	1566	1563
6	Berat air	(4 - 5)	Grm	381	383	380	368	376	374	366	364	364	368	382	384
7	Volume contoh	(3 - 6)	Grm	255	258	254	263	256	261	263	261	269	264	248	253
8	Max Specific Gravity (Gmm)	(3 : 7)	Grm / cc	2,49	2,48	2,50	2,40	2,47	2,43	2,39	2,39	2,35	2,39	2,54	2,52
9	Temperatur air T °C		Grm	25	25	25	25	25	25	25	25	25	25	25	25
10	Koreksi suhu		Grm	1	1	1	1	1	1	1	1	1	1	1	1
11	Max Specific Gravity (Gmm)	(8 x 10	Grm / cc	2,494	2,484	2,496	2,399	2,469	2,433	2,392	2,395	2,353	2,394	2,540	2,518
Rata - Rata GMM				2,492			2,434			2,380			2,484		
				0,00%			2,00%			4,00%			6,00%		

Table 13 presents the GMM results for the mixture containing 3% Bodri River sand and SBR contents of 0%, 2%, 4%, and 6%. The test was again conducted using three specimens for each SBR variation to evaluate the changes in the physical characteristics of the mixture. The corrected GMM values for the specimens varied across the four SBR contents, with values such as 2.494, 2.484, and

2.496 g/cc in the first group and progressively different values in the subsequent groups. The source discussion reports a GMM value of 2.492 g/cc for the 3% Bodri River sand mixture. This value indicates that the theoretical maximum specific gravity remained relatively close to the values obtained for the other Bodri River sand contents. The result demonstrates that increasing the Bodri River sand content to 3% did not produce an extreme change in the theoretical maximum density of the mixture. The GMM result was subsequently used as the reference value for calculating the volumetric characteristics of the 3% Bodri River sand mixtures.

Table 14. Determination of Mixture Specific Gravity (GMM) with 5% Bodri River Sand and Styrene-Butadiene Rubber (0%, 2%, 4%, and 6%)

No.	Bahan Tambah Pasir Sungai Bodri 5% + Bahan Tambah Styrene Butadiene Rubber (0%, 2%, 4%, 6%)			Pengujian Berat Jenis Campuran Aspal (GMM)											
				1	2	3	1	2	3	1	2	3	1	2	3
1	Berat Botol + Contoh		Grm	1402	1404	1408	1410	1403	1407	1402	1398	1399	1401	1403	1398
2	Berat Botol		Grm	767	767	767	767	767	767	767	767	767	767	767	767
3	Berat Contoh	(1 - 2)	Grm	635	637	641	643	636	640	635	631	632	634	636	631
4	Berat Botol + Contoh + Air (batas kaliberasi)		Grm	1947	1942	1945	1952	1955	1951	1946	1949	1948	1944	1952	1948
5	Berat botol + Air (batas kaliberasi)		Grm	1563	1562	1566	1573	1571	1569	1569	1566	1570	1577	1571	1569
6	Berat air	(4 - 5)	Grm	384	380	379	379	384	382	377	383	378	367	381	379
7	Volume contoh	(3 - 6)	Grm	251	257	262	264	252	258	258	248	254	267	255	252
8	Max Specific Gravity (Gmm)	(3 : 7)	Grm / cc	2,53	2,48	2,45	2,44	2,52	2,48	2,46	2,54	2,49	2,37	2,49	2,50
9	Temperatur air T °C		Grm	25	25	25	25	25	25	25	25	25	25	25	25
10	Koreksi suhu		Grm	1	1	1	1	1	1	1	1	1	1	1	1
11	Max Specific Gravity (Gmm)	(8 x 10	Grm / cc	2,530	2,479	2,447	2,436	2,524	2,481	2,461	2,544	2,488	2,375	2,494	2,504
Rata - Rata GMM				**2,485**			**2,480**			**2,498**			**2,458**		
				0,00%			**2,00%**			**4,00%**			**6,00%**		

Table 14 presents the GMM examination for mixtures containing 5% Bodri River sand and SBR contents of 0%, 2%, 4%, and 6%. Three specimens were used for each SBR variation to determine the maximum specific gravity of the modified mixtures. The corrected GMM values shown in the table include 2.530, 2.479, and 2.447 g/cc for the first SBR group, followed by the corresponding values for the other SBR contents. The reported average GMM values include 2.485 and 2.480 g/cc, while the source also reports a value of 2.458 g/cc for the final variation. The source discussion identifies 2.498 g/cc as the maximum specific gravity value obtained for the modified mixture. The GMM results indicate that the addition of 5% Bodri River sand produced measurable changes in the theoretical maximum density as the SBR content was varied. These results complete the GMM examination for all four Bodri River sand proportions before the analysis proceeds to the Marshall test.

The GMM results from Tables 11–14 provide the theoretical maximum specific-gravity values required for evaluating the volumetric characteristics of the modified AC-WC mixtures. The four Bodri River sand proportions produced different GMM responses when combined with SBR contents of 0%, 2%, 4%, and 6%. The differences in GMM are related to the composition of the aggregate and binder system and reflect changes in the theoretical density of the mixture under void-free conditions. The values obtained from the GMM examination are subsequently used in calculating parameters such as VIM, VMA, and VFB during the Marshall analysis. The GMM results therefore cannot be interpreted independently from the Marshall results because they provide one of the fundamental inputs for the volumetric calculations. The comparison of GMM values across the four Bodri River sand contents also provides an initial indication of how the modification affects the physical characteristics of the AC-WC mixture. The next stage of the analysis is therefore the Marshall test, which evaluates the volumetric and mechanical performance of each modified mixture.

Marshall Test Results

The Marshall test was conducted to evaluate the volumetric and mechanical characteristics of the AC-WC mixtures containing different proportions of Bodri River sand and Styrene-Butadiene Rubber (SBR). The evaluated parameters consisted of Void in Mineral Aggregate (VMA), Void in Mix

(VIM), Void Filled with Bitumen (VFB), stability, flow, and Marshall Quotient (MQ). These parameters were used to assess the quality and performance of each mixture variation under the applicable Bina Marga requirements. The experimental program included Bodri River sand contents of 0%, 1%, 3%, and 5%, combined with SBR contents of 0%, 2%, 4%, and 6%. Each mixture variation was evaluated using the Marshall testing procedure to obtain quantitative performance data. The results were then compared between mixture variations to identify changes associated with the addition of Bodri River sand and SBR. The complete Marshall results for each Bodri River sand content are presented in Tables 15–18, followed by the overall recapitulation in Table 19.

Table 15. Summary of Average Marshall Test Results for 0% Bodri River Sand and Styrene-Butadiene Rubber (0%, 2%, 4%, and 6%)

Description	Bodri River Sand Content	Styrene-Butadiene Rubber Content	Specification	Laboratory Test Result	Remarks
Bodri River Sand 0% + Styrene-Butadiene Rubber 0%					
Air Voids (VIM)	0%	0%	3.0%–5.0%	4.26	Complies
Voids in Mineral Aggregate (VMA)	0%	0%	Min. 15%	15.97	Complies
Voids Filled with Bitumen (VFB)	0%	0%	Min. 65%	73.34	Complies
Stability	0%	0%	Min. 800 kg	850.81	Complies
Plastic Flow/Flow	0%	0%	2.0–4.0 mm	2.80	Complies
Marshall Quotient	0%	0%	–	303.86	–
Bodri River Sand 0% + Styrene-Butadiene Rubber 2%					
Air Voids (VIM)	0%	2%	3.0%–5.0%	4.79	Complies
Voids in Mineral Aggregate (VMA)	0%	2%	Min. 15%	16.71	Complies
Voids Filled with Bitumen (VFB)	0%	2%	Min. 65%	71.30	Complies
Stability	0%	2%	Min. 800 kg	854.08	Complies
Plastic Flow/Flow	0%	2%	2.0–4.0 mm	2.57	Complies
Marshall Quotient	0%	2%	–	332.76	–
Bodri River Sand 0% + Styrene-Butadiene Rubber 4%					
Air Voids (VIM)	0%	4%	3.0%–5.0%	3.77	Complies
Voids in Mineral Aggregate (VMA)	0%	4%	Min. 15%	16.45	Complies
Voids Filled with Bitumen (VFB)	0%	4%	Min. 65%	77.11	Complies
Stability	0%	4%	Min. 800 kg	912.98	Complies
Plastic Flow/Flow	0%	4%	2.0–4.0 mm	3.23	Complies
Marshall Quotient	0%	4%	–	282.37	–
Bodri River Sand 0% + Styrene-Butadiene Rubber 6%					
Air Voids (VIM)	0%	6%	3.0%–5.0%	4.18	Complies
Voids in Mineral Aggregate (VMA)	0%	6%	Min. 15%	15.93	Complies
Voids Filled with Bitumen (VFB)	0%	6%	Min. 65%	73.78	Complies
Stability	0%	6%	Min. 800 kg	755.91	Does Not Comply
Plastic Flow/Flow	0%	6%	2.0–4.0 mm	4.80	Does Not Comply
Marshall Quotient	0%	6%	–	157.48	–

The Marshall results for the mixtures containing 0% Bodri River sand show that most of the variations satisfied the specified requirements. The P0S0 mixture produced VIM of 4.26%, VMA of 15.97%, VFB of 73.34%, stability of 850.81 kg, and flow of 2.80 mm. The P0S2 mixture also complied with the requirements, with stability increasing slightly to 854.08 kg and flow decreasing to 2.57 mm. The P0S4 mixture produced a higher stability value of 912.98 kg while maintaining VIM, VMA, VFB, and flow within the specified ranges. In contrast, P0S6 produced stability of 755.91 kg and flow of 4.80 mm, so this variation did not comply with the stability and flow requirements. The Marshall Quotient values for these four mixtures were 303.86, 332.76, 282.37, and 157.48, respectively. Therefore, the results indicate that the addition of SBR up to 4% produced acceptable Marshall characteristics for the 0% Bodri River sand mixture, whereas the 6% SBR variation resulted in a decline in overall compliance.

Table 16. Summary of Average Marshall Test Results for 1% Bodri River Sand and Styrene-Butadiene Rubber (0%, 2%, 4%, and 6%)

Description	Bodri River Sand Content	Styrene-Butadiene Rubber Content	Specification	Laboratory Test Result	Remarks
Bodri River Sand 1% + Styrene-Butadiene Rubber 0%					
Air Voids (VIM)	1%	0%	3.0%–5.0%	5.55	Does Not Comply
Voids in Mineral Aggregate (VMA)	1%	0%	Min. 15%	18.16	Complies
Voids Filled with Bitumen (VFB)	1%	0%	Min. 65%	69.46	Complies
Stability	1%	0%	Min. 800 kg	818.08	Complies
Plastic Flow/Flow	1%	0%	2.0–4.0 mm	4.23	Does Not Comply
Marshall Quotient	1%	0%	–	193.25	–
Bodri River Sand 1% + Styrene-Butadiene Rubber 2%					
Air Voids (VIM)	1%	2%	3.0%–5.0%	4.23	Complies
Voids in Mineral Aggregate (VMA)	1%	2%	Min. 15%	18.56	Complies
Voids Filled with Bitumen (VFB)	1%	2%	Min. 65%	77.24	Complies
Stability	1%	2%	Min. 800 kg	942.43	Complies
Plastic Flow/Flow	1%	2%	2.0–4.0 mm	3.00	Complies
Marshall Quotient	1%	2%	–	314.14	–
Bodri River Sand 1% + Styrene-Butadiene Rubber 4%					
Air Voids (VIM)	1%	4%	3.0%–5.0%	3.43	Complies
Voids in Mineral Aggregate (VMA)	1%	4%	Min. 15%	17.65	Complies
Voids Filled with Bitumen (VFB)	1%	4%	Min. 65%	80.55	Complies
Stability	1%	4%	Min. 800 kg	1047.15	Complies
Plastic Flow/Flow	1%	4%	2.0–4.0 mm	3.07	Complies
Marshall Quotient	1%	4%	–	341.46	–
Bodri River Sand 1% + Styrene-Butadiene Rubber 6%					
Air Voids (VIM)	1%	6%	3.0%–5.0%	4.53	Complies
Voids in Mineral Aggregate (VMA)	1%	6%	Min. 15%	18.11	Complies
Voids Filled with Bitumen (VFB)	1%	6%	Min. 65%	75.05	Complies
Stability	1%	6%	Min. 800 kg	1125.68	Complies

Plastic Flow/Flow	1%	6%	2.0–4.0 mm	4.10	Does Not Comply
Marshall Quotient	1%	6%	–	274.56	–

The results for the 1% Bodri River sand mixtures demonstrate a different response to SBR addition compared with the 0% Bodri River sand mixtures. The P1S0 variation did not comply with the VIM and flow requirements, recording VIM of 5.55% and flow of 4.23 mm. After the addition of 2% SBR, P1S2 satisfied all evaluated requirements and produced stability of 942.43 kg. The P1S4 mixture also satisfied all requirements and produced stability of 1,047.15 kg, with a Marshall Quotient of 341.46. The P1S6 mixture achieved the highest stability in this group at 1,125.68 kg, but its flow value of 4.10 mm exceeded the maximum specified value. The results therefore show that increasing SBR content did not always result in complete compliance because the increase in stability could be accompanied by an increase in flow. Among the four variations, P1S4 provided a favorable balance because it achieved high stability while all of its reported Marshall parameters remained within the specified limits.

Table 17. Summary of Average Marshall Test Results for 3% Bodri River Sand and Styrene-Butadiene Rubber (0%, 2%, 4%, and 6%)

Description	Bodri River Sand Content	Styrene-Butadiene Rubber Content	Specification	Laboratory Test Result	Remarks
Bodri River Sand 3% + Styrene-Butadiene Rubber 0%					
Air Voids (VIM)	3%	0%	3.0%–5.0%	6.49	Does Not Comply
Voids in Mineral Aggregate (VMA)	3%	0%	Min. 15%	18.12	Complies
Voids Filled with Bitumen (VFB)	3%	0%	Min. 65%	64.19	Does Not Comply
Stability	3%	0%	Min. 800 kg	782.09	Does Not Comply
Plastic Flow/Flow	3%	0%	2.0–4.0 mm	4.63	Does Not Comply
Marshall Quotient	3%	0%	–	168.80	–
Bodri River Sand 3% + Styrene-Butadiene Rubber 2%					
Air Voids (VIM)	3%	2%	3.0%–5.0%	4.35	Complies
Voids in Mineral Aggregate (VMA)	3%	2%	Min. 15%	18.20	Complies
Voids Filled with Bitumen (VFB)	3%	2%	Min. 65%	76.10	Complies
Stability	3%	2%	Min. 800 kg	952.25	Complies
Plastic Flow/Flow	3%	2%	2.0–4.0 mm	3.20	Complies
Marshall Quotient	3%	2%	–	297.58	–
Bodri River Sand 3% + Styrene-Butadiene Rubber 4%					
Air Voids (VIM)	3%	4%	3.0%–5.0%	3.32	Complies
Voids in Mineral Aggregate (VMA)	3%	4%	Min. 15%	19.15	Complies
Voids Filled with Bitumen (VFB)	3%	4%	Min. 65%	82.68	Complies
Stability	3%	4%	Min. 800 kg	1092.96	Complies
Plastic Flow/Flow	3%	4%	2.0–4.0 mm	3.00	Complies
Marshall Quotient	3%	4%	–	364.32	–
Bodri River Sand 3% + Styrene-Butadiene Rubber 6%					

Air Voids (VIM)	3%	6%	3.0%–5.0%	4.85	Complies
Voids in Mineral Aggregate (VMA)	3%	6%	Min. 15%	16.95	Complies
Voids Filled with Bitumen (VFB)	3%	6%	Min. 65%	71.41	Complies
Stability	3%	6%	Min. 800 kg	1027.51	Complies
Plastic Flow/Flow	3%	6%	2.0–4.0 mm	3.50	Complies
Marshall Quotient	3%	6%	–	293.58	–

The Marshall results for the 3% Bodri River sand mixtures show a clear improvement following the addition of SBR. The P3S0 mixture did not meet the VIM, VFB, stability, and flow requirements, indicating that the unmodified mixture was not suitable based on the evaluated criteria. The addition of 2% SBR changed the result substantially, with P3S2 achieving VIM of 4.35%, VMA of 18.20%, VFB of 76.10%, stability of 952.25 kg, and flow of 3.20 mm. The P3S4 mixture produced stability of 1,092.96 kg and a Marshall Quotient of 364.32 while maintaining all other parameters within the required limits. The P3S6 mixture also complied with the specified requirements, with stability of 1,027.51 kg and flow of 3.50 mm. The highest stability within this group was therefore obtained at 4% SBR, while the highest Marshall Quotient was also recorded at the same SBR level. These results identify P3S4 as a particularly favorable combination within the 3% Bodri River sand group because it simultaneously provided high stability and acceptable volumetric and flow characteristics.

Table 18. Summary of Average Marshall Test Results for 5% Bodri River Sand and Styrene-Butadiene Rubber (0%, 2%, 4%, and 6%)

Description	Bodri River Sand Content	Styrene-Butadiene Rubber Content	Specification	Laboratory Test Result	Remarks
Bodri River Sand 5% + Styrene-Butadiene Rubber 0%					
Air Voids (VIM)	5%	0%	3.0%–5.0%	6.86	Does Not Comply
Voids in Mineral Aggregate (VMA)	5%	0%	Min. 15%	18.68	Complies
Voids Filled with Bitumen (VFB)	5%	0%	Min. 65%	63.26	Does Not Comply
Stability	5%	0%	Min. 800 kg	726.46	Does Not Comply
Plastic Flow/Flow	5%	0%	2.0–4.0 mm	4.60	Does Not Comply
Marshall Quotient	5%	0%	–	157.93	–
Bodri River Sand 5% + Styrene-Butadiene Rubber 2%					
Air Voids (VIM)	5%	2%	3.0%–5.0%	6.06	Does Not Comply
Voids in Mineral Aggregate (VMA)	5%	2%	Min. 15%	18.14	Complies
Voids Filled with Bitumen (VFB)	5%	2%	Min. 65%	66.62	Complies
Stability	5%	2%	Min. 800 kg	840.99	Complies
Plastic Flow/Flow	5%	2%	2.0–4.0 mm	4.80	Does Not Comply
Marshall Quotient	5%	2%	–	175.21	–
Bodri River Sand 5% + Styrene-Butadiene Rubber 4%					
Air Voids (VIM)	5%	4%	3.0%–5.0%	6.74	Does Not Comply

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Voids in Mineral Aggregate (VMA)	5%	4%	Min. 15%	18.14	Complies
Voids Filled with Bitumen (VFB)	5%	4%	Min. 65%	62.94	Does Not Comply
Stability	5%	4%	Min. 800 kg	903.16	Complies
Plastic Flow/Flow	5%	4%	2.0–4.0 mm	5.10	Does Not Comply
Marshall Quotient	5%	4%	–	177.09	–
Bodri River Sand 5% + Styrene-Butadiene Rubber 6%					
Air Voids (VIM)	5%	6%	3.0%–5.0%	6.19	Does Not Comply
Voids in Mineral Aggregate (VMA)	5%	6%	Min. 15%	18.98	Complies
Voids Filled with Bitumen (VFB)	5%	6%	Min. 65%	67.43	Complies
Stability	5%	6%	Min. 800 kg	935.89	Complies
Plastic Flow/Flow	5%	6%	2.0–4.0 mm	6.00	Does Not Comply
Marshall Quotient	5%	6%	–	155.98	–

The mixtures containing 5% Bodri River sand generally showed the lowest level of compliance among the four Bodri River sand proportions. The P5S0 mixture produced VIM of 6.86%, VFB of 63.26%, stability of 726.46 kg, and flow of 4.60 mm, resulting in non-compliance with several requirements. Increasing the SBR content to 2% increased stability to 840.99 kg, but VIM of 6.06% and flow of 4.80 mm remained outside the specified ranges. At 4% SBR, stability increased further to 903.16 kg, although VIM, VFB, and flow still did not satisfy the requirements. The P5S6 mixture achieved the highest stability in this group at 935.89 kg, but its VIM of 6.19% and flow of 6.00 mm prevented it from meeting the complete specification. The Marshall Quotient values for P5S0, P5S2, P5S4, and P5S6 were 157.93, 175.21, 177.09, and 155.98, respectively. These results indicate that increasing SBR content improved stability to some extent, but the 5% Bodri River sand content still resulted in excessive VIM and flow values across the tested variations.

Table 19. Recapitulation of Marshall Test Results for All Material Variations

Variation	Bodri River Sand	Styrene-Butadiene Rubber	Marshall Test Results Parameters						Remarks
			VIM 3.0–5.0%	**VMA** Min. 15%	**VFB** Min. 65%	**Stability** Min. 800 kg	**Flow** 2–4 mm	**MQ**	
P0S0	0%	0%	4.26	15.97	73.34	850.81	2.80	303.86	Complies
P0S2	0%	2%	4.79	16.71	71.30	854.08	2.57	332.76	Complies
P0S4	0%	4%	3.77	16.45	77.11	912.98	3.23	282.37	Complies
P0S6	0%	6%	4.18	15.93	73.78	755.91	4.80	157.48	Does Not Comply
P1S0	1%	0%	5.27	17.92	70.58	834.45	4.20	193.25	Does Not Comply
P1S2	1%	2%	3.93	18.31	78.53	942.43	3.30	314.14	Complies
P1S4	1%	4%	3.51	17.71	80.21	1030.79	3.50	341.46	Complies
P1S6	1%	6%	4.01	17.67	77.31	1148.59	4.10	274.56	Does Not Comply
P3S0	3%	0%	6.60	18.22	63.76	795.18	4.70	168.80	Does Not Comply
P3S2	3%	2%	4.59	18.40	75.06	932.62	2.80	297.58	Complies
P3S4	3%	4%	3.53	19.33	81.73	1119.14	3.00	364.32	Complies
P3S6	3%	6%	5.08	17.16	70.37	1020.97	3.00	293.58	Complies

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P5S0	5%	0%	6.84	18.66	63.35	726.46	4.90	157.93	Does Not Comply
P5S2	5%	2%	6.60	18.61	64.55	814.81	4.50	175.21	Does Not Comply
P5S4	5%	4%	6.20	17.67	64.93	883.53	5.10	177.09	Does Not Comply
P5S6	5%	6%	5.78	18.63	68.96	952.25	6.00	155.98	Does Not Comply

Table 19 provides the overall comparison of the sixteen combinations of Bodri River sand and SBR. The recapitulation shows that all mixtures achieved VMA values above the minimum requirement of 15%, indicating that the VMA criterion was satisfied throughout the experimental variations. The VIM results were more varied because the required range was 3.00%–5.00%, resulting in both compliant and non-compliant mixtures. The VFB results similarly showed that most mixtures exceeded the minimum requirement of 65%, although several variations fell below this limit. Stability was above the minimum requirement of 800 kg for most mixtures, with P1S6 producing the highest recorded value of 1,148.59 kg, while P0S6, P3S0, and P5S0 did not meet the stability requirement. The flow results also varied, with several mixtures exceeding the specified maximum of 4.00 mm. Overall, the recapitulation demonstrates that the performance of the mixtures depended on the combined proportions of Bodri River sand and SBR rather than on an increase in either material alone.

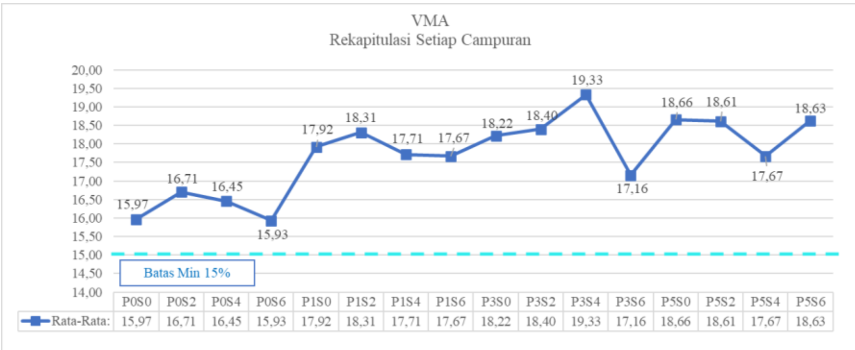

Figure 1. VMA Values of All Mixture Variations

The VMA comparison confirms that all sixteen mixture variations remained above the minimum specification of 15%. The values ranged from 15.93% for P0S6 to 19.33% for P3S4. This relatively narrow range indicates that changes in Bodri River sand and SBR contents did not cause any mixture to fall below the required aggregate void criterion. The highest VMA value obtained for P3S4 also coincided with a mixture that showed favorable results for the other Marshall parameters. In contrast, the lowest VMA value at P0S6 was still above the minimum requirement. Therefore, VMA did not become a limiting parameter in the selection of the compliant mixtures. Overall, the VMA results indicate that the mineral aggregate structure remained adequate across all tested compositions.

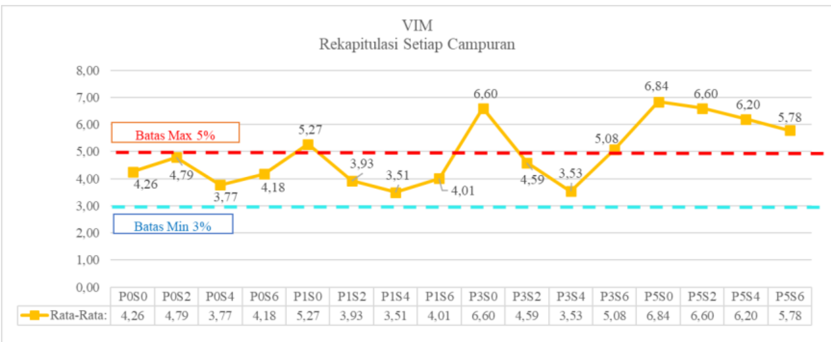

Figure 2. VIM Values of All Mixture Variations

The VIM comparison shows greater variation than the VMA results. The required VIM range was 3.00%–5.00%, so values outside this range were classified as not complying with the specification. Several mixtures with higher Bodri River sand contents, particularly those containing 5% sand, produced VIM values above 5.00%. The highest VIM value was recorded for P5S0 at 6.84%, whereas the lowest value among the sixteen mixtures was P1S4 at 3.51%. The results demonstrate that increasing the Bodri River sand content did not necessarily produce a more favorable void structure. The SBR addition was able to reduce VIM in several mixtures, but the effect depended on the Bodri River sand proportion. Thus, VIM was one of the parameters that contributed substantially to distinguishing compliant and non-compliant mixture variations.

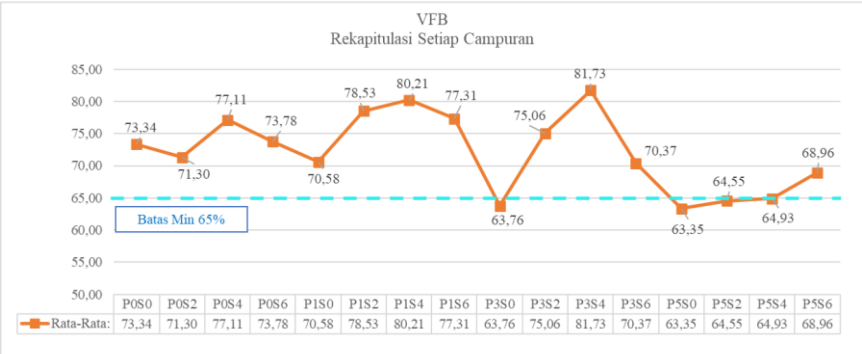

Figure 3. VFB Values of All Mixture Variations

The VFB comparison indicates that most mixture variations satisfied the minimum requirement of 65%. However, P3S0, P5S0, and P5S4 produced values below the required limit, with VFB values of 63.76%, 63.35%, and 64.93%, respectively. The highest VFB value was obtained by P3S4 at 81.73%. The high VFB value of P3S4 indicates that a large proportion of the available aggregate void space was filled with bitumen. The results also show that increasing SBR content could improve VFB in some mixture groups, particularly for the 3% Bodri River sand variations. Nevertheless, the response was not uniform because the 5% Bodri River sand mixtures still showed VFB values below the specification at several SBR levels. Therefore, VFB must be considered together with VIM and VMA when evaluating the volumetric suitability of the mixture.

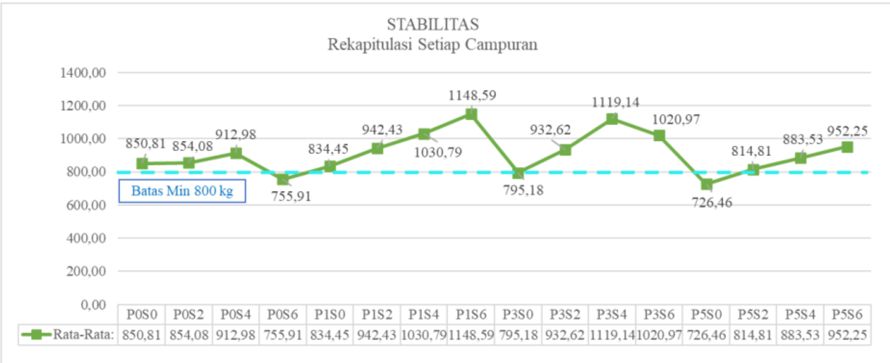

Figure 4. Stability Values of All Mixture Variations

The stability comparison shows that most of the tested mixtures exceeded the minimum requirement of 800 kg. The highest stability value was obtained by P1S6 at 1,148.59 kg, followed by P3S4 at 1,119.14 kg. However, P1S6 was not classified as fully compliant because its flow value exceeded the specified maximum. The mixtures that failed the stability requirement were P0S6, P3S0, and P5S0. Their stability values were 755.91 kg, 795.18 kg, and 726.46 kg, respectively. These results indicate that SBR addition generally increased stability in several mixture groups, particularly when the Bodri River sand content was 1% or 3%. Nevertheless, the stability parameter cannot be used independently because the mixture must also satisfy VIM, VFB, and flow requirements.

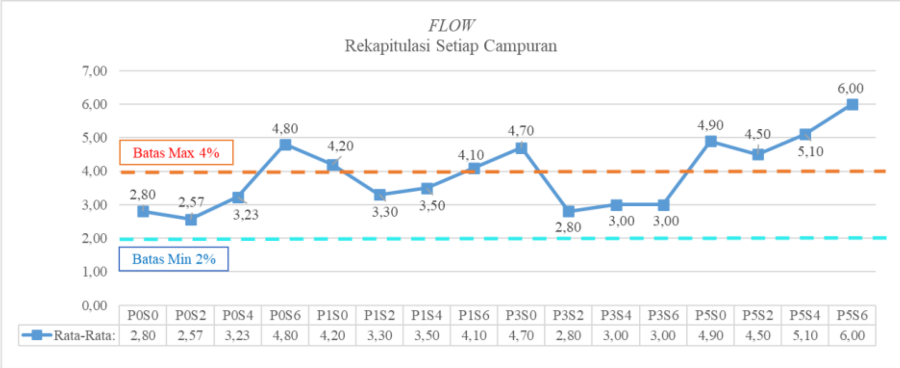

Figure 5. Flow Values of All Mixture Variations

The flow comparison shows that the deformation response differed substantially among the tested mixtures. The required flow range was 2.00–4.00 mm, meaning that values above 4.00 mm were considered non-compliant. The highest flow value was recorded by P5S6 at 6.00 mm, while the lowest value was recorded by P0S2 at 2.57 mm. Several mixtures with high SBR or high Bodri River sand contents produced flow values above the maximum requirement. These included P0S6, P1S0, P1S6, P3S0, P5S0, P5S2, P5S4, and P5S6. The results demonstrate that an increase in stability does not automatically correspond to acceptable flow characteristics, as shown particularly by P1S6. Therefore, the flow parameter provides an important limitation when determining the overall suitability of the modified AC-WC mixtures.

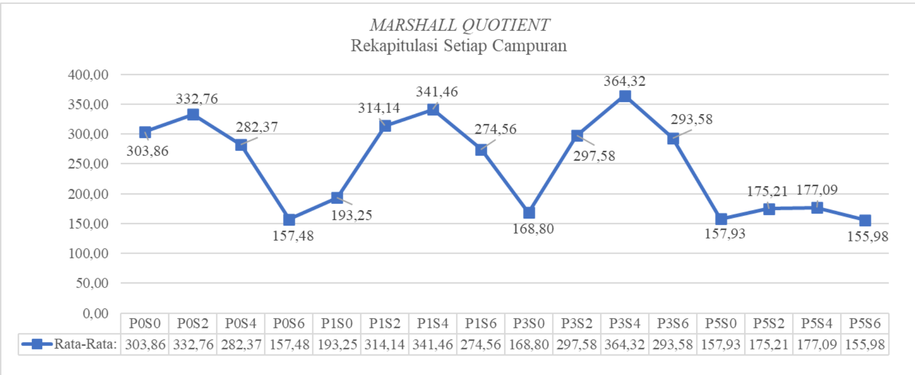

Figure 6. Marshall Quotient Values of All Mixture Variations

The Marshall Quotient comparison provides an additional indication of the relationship between stability and flow for each mixture variation. The MQ values ranged from 155.98 to 364.32 across the sixteen mixtures. The highest MQ value was obtained by P3S4 at 364.32, followed by P1S4 at 341.46 and P0S2 at 332.76. The lowest value was obtained by P5S6 at 155.98. The relatively high MQ value of P3S4 corresponds to its high stability and acceptable flow value of 3.00 mm. In contrast, the lower MQ values in several 5% Bodri River sand mixtures reflect their combination of relatively high flow and comparatively lower stability. The MQ results therefore reinforce the identification of P3S4 as one of the most favorable combinations among the tested mixture variations.

Overall, the Marshall test results indicate that the proportion of Bodri River sand and SBR had a clear influence on the volumetric and mechanical characteristics of the AC-WC mixtures. All variations satisfied the minimum VMA requirement, but the VIM, VFB, stability, and flow parameters showed different levels of compliance. The mixtures containing 5% Bodri River sand generally showed poorer overall performance because their VIM and flow values frequently exceeded the specified limits. The 1% and 3% Bodri River sand mixtures produced more favorable combinations, particularly when SBR was added at moderate levels. Among all variations, P3S4 recorded stability of 1,119.14 kg, VIM of 3.53%, VMA of 19.33%, VFB of 81.73%, flow of 3.00 mm, and MQ of 364.32. These results show that P3S4 achieved a strong balance between volumetric characteristics, stability, and deformation. Therefore, based on the complete Marshall test results, 3% Bodri River sand combined with 4%

Styrene-Butadiene Rubber (P3S4) represents the most favorable mixture variation among the combinations evaluated in this study.

CONCLUSION

Based on the results of the data analysis conducted in this study, the best Job Mix Design characteristics for Asphalt Concrete Wearing Course (AC-WC) were obtained from the P3S4 mixture, consisting of 3% Bodri River sand and 4% Styrene-Butadiene Rubber (SBR). The P3S4 mixture successfully satisfied the applicable Bina Marga 2025 specifications based on the Marshall test results. The mixture produced a VMA value of 19.33%, a VIM value of 3.53%, and a VFB value of 81.73%. In addition, the P3S4 mixture achieved a stability value of 1,119.14 kg and a flow value of 3.00 mm. The Marshall Quotient value obtained from the P3S4 mixture was 364.32 kg/mm based on the Marshall test results presented in the study. These results demonstrate that the P3S4 composition provided a favorable combination of volumetric and mechanical characteristics. Therefore, the P3S4 mixture can be considered suitable as an AC-WC pavement material because it fulfilled the required Marshall parameters in accordance with the Bina Marga 2025 specifications.

The Marshall test results further indicate that the P3S4 mixture provided the most favorable overall performance among the mixture variations evaluated in this study. The mixture containing 3% Bodri River sand and 4% SBR achieved the highest stability value among the variations, reaching 1,119.14 kg. This stability value indicates that the mixture had adequate resistance to loading while remaining within the required flow range of 3.00 mm. The mixture also produced a Marshall Quotient value of 364.32 kg/mm, reflecting a favorable relationship between its stability and flow characteristics. The VMA, VIM, and VFB values of 19.33%, 3.53%, and 81.73%, respectively, further demonstrate that the mixture possessed acceptable volumetric characteristics. Thus, the combination of 3% Bodri River sand and 4% SBR can be regarded as the optimum mixture variation based on the overall Marshall test results. Overall, the P3S4 composition provides a suitable alternative for AC-WC pavement material based on the requirements and results evaluated in this research.

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