

Aggregate Gradation Influence on Marshall and Stiffness of AC-WC Mixtures

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ABSTRACT

Aggregate gradation plays an important role in determining the performance of asphalt mixtures used in road pavement structures. Numerous studies have investigated the influence of aggregate gradation on Marshall characteristics and volumetric properties of asphalt mixtures. However, limited studies have examined the combined effect of aggregate gradation variations within the specification limits on both Marshall characteristics and stiffness performance of AC-WC mixtures. In addition, the influence of proportional gradation variations across the specification envelope has not been widely discussed. Therefore, this study aims to investigate the influence of aggregate gradation variations within the specification limits of Asphalt Concrete Wearing Course (AC-WC) on optimum asphalt content, Marshall characteristics, and mixture stiffness. Five aggregate gradation variations were prepared using the proportional method based on gradation limits. Laboratory tests were conducted using Marshall testing and Indirect Tensile Stiffness Modulus (ITSM) to evaluate mixture performance. The results show that aggregate gradation significantly affects the optimum asphalt content and mechanical characteristics of the mixture. Finer aggregate gradation increases the aggregate surface area and requires higher asphalt content. The optimum asphalt content for different gradation variations ranged from 5.7% to 6.3%. In addition, finer gradation produced lower air voids (VIM) and resulted in higher Marshall stability and mixture stiffness. These findings indicate that aggregate gradation has a significant influence on the volumetric and mechanical properties of AC-WC mixtures.

Keywords: aggregate gradation; asphalt mixture; optimum asphalt content; Marshall characteristics; mixture stiffness

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1. INTRODUCTION

Aggregate gradation plays an important role in determining the performance of asphalt mixtures used in road pavement structures. The gradation of aggregates controls the internal structure of the mixture, influencing volumetric properties, stability, stiffness, and resistance to deformation of asphalt concrete mixtures [1]–[4]. Several previous studies have shown that aggregate gradation significantly affects density, air void distribution, and rutting resistance in asphalt mixtures [5]–[7]. In asphalt concrete mixtures such as Laston or Asphalt Concrete Wearing Course (AC-WC), aggregate gradation is defined within specification limits consisting of upper and lower boundaries. These gradation limits allow the mixture to be composed of different proportions of coarse aggregates, fine aggregates, and mineral fillers. Mixtures with gradation closer to the lower boundary

tend to have coarser aggregate structures, while mixtures near the upper boundary contain higher proportions of fine aggregates and filler materials [8]. Therefore, the ideal gradation is generally located near the middle of the specification range because it provides a balanced composition of aggregate particles and improves the mechanical performance of the asphalt mixture [9], [10].

However, achieving an ideal aggregate gradation during asphalt mixture production and field construction is often difficult. Variations in gradation frequently occur due to operational conditions in asphalt mixing plants, aggregate stockpile management, and construction practices during the paving process. Several studies have reported deviations between the designed Job Mix Formula (JMF) and the gradation obtained during field implementation. Anggraini [11] reported that the deviation of aggregate gradation in AC-WC mixtures reached -3.11% at the asphalt mixing plant and -1.69% after paving. Similarly, Wirahaji [12] observed that aggregate gradation of AC-BC mixtures before compaction deviated by -5.38% from the designed JMF and -4.20% after compaction. Negative deviations indicate that the extracted gradation curve lies above the JMF curve but still within the maximum limits specified in the Indonesian highway specifications [13]. Similar findings have also been reported in previous studies that investigated gradation segregation and its impact on asphalt mixture performance [14], [15].

Field experience also indicates that variations in aggregate gradation can be influenced by construction practices and operational factors. Improper calibration of cold bin feeders, inadequate separation of aggregate fractions in stockpiles, and excessive filling of cold bins may cause mixing of aggregate sizes, resulting in deviations from the designed gradation. In addition, aggregate properties and construction processes such as compaction passes, aggregate abrasion resistance, and particle shape may also influence gradation changes and mixture performance [16]. These variations in gradation may significantly affect the characteristics of asphalt mixtures, including volumetric properties, Marshall stability, stiffness, and durability [17], [18].

Numerous studies have investigated the influence of aggregate gradation on asphalt mixture performance. Previous research shows that aggregate gradation strongly affects volumetric properties, rutting resistance, and mechanical performance of asphalt mixtures [2], [6], [7]. Wang et al. [19] reported that the strength of asphalt mixtures can be improved by optimizing aggregate gradation. Devulapalli et al. [20] explained that aggregate gradation significantly influences the interlocking behavior of aggregates and the binder drain-down characteristics in stone matrix asphalt mixtures. Furthermore, Ferreira et al. [21] indicated that appropriate gradation can reduce deformation in asphalt mixtures by improving aggregate interlocking and load distribution within the pavement structure. Other studies also confirmed that gradation variations influence stiffness, durability, and long-term pavement performance of asphalt mixtures [22], [23].

In addition, several studies conducted in Indonesia also highlight the importance of pavement performance and maintenance in road infrastructure systems. Pavement deterioration may occur due to traffic loading, environmental conditions, and inadequate material quality, which eventually reduces road serviceability and requires proper maintenance strategies [24]. Furthermore, research on Asphalt Concrete Wearing Course (AC-WC) mixtures indicates that the characteristics of asphalt mixtures are strongly influenced by material composition, including filler materials and aggregate properties, which affect Marshall parameters such as stability, flow, and volumetric characteristics [25].

Based on these considerations, this study investigates the influence of aggregate gradation variations within the specification limits of Asphalt Concrete Wearing Course (AC-WC) mixtures. The objective of this research is to determine the optimum asphalt content for different aggregate gradation variations and to evaluate the influence of these variations on the Marshall characteristics and stiffness performance of asphalt mixtures. The findings of this study are expected to provide a better understanding of how aggregate gradation affects the mechanical performance of AC-WC mixtures and contribute to improving asphalt mixture design and pavement construction practices.

2. RESEARCH METHOD

2.1 Materials and Equipment

The materials used in this study consisted of natural aggregates obtained from the Sukadana quarry, Karangasem, Bali, and penetration grade 60/70 asphalt produced by Pertamina. Asphalt mixture preparation and Marshall testing were conducted at the PT. Wangun Jaya laboratory, while material property tests, Cantabro abrasion loss, and Indirect Tensile Stiffness Modulus (ITSM) tests were carried out at the Highway Engineering Laboratory, Department of Civil Engineering, Faculty of Engineering, Udayana University.

Five aggregate gradation variations were prepared based on the specification limits. For each gradation variation, asphalt mixtures were produced using five asphalt content levels. Marshall specimens were prepared with three replicates for each asphalt content, resulting in 75 Marshall specimens in total. The average values of the three specimens were used to determine the Marshall characteristics.

The stiffness characteristics of the asphalt mixtures were evaluated using a Dynapave Universal Testing Machine (UTM-30) through the Indirect Tensile Stiffness Modulus (ITSM) test following established testing procedures [14].

2.2 Selection of Aggregate Gradation

In this study, the aggregate gradation used for the asphalt mixture followed the specification limits for AC-WC mixtures according to the Indonesian highway specification [8]. Five variations of aggregate gradation were selected to represent different gradation conditions within the allowable specification limits, namely the upper limit gradation, middle gradation, lower limit gradation, diagonal gradation 1, and diagonal gradation 2. These gradation variations were chosen to simulate potential gradation conditions that may occur during asphalt mixture production and construction processes, enabling an evaluation of their influence on optimum asphalt content and the performance characteristics of AC-WC mixtures.

These gradation variations represent different aggregate structures within the allowable specification limits. The selected gradations were intended to represent possible gradation variations that may occur during asphalt mixture production and field construction.

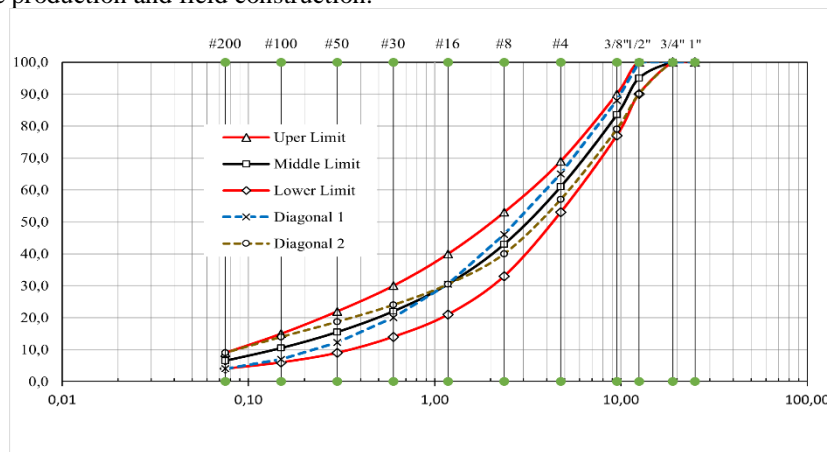


Figure 1. Aggregate gradation variations

Based on Figure 1, the cumulative gradation percentages and equivalent aggregate surface area for each gradation variation were calculated. The proportions of coarse aggregates, fine aggregates, and filler used in the AC-WC mixture are presented in Table 1.

Table 1. Aggregate gradation variations and equivalent surface area

ASTM	Sieve Size (mm)	Gradation Variations				
		Upper Limit	Middle	Lower Limit	Diagonal 1	Diagonal 2
1"	25,0	100,0	100,0	100,0	100,0	100,0
3/4"	19,0	100,0	100,0	100,0	100,0	100,0
1/2"	12,5	100,0	95,0	90,0	100,0	90,0
3/8"	9,5	90,0	83,5	77,0	88,0	79,0
# 4	4,8	69,0	61,0	53,0	65,0	57,0
# 8	2,36	53,0	43,0	33,0	46,0	40,0
# 16	1,18	40,0	30,5	21,0	30,5	30,5
# 30	0,60	30,0	22,0	14,0	20,0	24,0
# 50	0,30	22,0	15,5	9,0	12,3	18,8
# 100	0,15	15,0	10,5	6,0	7,0	14,0
# 200	0,075	9,0	6,5	4,0	4,0	9,0
Surface Area (m2/kg)		8,79	6,52	4,24	5,05	7,98
Fine Aggregate (%) (Pass #4)		60,0	54,5	49,0	61,0	48,0
Coarse Aggregate (%) (Ret #4)		31,0	39,0	47,0	35,0	43,0
Filler (%) (Pass #200)		9,0	6,5	4,0	4,0	9,0

2.3 Calculation of Aggregate Surface Area

The equivalent aggregate surface area was calculated using the Surface Area Factor (SAF) method developed by the Asphalt Institute [15]. The equivalent surface area was obtained by multiplying the percentage passing each sieve size by the corresponding surface area factor and summing the results for all sieve sizes. The surface area factors used in this study are presented in Table 2.

Table 2. Surface Area Factor (SAF)

Total % passing sieve No.	Maximum size (all sizes greater than 4,75mm)	4,75 mm (No.4)	2,36 mm (No.8)	1,18 mm (No.16)	600 µm (No.30)	300 µm (No.50)	150 µm (No.100)	75 µm (No.200)
SAF (m ² /kg)	0,41	0,41	0,82	1,64	2,87	6,14	12,29	32,77

2.4 Mixing Process and Initial Asphalt Content

After testing the material properties, the aggregates and asphalt binder were mixed to produce asphalt mixture specimens. The aggregate proportioning method used in this study did not involve blending individual aggregate fractions. Instead, the gradation limits specified for AC-WC mixtures were directly used by sieving aggregates for each sieve size as presented in Table 1.

The initial asphalt content was estimated using the empirical equation commonly used in asphalt mixture design, as expressed in Equation (1):

$$P_b = 0,035(\%CA) + 0,045(\%FA) + 0,18(\%FF) + k \quad (1)$$

where:

P _b	= estimated asphalt content (%)
CA	= percentage of coarse aggregate
FA	= percentage of fine aggregate
FF	= percentage of filler
k	= constant

For asphalt concrete mixtures, the constant value generally ranges from 0.5 to 1.0 depending on the aggregate absorption characteristics. In this study, a constant value of 1 was used because the aggregate absorption properties were within the normal range.

2.5 Indirect Tensile Stiffness Modulus (ITSM)

The stiffness characteristics of asphalt mixtures were evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test. This test was conducted using a Dynapave Universal Testing Machine (UTM-30) following the testing procedure specified by the British Standards Institution (BSI) [16].

In the ITSM test, repeated dynamic loads are applied through two loading strips placed on opposite sides of a cylindrical specimen. The horizontal deformation produced during loading is measured and used to determine the stiffness modulus of the asphalt mixture. The ITSM value represents the resistance of asphalt mixtures to deformation under repeated traffic loading and is commonly used as an indicator of pavement structural performance.

3. RESULTS AND DISCUSSION

3.1 Material Characteristics

The evaluation of aggregate and asphalt properties was conducted to ensure that the materials used in the asphalt mixture met the requirements specified for asphalt pavement construction. The physical properties of coarse aggregates, fine aggregates, filler, and penetration grade 60/70 asphalt must comply with the specifications defined by the Indonesian highway standard [8].

The aggregates used in this study consisted of coarse aggregates, fine aggregates, and filler obtained from PT. Wangun Jaya quarry located in Kubu, Karangasem, Bali. The asphalt binder used was penetration grade 60/70 asphalt produced by Pertamina. The results of laboratory testing for coarse aggregates, fine aggregates, filler, and asphalt binder are presented in Tables 3–5.

Table 3. Physical properties of coarse aggregates

Test	Test Method	Result	Specification
Bulk Specific Gravity		2,428	-
SSD Specific Gravity		2,476	-
Apparent Specific Gravity	SNI 1969:2016	2,549	-
Water Absorption (%)		1,945	Max. 3%
Aggregate Soundness			
Sodium Sulfate	SNI 3407:2008	6,74	Max. 12%
Los Angeles Abrasion			
100 revolutions	SNI 2417:2008	7,21	Max. 8%
500 revolutions		27,60	Max. 40%
Aggregate–Bitumen Adhesion	SNI 2439:2011	99,15	Min. 95%
Crushed Particles in Coarse Aggregate	SNI 7619:2012	91,90	95/90
Flat and Elongated Particles	SNI 8287 : 2016 Perbandingan 1 : 5	8,97	Max. 10%
Material Passing No. 200 Sieve	SNI ASTM C117 : 2012	0,32	Max. 1%

Table 4. Physical properties of fine aggregates and filler

No.	Test	Test Method	Result	Spec.
1	Bulk Specific Gravity		2,523	-
2	SSD Specific Gravity		2,571	-
3	Apparent Specific Gravity	SNI 1970:2016	2,649	-
4	Water Absorption (%)		1,885	Maks. 3%
5	Sand Equivalent	SNI 03-4428-1997	87,5	Min.50%
6	Uncompacted Void Content (%)	SNI 03-6877-2002	49,88	Min. 45
7	Clay Lumps	SNI 03-4141-1996	0,874	Maks 1%
8	Material Passing No. 200 Sieve (%)	SNI ASTM C117:2012	8,2	Maks. 10%
9	Filler Specific Gravity	B S 812	2,750	-

Table 5. Physical properties of penetration grade 60/70 asphalt

No.	Test	Test Method	Result	Spec.
1	Penetration at 25°C, 100 g, 5 s (0.1 mm)	SNI 2456-2011	67,17	60-70
2	Softening Point (°C)	SNI 2434-2011	48,5	≥48
3	Ductility at 25°C (cm)	SNI 2432-2011	152,1	≥100
4	Flash Point (°C)	SNI 2433-2011	273,0	≥232
5	Specific Gravity	SNI 2441:2011	1,031	≥1,0
TFOT Residue Test				
6	Loss on Heating (%)	SNI 06-2441-1991	0,668	≤0,8
7	Penetration after TFOT (0.1 mm)	SNI 2456-2011	62,51	≥54
8	Ductility after TFOT at 25°C (cm)	SNI 2432:2011	141,0	≥50

Based on the results presented in Tables 3–5, all tested material properties satisfied the requirements specified in the national asphalt mixture specifications [8]. These results indicate that the materials used in this study were suitable for the preparation of Asphalt Concrete Wearing Course (AC-WC) mixtures.

3.2 Marshall Characteristics for Determination of Optimum Asphalt Content

The performance of asphalt mixtures was evaluated using the Marshall test method, which is widely used to determine the stability, flow, density, and volumetric characteristics of asphalt mixtures [17]. From the Marshall test results, parameters such as stability, flow, Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB) were obtained.

Figures 2–7 present the relationships between asphalt content and the Marshall parameters, including stability, flow, density, VIM, VMA, and VFB.

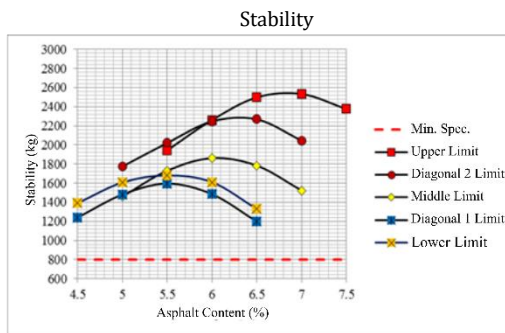


Figure 1. Asphalt content vs. stability

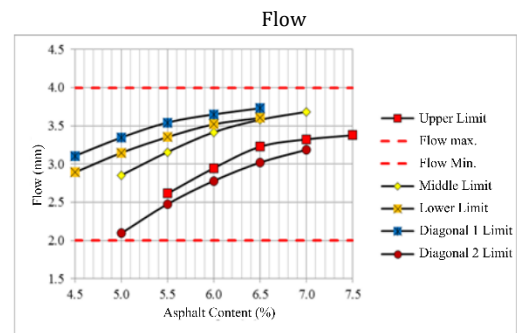


Figure 2. Asphalt content vs. flow

Density Analysis

VIM Analysis

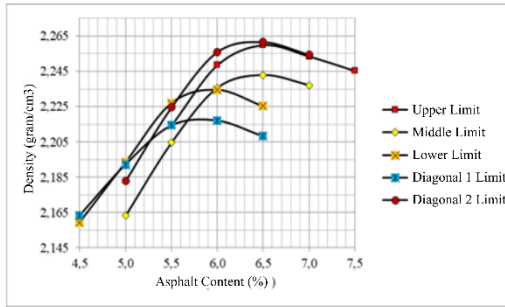


Figure 3. Asphalt content vs. density

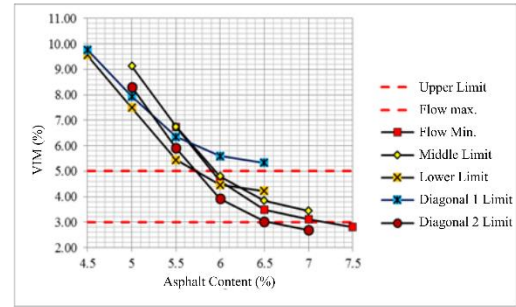


Figure 4. Asphalt content vs. VIM

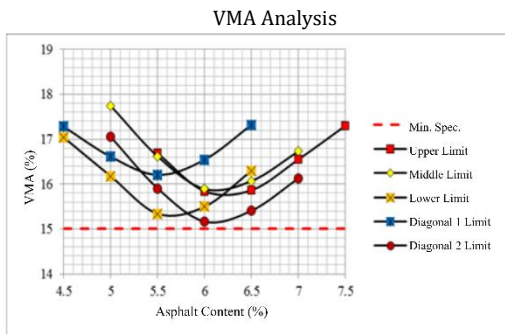


Figure 5. Asphalt content vs. VMA

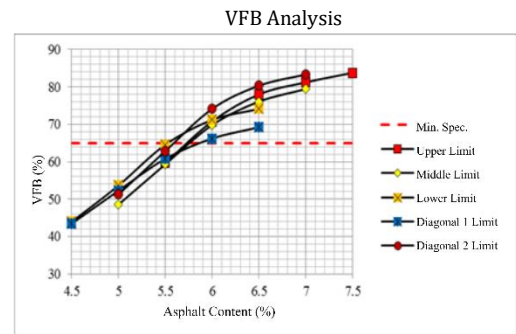


Figure 6. Asphalt content vs. VFB

3.3 Determination of Optimum Asphalt Content (OAC)

The Optimum Asphalt Content (OAC) for each aggregate gradation variation was determined using the bar chart approach based on the Marshall mix design parameters. In this approach, the experimental results obtained from various asphalt content levels were analyzed to assess the relationship between asphalt content and the corresponding Marshall characteristics.

The parameters considered in the OAC determination included stability, flow, density, Marshall quotient (MQ), Voids in the Mix (VIM), Voids in Mineral Aggregate (VMA), Voids Filled with Bitumen (VFB), and Voids in the Mix at Refusal Density (VIM PRD). Each parameter was evaluated against the specified criteria to identify the range of asphalt content that satisfies the Marshall design requirements.

The final OAC was selected from the asphalt content range that fulfills all specification limits while providing balanced volumetric and mechanical performance of the asphalt mixture.

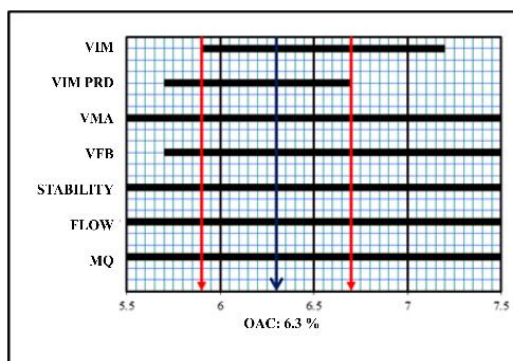


Figure 1. OAC for Upper Limit Gradation

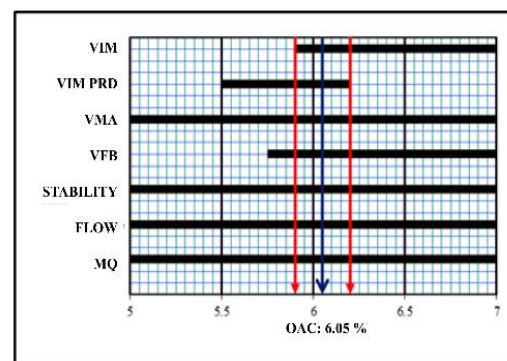


Figure 2. OAC for Upper Middle Limit

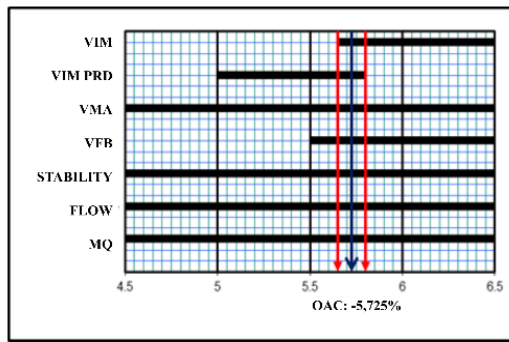


Figure 3. OAC for Lower Limit Gradation

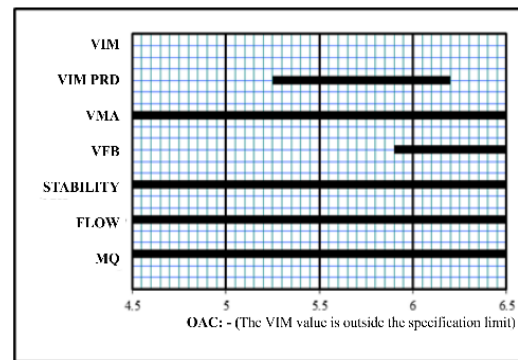


Figure 4. OAC for Diagonal 1 Gradation

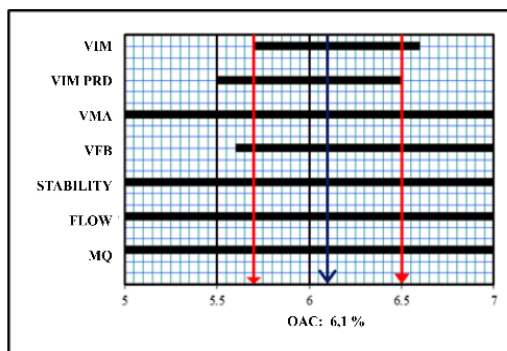


Figure 5. OAC for Diagonal 2 Gradation

Table 1. OAC Resume

Aggregate Gradation Variation	Gradation Type	Optimum Asphalt Content (OAC) (%)
Upper Limit	Fine	6.30
Middle Limit	Ideal	6.05
Lower Limit	Coarse	5.70
Diagonal 1	Coarse – Fine	–
Diagonal 2	Fine – Coarse	6.10

Table 6 shows that the upper limit gradation required the highest optimum asphalt content of 6.3%, while the lower limit gradation required the lowest asphalt content of 5.7%. The diagonal gradation 2 mixture required an OAC of 6.1%. Meanwhile, the diagonal gradation 1 mixture did not satisfy the VIM specification requirements for all asphalt content levels tested; therefore, the optimum asphalt content for this gradation could not be determined.

3.4 Marshall Characteristics at Optimum Asphalt Content

The Marshall characteristics of the asphalt mixtures at their respective optimum asphalt contents are summarized in Table 7.

Table 7. Marshall characteristics of asphalt mixtures at OAC

Mixture Properties	Unit	Result				Spec.
		Gradation Variations				
		Upper Limit	Middle Limit	Lower Limit	Diagonal 2	
Compaction blows per face	Time	75	75	75	75	75
Optimum Asphalt Content (OAC)	%	6,30	6,05	5,70	6,10	-
Asphalt Absorption	%	0,91	0,94	0,97	0,92	-
Effective Asphalt Content	%	5,39	5,11	4,73	5,18	-
Dust-to-Effective Binder Ratio (Passing No. 200)		0,60	0,79	1,18	0,58	0,6 - 1,6
Voids in Mixture (VIM)	%	3,95	4,31	4,87	3,72	3 - 5
Voids in Mineral Aggregate (VMA)	%	15,86	15,56	15,24	15,19	Min. 15
Voids Filled with Bitumen (VFB)	%	75,11	72,31	68,07	75,51	Min. 65
Marshall Stability	kg	2374,8	1866,6	1693,8	2219,2	Min. 800
Flow	mm	3,10	3,16	3,5	2,87	2 - 4
Retained Marshall Stability	%	92,97	92,22	90,61	94,70	Min. 90
Voids in Mixture at Refusal Density	%	3,05	3,57	2,97	2,58	Min. 2

The results show that the Marshall characteristics for the tested gradation variations generally met the specification requirements for AC-WC mixtures according to Indonesian highway standards [8]. The mixture with the upper limit gradation produced the highest Marshall stability value of 2374.8 kg, while the lower limit gradation produced the lowest stability value.

These results indicate that aggregate gradation significantly affects the volumetric and mechanical characteristics of asphalt mixtures. Previous studies also reported that variations in aggregate gradation can influence mixture stability and volumetric properties [1], [3], [4].

3.5 Indirect Tensile Stiffness Modulus (ITSM)

The stiffness characteristics of asphalt mixtures were evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test. The ITSM test measures the resistance of asphalt mixtures to deformation under repeated loading conditions [16]. The ITSM values obtained for each gradation variation are presented in Table 8.

Table 8. ITSM values for different gradation variations

Gradation	Gradation Type	ITSM (MPa)	
		20°C	VIM (%)
Lower Limit	Coarse	2644,0	4,87
Middle	Ideal	2994,0	4,31
Upper Limit	Fine	3292,0	3,95
Diagonal 2	Fine to Coarse	3688,5	3,72

The results show that the ITSM value increased as the air void content (VIM) decreased. The mixture with diagonal gradation 2 produced the highest stiffness value of 3688.5 MPa with the lowest VIM value of 3.72%. Conversely, the mixture with lower limit gradation produced the lowest stiffness value. The relationship between VIM and ITSM is illustrated in Figure 13.

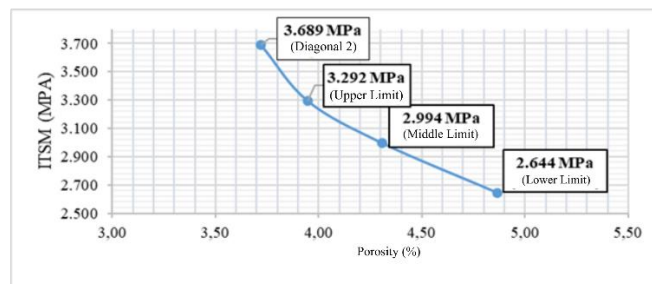


Figure 13. Relationship between VIM and ITSM

These results indicate that mixtures with lower air void content tend to produce higher stiffness values. Similar findings were reported by Al-Mosawe et al. [18], who observed that increased mixture density leads to higher stiffness values in asphalt mixtures.

3.6 Cantabro Abrasion Loss

The Cantabro Abrasion Loss (CAL) test was conducted to evaluate the resistance of asphalt mixtures to aggregate loss due to repeated abrasion. The results of the Cantabro test for each gradation variation at the respective optimum asphalt contents are shown in Figure 14.

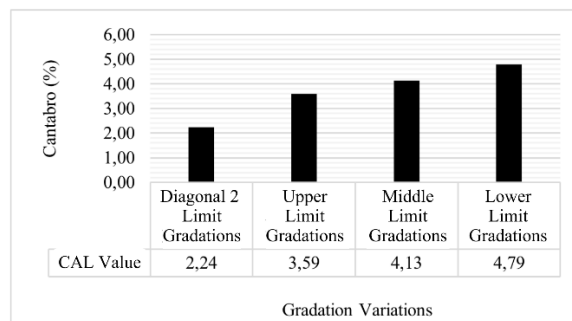


Figure 14. Cantabro abrasion loss for different gradation variations

The results indicate that the Cantabro abrasion loss values are closely related to the air void content (VIM) of the mixtures. Mixtures with higher VIM values tend to exhibit higher abrasion loss because the larger void spaces reduce the internal cohesion of the asphalt mastic and weaken the bonding between aggregates. As a result, aggregates are more easily detached from the mixture when subjected to abrasion.

In contrast, mixtures with lower VIM values generally demonstrate better resistance to abrasion due to the denser internal structure and improved aggregate interlock. The presence of finer aggregate particles increases the total surface area of aggregates and allows the asphalt binder to coat the particles more uniformly,

which enhances the adhesive bonding between aggregates and asphalt binder. This condition improves the internal stability of the mixture and reduces the tendency for aggregate loss.

Although there is no specific specification requirement for Cantabro abrasion loss in AC-WC mixtures, all mixtures in this study satisfied the recommended maximum value of 16% suggested by previous studies [19]. These results indicate that the aggregate gradation plays an important role in controlling the internal structure of the mixture, which subsequently affects its resistance to abrasion and particle loss.

4. CONCLUSION

Based on the results and discussion presented in this study, it can be concluded that aggregate gradation significantly influences the performance characteristics of Asphalt Concrete Wearing Course (AC-WC) mixtures.

First, the optimum asphalt content (OAC) is influenced by variations in aggregate gradation that produce different aggregate surface areas. Mixtures with larger aggregate surface areas require higher asphalt content to adequately coat the aggregate particles while still satisfying the specification parameters.

Second, the Marshall characteristics of mixtures with upper limit, middle, lower limit, and diagonal 2 gradations satisfied the AC-WC specification requirements according to the Indonesian highway specifications. The upper limit gradation produced the highest Marshall stability due to higher density obtained during compaction, while the lower limit gradation produced the highest air void content (VIM).

Third, the stiffness characteristics evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test show an inverse relationship with the air void content in the mixture. Mixtures with lower VIM values produced higher stiffness values. The diagonal 2 gradation produced the highest stiffness value due to the lowest VIM value among the tested mixtures. Furthermore, the stiffness value is inversely related to Cantabro Abrasion Loss, indicating that mixtures with higher stiffness tend to have better resistance to aggregate loss.

The results of this study indicate that controlling aggregate gradation is important in asphalt mixture design to achieve optimal volumetric properties and mechanical performance. Further studies are recommended to investigate the influence of aggregate gradation under field conditions and its relationship with long-term pavement performance.

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CONFLICT OF INTEREST STATEMENT

The Authors state no conflict of interest.

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