

Study On Marshal Characteristics and Residual Stability During Variations In Soaking Time Of AC-WC Asphalt Mixtures Due To The Addition of LDPE Plastic Aggregates

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Abstract. This study aims to analyze the Marshall characteristics and retained stability of Asphalt Concrete-Wearing Course (AC-WC) mixtures incorporating Low-Density Polyethylene (LDPE) plastic with variations in immersion duration. The research was motivated by the premature deterioration of pavement structures caused by water infiltration and the quality of asphalt mixtures. An experimental laboratory method was employed in accordance with the 2018 General Specifications of Bina Marga, including the determination of the Optimum Asphalt Content (OAC), specimen preparation, and Marshall as well as retained stability testing with immersion periods of 1 and 4 days and LDPE contents of 6%, 9%, and 12%. The results indicated an Optimum Asphalt Content (OAC) of 5.88%. The highest stability values were obtained from the mixture containing 12% LDPE, reaching 2360.23 kg after 1 day of immersion and 1936.87 kg after 4 days of immersion. Flow values and volumetric parameters (VIM, VMA, and VFA) generally satisfied the specification requirements. The highest retained stability values reached 96.0% for the 1-day immersion period and 104.5% for the 4-day immersion period, while the lowest value was 84.0%. Although stability decreased with increasing immersion duration, most mixtures still met the minimum specification requirements. It can be concluded that the incorporation of LDPE into AC-WC mixtures enhances Marshall characteristics and improves resistance to water-induced damage.

Keywords: author AC-WC, Marshall Characteristics, Retained Stability, Low-Density Polyethylene (LDPE), Immersion Duration, Optimum Asphalt Content (OAC)

1. Introduction

Road conditions in Indonesia frequently experience deterioration before reaching their designated design life. Various forms of pavement distress, such as cracking, rutting, potholes, and ravelling, commonly occur due to high traffic volumes, inadequate material quality, and environmental factors, particularly water accumulation on pavement surfaces (Nugroho et al., 2025). Among these factors, water is considered one of the primary causes of accelerated deterioration in asphalt pavements. One approach to improving asphalt performance is the incorporation of additives, such as polymers, plastics, or charcoal-based materials, resulting in what is commonly referred to as modified asphalt. The

addition of polymers to asphalt mixtures is expected to enhance the physical properties of asphalt, particularly in terms of improving stability (Priyatno et al., 2017). The type of plastic used in this study is Low-Density Polyethylene (LDPE) pellets. The mixing process was carried out using 60/70 penetration-grade asphalt binder for application in the Asphalt Concrete–Wearing Course (AC-WC) pavement layer (Priyatno et al., 2017) (Finanditho et al., 2025)

2. Road Pavement

Road pavement is a critical component of land transportation infrastructure, as it functions to support traffic loads and effectively distribute them to the subgrade. Road pavements can generally be classified into three main types: flexible pavement, rigid pavement, and composite pavement. Each type possesses distinct characteristics, structural configurations, material compositions, and construction methods (Wibowo et al., 2025).

2.1 Surface Layer

One of the most widely used types of hot-mix asphalt is Asphalt Concrete (AC), commonly referred to in Indonesia as Lapis Beton Aspal (Laston). In pavement specifications, Asphalt Concrete is recognized as a pavement material with good resistance to plastic deformation, although it is relatively susceptible to cracking. AC-WC (Asphalt Concrete-Wearing Course) is one of the three types of Asphalt Concrete mixtures, alongside AC-Base and AC-Binder Course (AC-BC). These Asphalt Concrete mixtures are based on asphalt mixture specifications that have been developed and refined by the Directorate General of Highways (Bina Marga) in collaboration with the Road Research and Development Center (Pusat Penelitian dan Pengembangan Jalan) (Harnaeni et al., 2022).

2.2 Aggregate

Aggregate is a hard and rigid material used as a constituent component in asphalt mixtures. It may consist of various granular or crushed materials, such as sand, gravel, crushed stone, stone dust, and other aggregate types that serve as the primary structural framework of the mixture (Priyatno et al., 2017). According to ASTM, aggregate is a solid material in either coarse or fine particle form that constitutes the major component of pavement structures, accounting for approximately 90–95% of the total mixture weight. Therefore, aggregate quality has a significant influence on pavement performance. Aggregate selection should consider factors such as the type of construction, gradation, particle size, cleanliness, durability, particle shape, surface texture, adhesion to asphalt binder, and specific gravity. Aggregate particles typically range in size from 19 mm to 0.075 mm (Sukirman, 2016)

2.3 AC-WC Mixture Design

The design of the Asphalt Concrete–Wearing Course (AC-WC) mixture refers to the 2018 General Specifications of the Directorate General of Highways (Bina Marga), which consist of coarse aggregate, fine aggregate, mineral filler, and asphalt binder. Aggregate gradation is designed to comply with the specified standards to produce a dense, stable, and impermeable pavement layer. The 60/70 penetration-grade asphalt functions as a binder while also providing flexibility and durability to the mixture. Meanwhile, the mineral filler serves to fill the voids within the aggregate structure and enhance the cohesion of the mixture. The Optimum Asphalt Content (OAC) is determined using the Marshall mix design method based on parameters including stability, flow, Voids in the Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA). These parameters are used to ensure that the resulting mixture possesses adequate strength, durability, and performance as a wearing course layer for road pavements (Direktorat Jenderal Bina Marga., 2025)

2.4 Asphalt

Bitumen is a dark-colored, viscous binding material that may exist in either solid or semi-solid form and can be obtained from natural sources or industrial processes. There are three main types of bitumen,

namely asphalt, tar, and pitch. Asphalt is derived either naturally or through petroleum refining processes, whereas tar and pitch are products of chemical processing. Among these materials, asphalt is the most widely used in road pavement construction; therefore, the term bitumen is often used interchangeably with asphalt(Sukirman, 2016).

2.5 Low-Density Polyethylene (LDPE) Pellets

Low-Density Polyethylene (LDPE) is a petroleum-based thermoplastic polymer characterized by a low density ranging from 0.910 to 0.940 g/cm³ and a melting point of approximately 105–115°C. LDPE exhibits high chemical stability, resistance to chemical reactions under ambient conditions, and excellent water resistance. These properties make LDPE a suitable additive for improving the resistance of asphalt mixtures to moisture damage and weathering. However, the material may undergo degradation when exposed to strong oxidizing agents or certain solvents (Harnaeni et al., 2022)

3. Research Methodology

3.1 Research Location

This study was conducted at the Materials and Pavement Laboratory, Civil Engineering Study Program, PGRI University of Semarang. The research activities included material preparation, specimen fabrication, and testing of Marshall characteristics and retained stability. All procedures were carried out systematically in accordance with the applicable standards and technical specifications

3.2 Research Flowchart

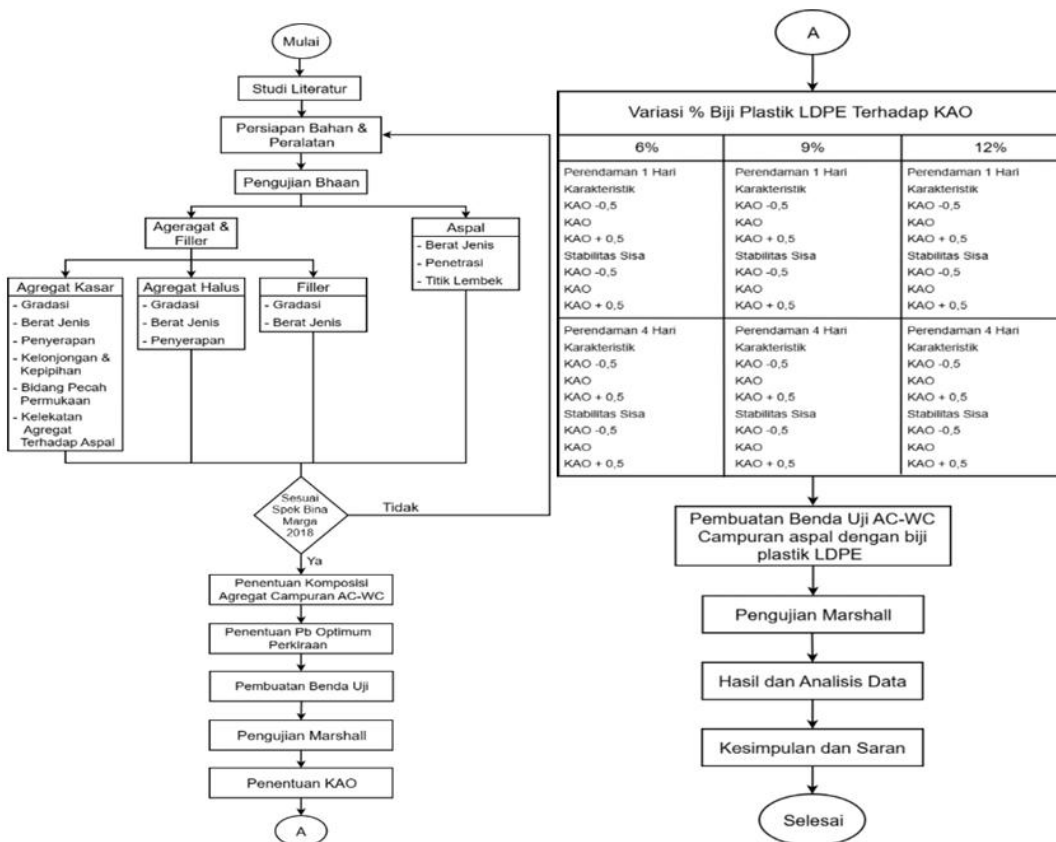


Figure 1. Research Methodology

3.3 Preparation of Equipment and Materials

- a. Research Equipment
 - 1) Marshall Stability Testing Machine
 - 2) Gas Stove/Heating Burner
 - 3) Heating Pan
 - 4) Digital Balance with an accuracy of 0.1 g
 - 5) Thermometer
 - 6) Water Bath
 - 7) Marshall Compaction Hammer
 - 8) Marshall Mold
 - 9) Mixing Spoon and Spatula
 - 10) Heat-Resistant Gloves
 - 11) Sieve Set
 - 12) Immersion Tank
 - 13) Proving Ring and Dial Gauge
- b. Research Materials
 - 1) Shell 60/70 Penetration-Grade Asphalt Binder
 - 2) 3/4-inch Coarse Aggregate
 - 3) 1/2-inch Coarse Aggregate
 - 4) Fine Aggregate (Stone Dust)
 - 5) Mineral Filler (Cement)
 - 6) Asphalt Mixture Specimens

3.4 Material Testing

- a. Aggregate Gradation Analysis
- b. Specific Gravity and Water Absorption Test
- c. Flakiness and Elongation Index Test
- d. Percentage of Crushed Faces Test
- e. Asphalt-Aggregate Adhesion Test
- f. Penetration Test
- g. Softening Point Test

3.5 Determination of AC-WC Aggregate Composition

The determination of the AC-WC aggregate composition was carried out by combining coarse aggregate, fine aggregate, and mineral filler to ensure that the resulting gradation complied with the 2018 General Specifications of the Directorate General of Highways (Bina Marga), Division 6 (Direktorat Jenderal Bina Marga., 2020). The mixture proportions were calculated based on the gradation data of each aggregate fraction using a trial-and-error approach until a combined gradation within the specified limits was achieved.

3.6 Specimen Preparation Procedure

The specimen preparation procedure began with determining the AC-WC mixture composition and the variations in asphalt content (approximately 4.5%–6.5%). The materials were then heated, with the asphalt binder maintained at 150–160°C and the aggregates at approximately 155°C. The materials were weighed to obtain a total mixture mass of approximately 1,200 g. The heated materials were mixed thoroughly until a homogeneous mixture was achieved. The mixture was then compacted using the

Marshall compaction method with 75 blows applied to each face of the specimen. After compaction, the specimens were allowed to cool and cure for approximately 24 hours. The specimens were subsequently removed from the molds and labeled according to their respective asphalt contents for further testing.

3.7 Marshall Testing

Specimen preparation for Marshall testing involved producing a minimum of three specimens for each asphalt content level. Each specimen was compacted with 75 blows per face and allowed to stand for approximately 24 hours before being labeled and weighed. The specimens were then immersed in water for 24 hours, weighed while submerged, conditioned in a water bath at a temperature of $60 \pm 1^\circ\text{C}$, and weighed in the Saturated Surface Dry (SSD) condition. Marshall testing was conducted using a calibrated Marshall testing machine at a loading rate of 50.8 mm/min until the maximum load was reached. During the test, the stability and flow values were recorded. The test results were subsequently calculated and analyzed to determine the Marshall characteristics of the mixtures, including stability, flow, Marshall Quotient (MQ), Voids in the Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA).

4. Results And Discussion

4.1 Coarse Aggregate Testing

Table 1. Coarse Aggregate Testing Maximum 3/4"

Sieve	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200
% Passing	100	44.41	17.08	0.20	0.13	0.10	0.10	0.10	0.10	0.06

Table 2. Coarse Aggregate Testing Maximum 1/2"

Sieve	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200
% Passing	100	99.3	94.1	12.4	2.0	1.2	1.1	1.1	0.8	0.4

The coarse aggregate gradation test was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the particle size distribution through sieve analysis. The testing procedure consisted of drying the aggregate sample, weighing the sample, performing a series of sieve analyses using progressively smaller sieve sizes, and weighing the aggregate retained on each sieve. The test results were calculated as cumulative percentages passing each sieve and subsequently compared with the specified gradation requirements. This evaluation was carried out to assess the suitability of the aggregate for use in asphalt mixture production.

Table 3. Specific Gravity and Absorption Testing Maximum 3/4"

Testing	Description	Sample 1	Sample 2	Unit
Dry Weight in Air	A	1624	1621	gram
Oven Dry Weight	B	1490	1488	gram
Weight in Water	C	952	949	gram
SSD Weight (Saturated Surface Dry)	D	1505	1502	gram
Testing				
Description	Sample 1	Sample 2		
Bulk Specific Gravity	2.694	2.681	2.688	
SSD Specific Gravity	2.722	2.710	2.716	
Apparent Specific Gravity	2.770	2.761	2.765	
Water Absorption (%)	1.01	1.08	1.04	

Table 4. Specific Gravity and Absorption Testing Maximum 1/2"

Testing	Description	Sample 1	Sample 2	Unit
Dry Weight in Air	A	1624	1625	gram

Oven Dry Weight	B	1489	1486	gram
Weight in Water	C	952	955	gram
SSD Weight (Saturated Surface Dry)	D	1506	1505	gram
Testing				
Description		Sample 1	Sample 2	
Bulk Specific Gravity		2.688	2.702	2.688
SSD Specific Gravity		2.718	2.736	2.716
Apparent Specific Gravity		2.773	2.761	2.765
Water Absorption (%)		1.14	1.28	1.21

The specific gravity and water absorption test of coarse aggregate was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the bulk specific gravity, apparent specific gravity, and water absorption characteristics of the aggregate. Low water absorption values indicate that the aggregate is denser and less permeable to water. When the test results satisfy the specified requirements, the aggregate is considered suitable for use in asphalt mixtures, as it is capable of providing adequate stability and strong bonding characteristics within the asphalt mixture.

Table 5. Flakiness and Elongation Testing
Flakiness & Elongation of Retained 1/2" Aggregate
Initial Aggregate Weight = 1500 grams

Description	Weight (Gram)	Percentage (%)
Flaky Particles	120.5	8%
Elongated Particles	137	9%
Total	1504	100%

Based on the test results, the percentage of flaky particles was 8%, while the percentage of elongated particles was 9%. Both values are below the maximum allowable limit of 25% specified in the 2018 General Specifications of the Directorate General of Highways (Bina Marga), indicating compliance with the required standards. The relatively low percentages of flaky and elongated particles indicate that the aggregate possesses a favorable particle shape. Such characteristics enhance aggregate interlocking and contribute positively to the stability of the asphalt mixture.

Table 6. Results of the Coarse Aggregate Crushed Faces Test

Weight of Aggregate with Crushed Faces (A) (g)			Weight of Retained Aggregate (B) (g)	Angularity = $A/B \times 100$ (%)		
0 Crushed Face	1 Crushed Face	> 2 Crushed Faces		0 Crushed Face	1 Crushed Face	> 2 Crushed Faces
45.7	32.5	1421.8	1500	3.05	2.17	94.79
				97.83		

The test was conducted to determine the percentage of aggregate particles possessing crushed faces, which serves as an indicator of the effectiveness of the rock crushing process. Aggregates with an adequate proportion of crushed faces exhibit rough surfaces and angular particle shapes, which enhance particle interlocking and improve the stability of asphalt mixtures.

4.2 Fine Aggregate Testing

Table 7. Fine Aggregate Gradation Testing

Sieve	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200
% Passing	100	100	100	96.9	80.5	56.9	36.6	28.3	10.6	5.3

The fine aggregate gradation test was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the particle size distribution through sieve analysis. The testing procedure involved drying the aggregate sample, weighing the sample, performing sieve analysis using a series of standard sieves, and weighing the material retained on each sieve. The test results were calculated as cumulative percentages passing each sieve and subsequently compared with the specified gradation limits. This comparison was carried out to evaluate the suitability of the fine aggregate for use in asphalt mixtures.

Table 8. Fine Aggregate Specific Gravity and Water Absorption Test

Test Parameter	Sample 1 (g)	Sample 2 (g)	Average
A. Weight of Pycnometer	186.1	185.8	
B. Weight in SSD Condition	500.0	500.0	
C. Weight of Pycnometer + Fine Aggregate (SSD Condition) + Water	995.3	996.8	
D. Weight of Pycnometer + Water	682.4	682.2	
E. Oven-Dry Weight of Fine Aggregate	492.0	493.0	
Apparent Specific Gravity	2.747	2.763	2.755
Bulk Specific Gravity (Dry Condition)	2.630	2.659	2.644
Bulk Specific Gravity (SSD Condition)	2.672	2.697	2.685
Water Absorption (%)	1.626	1.420	1.523

The fine aggregate specific gravity and water absorption test was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the bulk specific gravity, apparent specific gravity, and water absorption characteristics of the aggregate. Low water absorption values indicate that the aggregate has a denser structure and greater resistance to water penetration. When the test results satisfy the specified requirements, the fine aggregate is considered suitable for use in asphalt mixtures, as it can provide adequate stability and strong bonding characteristics within the mixture.

4.3 Filler Testing

Table 9. Filler Gradation Testing

Sieve	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200
% Passing	100	100	100	100	100	100	100	100	93.4	77.4

The cement filler gradation test was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the fineness of the particles, particularly those passing the No. 200 sieve (0.075 mm). Proper gradation helps fill voids, improve stability, and strengthen the bond between aggregate and asphalt. The test results were compared with the specification requirements to ensure the suitability of the filler and its ability to provide optimal performance.

Table 10. Filler Specific Gravity Testing

No	Description	Result	
		1	2
1	Specimen Weight	64	64
2	Initial Reading of Bottle + Kerosene	1	1
3	Final Reading of Bottle + Kerosene	21.4	21.6

4	Liquid Scale Reading + Specimen	22.4	22.6
5	Cement Specific Gravity Result	3.137	3.107
Average		3.122	

The fine aggregate specific gravity and water absorption test was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga) to determine the bulk and apparent specific gravity as well as the water absorption of the aggregate. Low absorption values indicate that the aggregate is denser and more resistant to water penetration. If the test results comply with the specification requirements, the aggregate is considered suitable for use in asphalt mixtures, as it can provide adequate stability and strong bonding properties.

4.4 Results of the Shell 60/70 Penetration-Grade Asphalt Binder Test

Table 11. Specific Gravity Testing of Asphalt

No	Measurement	Index	Sample 1	Sample 2
1	Pycnometer Weight	A	31.2	31.2
2	Pycnometer + Water Weight	B	59.4	59.4
3	Pycnometer + Specimen Weight	C	42.3	47.1
4	Pycnometer + Water + Specimen Weight	D	59.8	60
Calculation		Average	Sample 1	Sample 2
		1.038	1.037	1.039

Based on the test results, the specific gravity of the Shell 60/70 penetration-grade asphalt binder complies with the requirements of the 2018 General Specifications of the Directorate General of Highways (Bina Marga), Revision 2. This indicates that the asphalt binder possesses good quality and is suitable for use in asphalt mixture design.

Table 12. Results of the Penetration Test of Shell 60/70 Penetration-Grade Asphalt Binder

No.	Sample 1	Sample 2
1	64	64
2	64	64
3	63	63
4	64	65
5	64	65
Average	64	64.2
		64.1

The penetration test results of the Shell 60/70 penetration-grade asphalt binder showed values within the specification range of 60 to 70 (0.1 mm) as stipulated in the 2018 General Specifications of the Directorate General of Highways (Bina Marga). Therefore, the asphalt binder satisfies the requirements for a 60/70 penetration-grade asphalt binder.

Table 13. Results of the Softening Point Test of Shell 60/70 Penetration-Grade Asphalt Binder

No.	Temperature Observation		Time (Minute)		Softening Point (°C)	
	°C	°F	Sample 1	Sample 2	Sample 1	Sample 2
1	5	41	01.16.06	01.16.06		
2	10	50	04.13.99	04.13.99		
3	15	59	05.48.98	05.48.98		
4	20	68	07.51.93	07.51.93		
5	25	77	10.25.18	10.25.18		
6	30	89.6	13.28.97	13.28.97		
7	35	95	17.11.87	17.11.87		
8	40	104	20.43.21	20.43.21		
9			23.21.79	23.24.53	44	44

Based on the softening point test results of the 60/70 penetration-grade asphalt binder, the obtained value was below the minimum requirement specified in the 2018 General Specifications of the Directorate General of Highways (Bina Marga), Revision 2. Therefore, the asphalt binder did not satisfy the specified requirements. This result indicates that the asphalt binder has lower resistance to high temperatures and is more susceptible to softening or deformation when subjected to traffic loads and elevated temperature conditions.

4.5 Marshall Test Results for the Determination of Optimum Asphalt Content (OAC)

Table 14. Marshall Test Results for the Determination of Optimum Asphalt Content (OAC)

No.	Characteristic	Specification	% Asphalt Content by Total Aggregate				
			4.5%	5.0%	5.5%	6.0%	6.5%
1	Bulk Density		2.36	2.38	2.37	2.40	2.39
2	VMA (%)	Min 15	16.48	16.28	16.90	16.44	17.06
3	VIM (%)	3-5	7.446	6.019	5.518	3.774	3.263
4	VFA (%)	65	54.946	63.129	67.555	77.155	80.879
5	Stability (kg)	Min 800	1793.40	1532.62	1692.26	1433.25	1347.99
6	Flow (mm)	2-4	3.27	3.37	3.53	3.90	4.13
7	MQ (kg/mm)		551.79	458.62	480.06	368.22	326.26

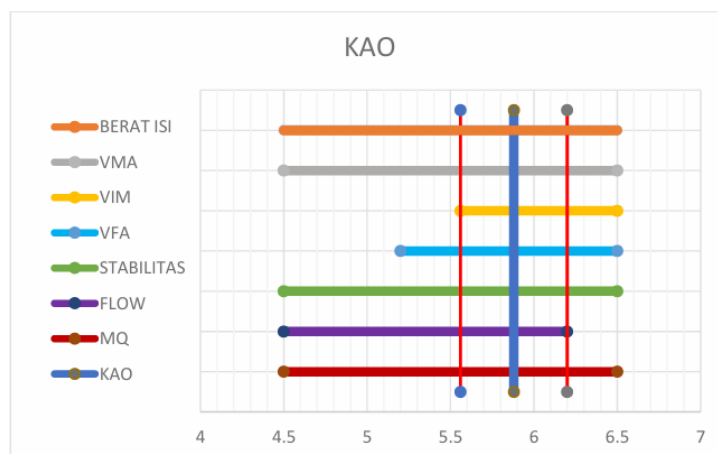


Figure 2. Optimum Asphalt Content (OAC) Graph

The determination of the Optimum Asphalt Content (OAC) for the AC-WC mixture was carried out using asphalt content variations ranging from 4.5% to 6.5% and a total of 15 specimens. The evaluation was conducted in accordance with the 2018 General Specifications of the Directorate General of Highways (Bina Marga), considering parameters such as bulk density, VMA, VIM, VFA, stability, flow, and MQ. The analysis results indicated an Optimum Asphalt Content (OAC) of 5.88%, with an effective asphalt content range of 5.56% to 6.20%, which satisfied the applicable technical requirements.

4.6 Marshall Characteristics of AC-WC Mixtures Incorporating 6% Low-Density Polyethylene (LDPE) Plastic Pellets

Table 15. Marshall Testing of 6% LDPE with 1-Day Immersion

No.	Characteristic	Specification	% Asphalt Content by Total Aggregate		
			5.38%	5.88%	6.38%
1	Bulk Density		2.37	2.38	2.38
2	VMA (%)	Min 15	16.96	16.85	17.37
3	VIM (%)	3-5	5.88	4.54	3.91
4	VFA (%)	65	65.36	73.05	77.46
5	Stability (kg)	Min 800	2517.23	1995.53	1375.92

6	Flow (mm)	2-4	2.58	2.84	3.41
7	MQ (kg/mm)		977.51	704.03	404.47

The test results showed that increasing the asphalt content from 5.38% to 6.38% resulted in relatively stable bulk density values, while the VMA values consistently satisfied the specification requirements. The VIM values decreased with increasing asphalt content and remained within the specified range at asphalt contents of 5.88% and 6.38%, whereas the VFA values increased and met the required criteria. On the other hand, both stability and Marshall Quotient (MQ) values decreased as the asphalt content increased, although they remained above the minimum specification limits. Meanwhile, the flow values increased, indicating that the asphalt mixture became more plastic and exhibited greater deformation under loading.

Table 16. Marshall Testing of 6% LDPE with 4-Day Immersion

No.	Characteristic	Specification	% Asphalt Content by Total Aggregate		
			5.38%	5.88%	6.38%
1	Bulk Density		2.36	2.38	2.38
2	VMA (%)	Min 15	17.28	17.59	17.37
3	VIM (%)	3-5	6.24	5.39	3.92
4	VFA (%)	65	63.90	69.36	77.46
5	Stability (kg)	Min 800	2377.87	1735.78	1407.67
6	Flow (mm)	2-4	2.71	3.06	3.38
7	MQ (kg/mm)		877.93	572.79	416.59

Based on the results of the Marshall test after 4 days of immersion for the mixture containing 6% LDPE, the bulk density values remained relatively stable, ranging from 2.36 to 2.38. All asphalt content variations satisfied the VMA requirement, whereas the VIM and VFA requirements were only met at asphalt contents of 5.88% and 6.38%; the mixture containing 5.38% asphalt content did not satisfy these criteria. The stability values remained above the minimum specification limit despite showing a decreasing trend. The flow values were within the specified range, while the Marshall Quotient (MQ) decreased, indicating that the mixture became increasingly plastic. Overall, an asphalt content of 5.88% was considered the most optimal, as it most closely satisfied all specification requirements.

4.7 Retained Stability Index (RSI) of AC-WC Asphalt Mixtures Incorporating Low-Density Polyethylene (LDPE) Plastic Pellets

Table 17. Marshall Retained Stability Test Results for AC-WC Mixtures with 6% LDPE Addition

Asphalt Content (%)	Specification (%)	Retained Stability (%)	
		1 Day Immersion	4 Days Immersion
5.38	Min. 90	98.1	90.4
5.88	Min. 90	101.1	98.8
6.38	Min. 90	92.3	81.2

Based on the retained stability test results of the mixture containing 6% LDPE, all asphalt content variations satisfied the minimum specification requirement of 90% after 1 day of immersion, with the highest value obtained at an asphalt content of 5.88%. After 4 days of immersion, a reduction in retained stability was observed for all mixtures, and only the mixture with an asphalt content of 6.38% failed to meet the specified requirement. Overall, the mixture with an asphalt content of 5.88% exhibited the best resistance to the effects of water immersion.

Table 18. Marshall Retained Stability Test Results for AC-WC Mixtures with 9% LDPE Addition

Asphalt Content (%)	Specification (%)	Retained Stability (%)	
		1 Day Immersion	4 Days Immersion
5.38	Min. 90	84.6	106.3
5.88	Min. 90	58.7	67.2

6.38	Min. 90	97.5	109.7
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Based on the retained stability test results of the mixture containing 9% LDPE, only the mixture with an asphalt content of 6.38% satisfied the specification requirement after 1 day of immersion, whereas the mixtures with asphalt contents of 5.38% and 5.88% did not meet the required criteria. After 4 days of immersion, the retained stability values increased for all asphalt content variations; however, the mixture with an asphalt content of 5.88% still failed to satisfy the specification requirement. Overall, the mixture with an asphalt content of 6.38% exhibited the best retained stability performance.

5. Conclusion

5.1 Conclusion

Based on the results and discussion of the study the following conclusions can be drawn:

- a. The results indicate that AC-WC mixtures incorporating LDPE satisfy the requirements of the 2018 General Specifications of the Directorate General of Highways (Bina Marga). The Optimum Asphalt Content (OAC) was determined to be 5.88%, with an acceptable asphalt content range of 5.56%–6.20%. All Marshall parameters, including stability, flow, VIM, VMA, VFA, and Marshall Quotient (MQ), were within the specified limits, indicating that the mixtures are suitable for practical application.
- b. Addition of LDPE into AC-WC mixtures affected the Marshall characteristics of the mixtures. VIM values decreased with increasing asphalt content, while VMA and VFA values increased, indicating a more effective filling of voids within the mixture. Stability values tended to decrease but remained within the specification requirements. Flow values increased, indicating greater flexibility of the mixtures, whereas MQ values decreased, suggesting a reduction in mixture stiffness.
- c. The retained stability test results demonstrated that stability was influenced by asphalt content, LDPE content, and immersion duration. The optimum retained stability values were obtained at asphalt contents of 5.88% (6% LDPE), 6.38% (9% LDPE), and 5.38% (12% LDPE). In general, retained stability decreased as the immersion duration increased; however, most mixtures still exhibited good resistance to the effects of water exposure.

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