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The Effect of Heating Temperature of Asphalt Mixture on The Stability of LDPE Plastic Modified Asphalt: Microstructure and Elemental Composition Study using SEM and XRF

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ABSTRACT: The use of LDPE plastic waste in asphalt mixtures is an innovation aimed at improving road pavement quality while reducing environmental pollution. The purpose of this study was to determine the effect of heating temperature on the stability value of conventional asphalt mixtures and modified LDPE plastic mixtures (AC-WC) through Marshall characteristic testing. It also examined changes in microscopic structure using SEM and changes in chemical composition using X-Ray Fluorescence. This study used a laboratory experimental method with varying LDPE content and asphalt heating temperatures (135°C for conventional asphalt, and 165°C, 170°C, 175°C, and 180°C for modified asphalt). The study was conducted at the Transportation and Highway Laboratory, Faculty of Engineering, Tadulako University, and the Integrated Laboratory of Tadulako University. The results showed that the addition of LDPE significantly increased the stability of the mixture, with the highest value of 2236.09 kg at a content of 1% and a temperature of 180°C, meeting the 2018 Bina Marga specifications. SEM analysis revealed the best microscopic structure at a 0.25% LDPE content (temperature 165°C), with a homogeneous distribution and reduced microcracks, while high content (>0.75%) caused agglomeration. XRF analysis showed an increase in light elements from LDPE, with fluctuations in SiO_2, Al_2O_3, and MgO, without disturbing the balance of the main minerals.

KEYWORDS: AC-WC, LDPE, Stability, Heating Temperature, SEM, XRF.

I. INTRODUCTION

The development of road infrastructure plays a highly significant role in supporting various aspects of social, economic, and regional development. Along with population growth that drives economic and social demands, traffic volume and loads have increased substantially. This condition necessitates the use of road materials with high stability to withstand the increasingly heavy vehicle loads.

Asphalt is the primary material used in the construction of highway infrastructure, requiring high stability to withstand vehicular loads [1]. However, conventional asphalt often undergoes damage due to repeated loading and extreme environmental conditions. Therefore, innovations are needed to enhance asphalt performance through the addition of additives. The incorporation of LDPE plastic into asphalt mixtures can improve their mechanical properties, such as stability and resistance to deformation [2].

On the other hand, environmental issues related to plastic waste have become an urgent challenge to address. According to data from the Environmental Agency (2024), waste in Palu City reaches 71,633 tons per year [3]. One of the dominant types of plastic waste is LDPE, which is a type of plastic that is difficult to decompose naturally. The reutilization of LDPE plastic waste as a construction material, particularly in asphalt mixtures, offers an innovative solution that can address two issues simultaneously: improving road quality and reducing plastic waste [4].

The Indonesian government has implemented plastic-based asphalt technology on several road sections, including 3 km in North Sumatra Province, 1.3 km in East Java, 5.7 km in South Sulawesi, and 9 km in East Nusa Tenggara. According to the Ministry of Public Works and Housing (2018), this innovation has been proven to improve asphalt pavement performance, particularly in extending road service life [5].

In the process of producing asphalt mixtures with the addition of LDPE plastic, heating temperature becomes a crucial parameter that significantly influences mixture quality. The appropriate heating temperature determines the degree of homogeneity between asphalt and LDPE, which ultimately affects the stability value of the mixture. A temperature that is too low results in poor dispersion of LDPE, while an excessively high temperature may lead to thermal degradation of the asphalt [6]. The addition of LDPE to asphalt mixtures generally increases stability, as LDPE can enhance the stiffness and elasticity of the asphalt.

To understand the influence of heating temperature on the characteristics of asphalt LDPE mixtures, an in-depth analysis at the microstructural level is required. SEM is an appropriate analytical tool for observing material structures, including surface topography at the nanometer to micrometer scale [7]. SEM analysis plays an important role in examining the relationship between asphalt heating temperature and stability values, as it can provide information on morphological changes that occur as a result of heating [8].

In addition to microstructural analysis, chemical composition characterization is also required to comprehensively understand the stability of asphalt mixtures. XRF is an elemental analysis technique capable of determining the mineral content within a sample [9]. XRF analysis is closely related to the stability of asphalt mixtures due to its ability to identify and assess the chemical composition of the materials that make up the mixture. The stability of an asphalt mixture, which refers to its ability to resist deformation caused by traffic loads, is strongly influenced by the chemical and physical characteristics of its constituent materials, such as aggregates, filler, and the asphalt binder itself. XRF analysis is an important tool for ensuring the quality and composition of constituent materials that support the stability and durability of asphalt mixtures [10].

Based on the explanations above, this study aims to determine the effect of asphalt heating temperature and stability values in mixtures modified with LDPE plastic, as well as to examine the microstructure of LDPE-modified asphalt concrete mixtures in relation to heating temperature and stability through experimental testing. In addition, the study seeks to identify changes in the chemical composition of asphalt mixtures with LDPE additives at various heating temperatures and stability levels through XRF analysis. It is expected that this research will provide significant contributions to the development of asphalt material science and yield practical impacts that can be directly applied in real-world conditions.

II. METHODS AND MATERIALS

A. Research Design

This study is a laboratory experimental research conducted systematically based on scientific principles to test hypotheses through sampling, examination, and testing in order to achieve the research objectives. Experimental research, which is part of quantitative research methods, aims to understand the effects of specific actions intentionally applied by the researcher. In this study, several variables are involved, including conditions, states, factors, treatments, or specific actions that are expected to influence the experimental outcomes.

B. Research Materials

The materials used in this study include asphalt, LDPE plastic, coarse aggregate, fine aggregate, and stone dust. The asphalt used is hard asphalt with a penetration grade of 60/70, while the LDPE plastic typically originates from waste materials (plastic bags). The 60/70 penetration-grade asphalt is produced by PT Pertamina and is available at the Highway Transportation Laboratory, Faculty of Engineering, Tadulako University. The provision of coarse and fine aggregates was carried out by obtaining materials from construction material suppliers. In this study, the coarse and fine aggregates were sourced from the processing of a stone-crushing machine located in Watusampu, Ulujadi District, Palu City, before being stored at the Asphalt Mixing Plant (AMP) owned by PT Sapta Unggul. Additionally, the stone dust used, which is a byproduct of the stone-crushing process at PT Sapta Unggul, served as the filler material.

C. Material Testing

Aggregate testing was carried out based on standard examination methods, including sieve analysis, specific gravity and water absorption tests for both coarse and fine aggregates, abrasion tests, and the No. 200 sieve passing test [11]. In addition, the types of tests conducted on asphalt materials include penetration testing, loss of weight due to heating, viscosity, ductility testing, softening point, flash and fire point testing, and specific gravity testing [12].

D. AC-WC Mix Design

The Marshall method was used to design the asphalt concrete mixture, aiming to determine the appropriate asphalt content to produce an aggregate asphalt mixture that meets technical specifications [13]. The mixture composition was obtained through a *trial and error* approach, referring to the specification values for AC-WC type asphalt mixtures. In this study, the process of determining the mix composition was conducted by adjusting the proportions of aggregates consisting of several fractions, such as 3/4", 3/8", and stone dust (filler).

E. Estimated Optimum Asphalt Content (EOAC)

The estimated optimum asphalt content can be obtained by considering the quantity of aggregates in each fraction, so that the asphalt content used is not excessive [14].To ensure that the asphalt content used in determining the Optimum Asphalt Content is not excessive, the following formula is applied:

EOAC = 0,035 (%CA) + 0,045 (% FA) + 0,18 (% FF) + C

Remarks:

CA : Coarse Aggregate

FA : Fine Aggregate

FF : Filler

C : Constant, ranging from 0.5–1.0 for Laston [15].

The percentages of CA, FA, and FF are taken from the combined gradation used in the mixture.

F. Determination of the Number of Test Specimens

In this study, the determination of the number of test specimens was carried out in two stages, namely determining the estimated optimum asphalt content (EOAC) by comparing conventional asphalt and modified asphalt using LDPE as an additive.

Table 1. Matrix of the Number of Test Specimens for Determining OAC

No.	Without Additives	EOAC					Total
		4,0 %	4,5 %	5,0 %	5,5 %	6,0 %	
1.	Conventional Asphalt	3	3	3	3	3	15
		Total					15

Table 2. Matrix of the Number of Test Specimens for OAC + LDPE

No	LDPE Content (%)	OAC + LDPE	Marshall Remaining	Total
1.	0,00	3	3	6
2.	0,25	3	3	6
3.	0,50	3	3	6
4.	0,75	3	3	6
5.	1,00	3	3	6
Total				**30**

G. Asphalt Mixing Process with Low-Density Polyethylene (LDPE)

The asphalt mixing process was carried out by incorporating LDPE at proportions of 0.25%, 0.50%, 0.75%, and 1% of the total asphalt weight.

H. Marshall Characteristics Testing

The Marshall characteristics were obtained by analyzing the data derived from laboratory experiments. The Marshall tests conducted included Stability, VMA (Void in Mineral Aggregate), VIM (Void in the Mix), VFB (Void Filled with Bitumen), Flow, Density, and the Marshall Quotient [16].

I. SEM (Scanning Electron Microscopy) Testing

SEM testing is a type of electron microscopy that examines a specimen by scanning its surface with a high-energy electron beam in a raster pattern [17]. SEM is capable of magnifying images from approximately 10 times comparable to a handheld magnifying glass up to more than 500,000 times, which is about 250 times greater than the magnification capability of an optical microscope [18].

J. XRF (X-Ray Fluorescence) Testing

X-Ray Fluorescence (XRF) is an elemental analysis technique that can be used to determine the mineral content of aggregates. XRF employs an analytical crystal to differentiate the X-rays emitted from the sample surface. The analytical crystal, with a known composition, emits different wavelengths corresponding to each mineral present in the sample under investigation [19]. The results of this test begin with XRF analysis, which is based on measuring the X-rays emitted by an element due to the refilling of electron vacancies in inner orbitals that were left by excited electrons. This process occurs when an electron from an outer orbital replaces an electron that has been ejected from an inner orbital [20].

K. Data Analysis

Data analysis was carried out to examine the influence of asphalt heating temperature and the stability values of asphalt mixtures, both without additives and with the addition of LDPE powder at levels of 0.25%, 0.50%, 0.75%, and 1.00%. The results of the analysis provide an overview of the relationship between asphalt heating temperature and mixture stability for each planned test variation. This will be followed by SEM analysis to observe the microscopic structure of the LDPE-modified asphalt concrete mixture, and XRF analysis to determine changes in the chemical composition of the asphalt mixture with LDPE additives.

III.RESULT AND DISCUSSION

A. Material Examination Results

1. Results of Specific Gravity and Water Absorption Tests for Aggregates

The Specific Gravity and Water Absorption Test for Coarse Aggregate refers to SNI 1969:2016, while the Specific Gravity and Water Absorption Test for Fine Aggregate refers to SNI 1970:2016.

Table 3. Results of Specific Gravity Tests for Coarse and Fine Aggregates

No.	Type of Test	Requirement	Result		Unit	Remarks
			3/4	3/8		
Coarse Aggregate						
1.	Bulk specific gravity	> 2,5	2,79	2,76	%	Meets requirements
2.	Saturated surface Dry	> 2,5	2,81	2,79		
3.	Apparent specific gravity	> 2,5	2,86	2,83		
4.	Absorption	< 3	0,90	0,89		
Fine Aggregate (Stone Dust)						
1.	Bulk specific Gravity	> 2,5	2,68		%	Meets requirements
2.	Saturated surface dry	> 2,5	2,75			
3.	Apparent specific gravity	> 2,5	2,89			
4.	Absorption	< 3	2,73			

2. Results of Sieve Analysis Testing and Material Passing No. 200 Sieve

Table 4. Results of No. 200 Sieve Passing Test

No.	Material Type	Material Type	Requirement	Remarks
Coarse Aggregate				
1.	Fraction 3/4	0,398	<1 %	Meets requirements
2.	Fraction 3/8	0,930		

Fine Aggregate				
1.	Stone Dust	9,017	<10%	Meets requirements

Based on the test results, the materials tested namely the 3/4" fraction, 3/8" fraction, and stone dust meet the specified requirements.

3. *Results of Abrasion Testing*

Table 5. Abrasion Test Results

Test Type	**Requirement**	**Result**	**Unit**	**Remarks**
500 Rotation Abrasion	< 30	16,45	%	Meets requirements

The results of the abrasion test indicate that the 500-rotation abrasion value meets the specified standard requirements.

4. *Asphalt Testing Results*

Two types of asphalt were used as binders: pure asphalt with a penetration grade of 60/70, and modified asphalt, which is a mixture incorporating LDPE plastic as an additive.

Table 6. Characteristics of Pen 60/70 Asphalt

Type of Test	**Test Result**	**Requirement**	**Unit**	**Remarks**
Penetration (25□C, 5 sec)	65	60 – 70	Mm	Meets requirements
Softening Point	48	≥ 48	□C	
Ductility (25□C, 5 cm/ sec)	153,43	≥ 100	Cm	
Flash Point	325,00	≥ 230	□C	
Specific Gravity (25□C)	1,04	≥ 1,0	-	
Weight Loss (25□C)	0,0014	≤ 0,8	%	
Viskositas (135□C)	434,88	≥ 300	cSt	

Table 7. Characteristics of Pen 60/70 Asphalt with LDPE

Test	**Test Result**				**Requirement**	**Unit**
	0,25%	**0,50%**	**0,75%**	**1,00%**		
Penetration	52,1	40,4	32,5	30,80	-	mm
Softening Point	49	51	67	68	-	^{o}C
Ductility	152,57	150,67	6,27	5,70	-	cm
Specific Gravity	1,25	1,69	1,75	2,03	-	-
Viscosity	2820,85	4173,22	5525,59	6000,67	≥ 300	cSt

The test results indicate that the addition of LDPE to Pen 60/70 asphalt reduces penetration values, making the asphalt harder. The softening point increases significantly up to 1% LDPE content, indicating improved resistance to high temperatures. Ductility decreases sharply at higher LDPE levels, reflecting a reduction in asphalt elasticity. Specific gravity and viscosity increase with the addition of LDPE, meaning the asphalt becomes denser and more viscous. The base Pen 60/70 asphalt also exhibits a high flash point and minimal weight loss, meeting safety standards and stability requirements at elevated temperatures.

B. Stages of Asphalt Mixture Preparation

1. Determination of Aggregate Composition in the Mixture

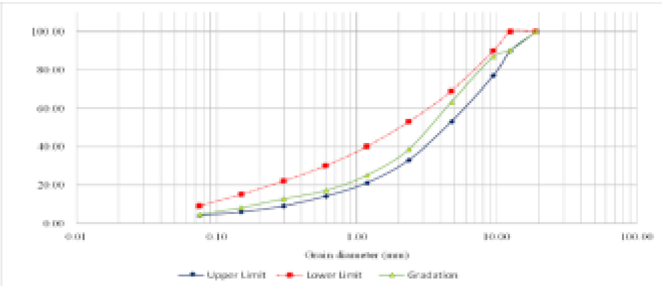

Figure 1. Combined Aggregate Gradation Curve

Based on the graph above, the Optimum Asphalt Content (OAC) is determined as follows:

FF = 4,60

CA = 100 % - (% Passing No. 8)
= 100% - 38,58%
= 61,42%

FA = (% Passing No. 8) - % Filler
= 38,58% - 4,60%
= 33,99%

C = Constant, taken as 0,5 (Range 0,5 – 1,0 for LASTON)

Thus, the Optimum Asphalt Content (OAC) is calculated as:

OAC = 0,035 (% CA) + 0,045 (% FA) + 0,18 (% FF) + C
= 0,035 (61,42%) + 0,045 (33,99%) + 0,18 (4,60%) + 0,5
= 5,01% □ 5,0%

2. Determination of Optimum Asphalt Content (OAC) for AC-WC Mixture Using Marshall Test

Table 8. Marshall Test Results for Determining OAC

Marshall Parameter	**Unit**	**Test Results**					**Spec.**
		Planned Asphalt Content (%)					
		4,0	4,5	5,0	5,5	6,0	
Density	g/cm^3	2,31	2,36	2,39	2,40	2,44	-
VIM	%	8,81	5,85	4,06	3,08	2,18	3 - 5
VMA	%	17,47	15,81	15,24	15,40	15,62	> 15
VFB	%	49,57	63,11	73,76	80,13	86,06	>65
Stability	Kg	711,5	942,2	1017,	918,3	905,89	>800

		4	1	6	0		
Flow	Mm	3,40	3,76	3,86	4,40	5,24	2 - 4
MQ	Kg/mm	194,10	260,95	265,90	195,07	166,90	>250

From the data in Table 8, the relationship between asphalt content and the volumetric characteristics of the AC-WC mixture, as well as the relationship between asphalt content and Marshall properties, can be observed. By referring to the Bina Marga 2018 Specifications, Revision 2, a graph was plotted to determine the range of asphalt content that meets the specifications and to identify the Optimum Asphalt Content (OAC), as shown below:

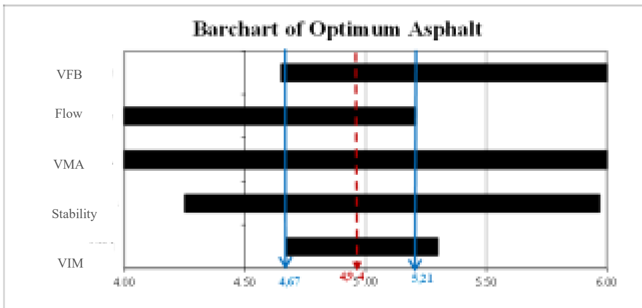

Figure 2. BarChart for Determining Optimum Asphalt Content (OAC)

From Figure 2, the asphalt content range for the AC-WC mixture is 4.67% – 5.21%. Therefore, the Optimum Asphalt Content (OAC) is determined as follows:

OAC = $\frac{A+B}{2} = \frac{4,67+5,21}{2}$ = 4,94% □ 5,00%

C. *Marshall Preparation of Test Specimens and Marshall Testing*

1. Marshall Test Results for Conventional Pen 60/70 Asphalt

Table 9. Marshall Test Results for Conventional Pen 60/70 Asphalt

Parameter *Marshall*	Satuan	Nilai Hasil Pengujian	Spesifikasi
Stability	Kg	985,87	>800
Flow	mm	3,65	2 - 4
VIM	%	4,19	3 - 5
VMA	%	15,78	>15
VFB	%	73,47	>65
Density	g/cm³	2,47	-

2. Marshall Test Results for LDPE-Modified Asphalt

The results of the Marshall test parameters for asphalt modified with LDPE plastic are presented in Table 10.

Table 10. Marshall Test Results for LDPE-Modified Asphalt

Marshall Parameter	Unit	Test Results Based on Variations in LDPE Content				Spec.
		0,25%	**0,50%**	**0,75%**	**1,00%**	
Stability	Kg	1683,26	1752,88	1903,67	2236,09	>1000
Flow	Mm	3,59	3,53	3,23	3,18	2 - 4
VIM	%	4,22	4,42	4,55	4,77	3 - 5
VMA	%	15,81	15,99	16,10	16,29	>15
VFB	%	73,31	72,43	71,76	70,75	>65
Density	g/cm³	2,47	2,46	2,46	2,45	-

D. *Analysis of Marshall Characteristics Data*

1. Effect of Stability Values on LDPE Plastic Content

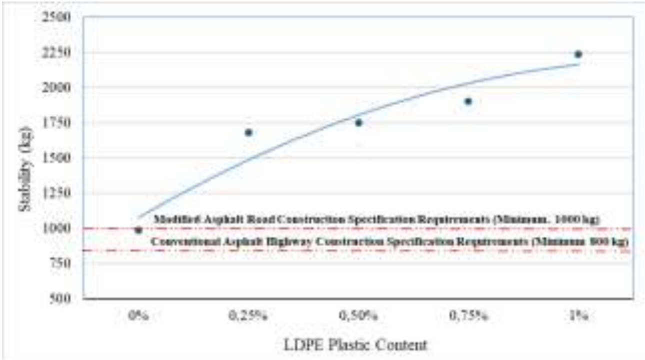

Figure 3. Relationship between Stability Values and LDPE Plastic Content

Based on Figure 3, the stability values of both conventional asphalt and LDPE-modified asphalt meet the Bina Marga 2018 specifications, with a minimum requirement of 800 kg for conventional asphalt and 1000 kg for LDPE-modified asphalt. Increasing the LDPE content leads to higher stability values because the asphalt more effectively coats the mixture voids and enhances bonding with the aggregates. This indicates that the addition of LDPE improves the strength of asphalt concrete mixtures in resisting loads, thanks to the plastic properties of LDPE acting as a binder between aggregates.

2. LDPE Effect of Flow Values on LDPE Plastic Content

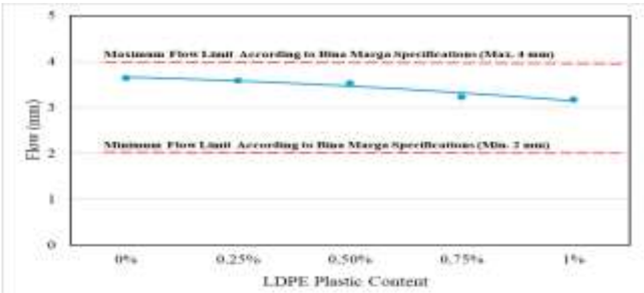

Figure 4. Relationship between Flow Values and LDPE Plastic Content

Based on Figure 4, the flow values of both conventional asphalt and LDPE-modified asphalt fall within the Bina Marga 2018 specification range of 2–4 mm. Increasing the LDPE content causes the flow values to decrease, indicating that the asphalt mixture becomes stiffer. Despite this reduction, the flow values remain within the allowable range, so the LDPE-modified asphalt mixture still meets the flexibility requirements.

3. Effect of VIM (Void in Mix) Values on LDPE Plastic Content

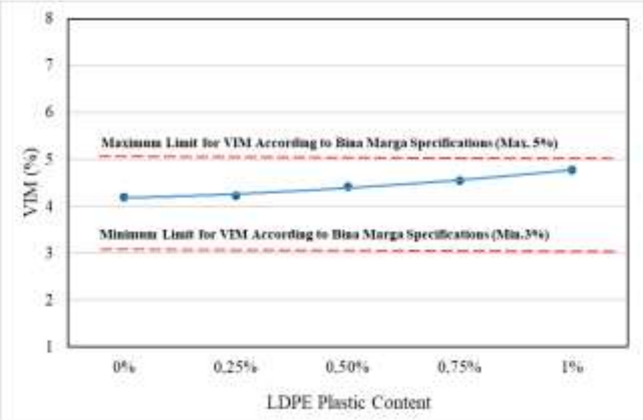

Figure 5. Relationship between VIM Values and LDPE Plastic Content

Based on Figure 5, the VIM values for both conventional asphalt and LDPE-modified asphalt fall within the Bina Marga 2018 specification range of 3–5%. As the LDPE content increases, the VIM values tend to rise due to higher viscosity and reduced asphalt workability. This condition prevents the mixture voids from being fully filled, resulting in an increase in the total void content.

4. Effect of VMA Values on LDPE Plastic Content

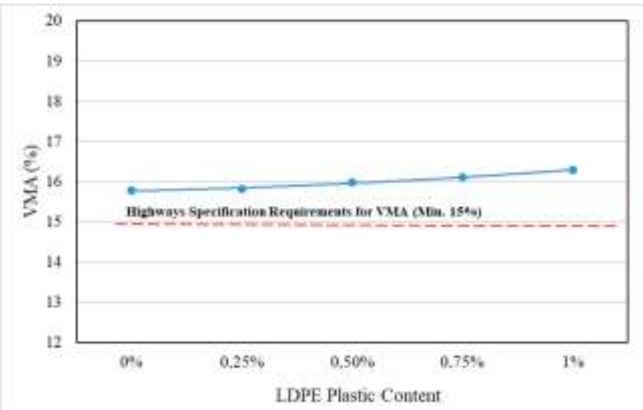

Figure 6. Relationship between VMA Values and LDPE Plastic Content

Based on Figure 6, the VMA values for both conventional asphalt and LDPE-modified asphalt meet the Bina Marga 2018 specification, with a minimum requirement of 15%. Increasing the LDPE content causes VMA values to rise due to higher viscosity and increased mixture stiffness. Despite this increase, all VMA values remain above the minimum requirement, indicating that the mixture is still suitable for use.

5. LDPE Effect of VFB Values on LDPE Plastic Content

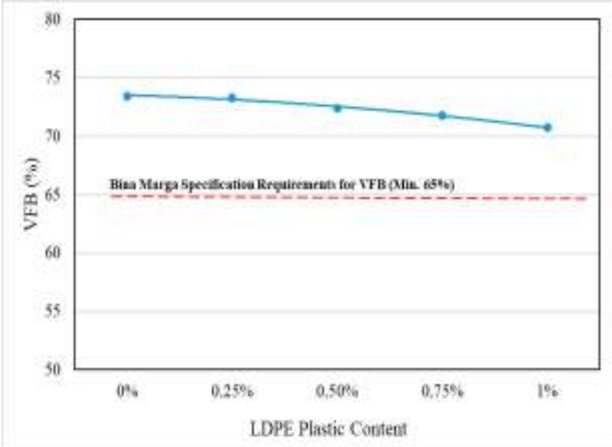

Figure 7. Relationship between VFB Values and LDPE Plastic Content

Based on Figure 7, the VFB values for both conventional asphalt and LDPE-modified asphalt meet the Bina Marga 2018 specification, with a minimum requirement of 65%. The VFB values gradually decrease as the LDPE content increases due to higher air voids (VIM) and the reduced ability of asphalt to fill the voids caused by increased viscosity and high temperatures. This decrease should be controlled to prevent further reduction at higher LDPE contents or temperatures.

6. Effect of Density Values on LDPE Plastic Content

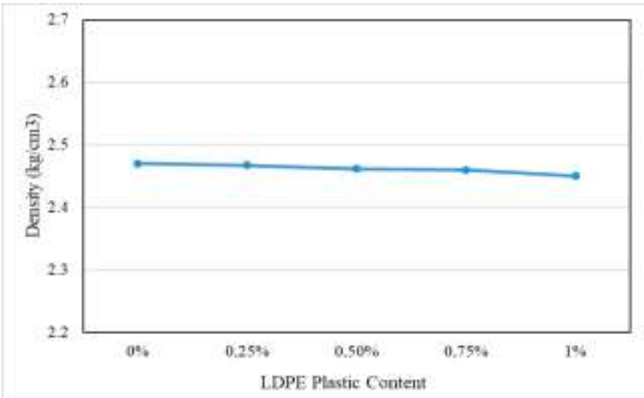

Figure 8. Relationship between Density Values and LDPE Plastic Content

Based on Figure 8, nilai kepadatan aspal kon Based on Figure 8, the density values of both conventional asphalt and LDPE-modified asphalt decrease with increasing heating temperature, reaching the highest density between 135°C–165°C and the lowest at 180°C. This decrease is influenced by thermal expansion at high temperatures. Additionally, the addition of LDPE causes a linear and gradual reduction in density because LDPE has a lower density compared to the base material.

7. Effect of MQ (Marshall Quotient) Values on LDPE Plastic Content

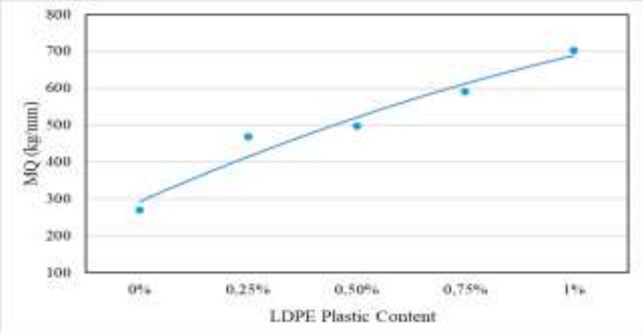

Figure 9. Relationship between MQ (Marshall Quotient) Values and LDPE Plastic Content

Based on Figure 9, the MQ values increase significantly with rising heating temperature, reaching the highest values at 180°C, with the largest jump occurring between 175°C–180°C. High temperatures are proven to be very effective in improving the mixture's quality modulus. The addition of LDPE also shows a positive linear relationship, where each 0.25% increase in LDPE content results in a consistent and substantial rise in MQ.

E. SEM Test Results of AC-WC Mixtures

The SEM testing was conducted on five specimens with LDPE plastic contents of 0%, 0.25%, 0.50%, 0.75%, and 1%.

1. SEM Results of Conventional Asphalt without LDPE Additive

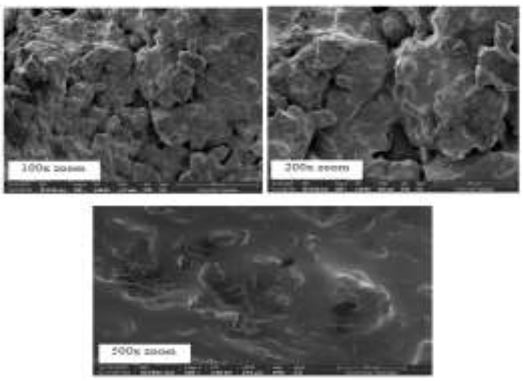

Figure 10. SEM Results of Conventional Asphalt

Based on SEM observations at magnifications of 100x, 200x, and 500x, conventional asphalt exhibits a non-homogeneous surface structure with a rough, wavy texture, along with visible microcracks and voids. The irregular topography and presence of microcracking can serve as weak points affecting elasticity and deformation resistance. A heating temperature of 135°C was sufficient for analysis without causing excessive decomposition.

2. SEM Results of Asphalt with 0.25% LDPE Additive

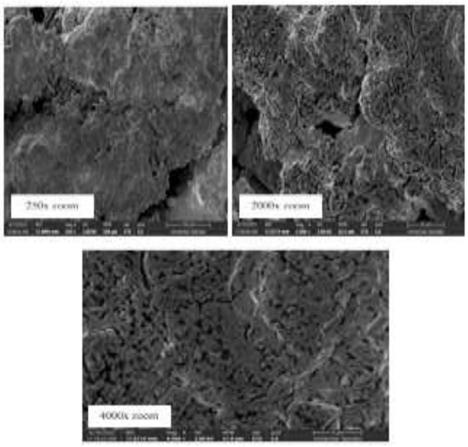

Figure 11. SEM Results of Asphalt with 0.25% LDPE Additive

Based on SEM observations with 0.25% LDPE addition, the asphalt surface appears smoother, more homogeneous, and exhibits fewer microcracks compared to conventional asphalt. The LDPE is evenly dispersed, filling small voids, resulting in a denser and more compact structure. A heating temperature of 165°C allows optimal mixing, producing a stronger microstructure with the potential to improve stability, durability, and deformation resistance.

3. SEM Results of Asphalt with 0.50% LDPE Additive

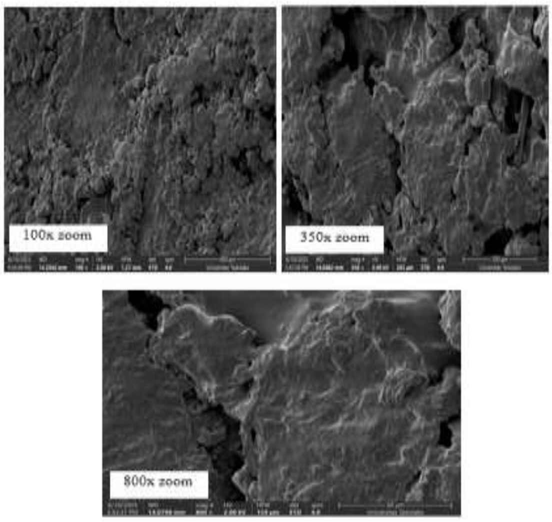

Figure 12. SEM Results of Asphalt with 0.50% LDPE Additive

Based on SEM observations with 0.50% LDPE addition, the bonding between asphalt and aggregates begins to improve, with aggregate surfaces more fully coated by the modified asphalt. The LDPE is evenly distributed, reducing the number of voids, while the microstructure becomes more compact. At higher magnifications, LDPE appears as an additional binding layer, although some microvoids are still present.

4. SEM Results of Asphalt with 0.75% LDPE Additive

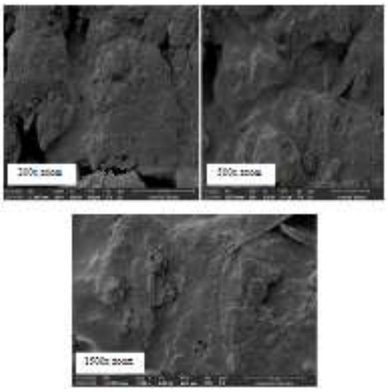

Figure 13. SEM Results of Asphalt with 0.75% LDPE Additive

Based on SEM observations with 0.75% LDPE addition, the asphalt–aggregate bonding appears tighter, and the aggregate surfaces are better coated, demonstrating the role of LDPE as both a filler and additional binder. At higher magnifications, the LDPE layer appears blended with the asphalt, forming a more homogeneous texture, although some microgaps remain. The more compact microstructure indicates improved viscoelasticity and reduced porosity.

5. SEM Results of Asphalt with 1.00% LDPE Additive

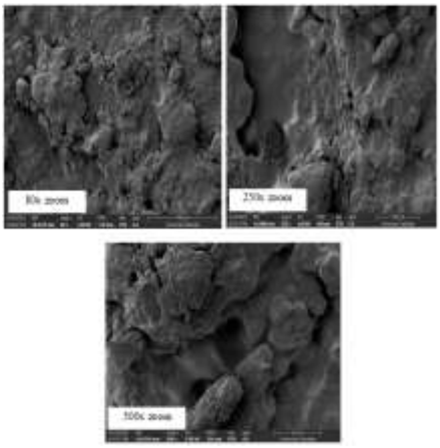

Figure 14. SEM Results of Asphalt with 1.00% LDPE Additive

Based on SEM observations with 1.00% LDPE addition, the LDPE-asphalt layer appears thicker but non-homogeneous, with some areas showing clumping due to LDPE agglomeration. The uneven distribution results in larger voids and pores at the micro scale. Excessive LDPE at this content leads to imperfect inter-particle bonding.

From the SEM test results, comparing conventional asphalt (0%) with LDPE-modified asphalt at 0.25%, 0.50%, 0.75%, and 1.00%, it can be concluded that the optimal LDPE addition is likely around 0.25%. Increasing the LDPE concentration above this level progressively reduces material quality, with 1.00% LDPE causing complete over-modification, producing counterproductive effects.

F. Hasil Uji XRF Campuran AC-WC

XRF operates on the principle that an XRF machine emits X-rays onto an asphalt sample (similar to shining a "flashlight" with very strong X-rays). When the sample is irradiated, each element in the asphalt emits secondary X-rays with characteristic energies. The XRF machine detects these emitted X-rays, and a computer analyzes the data to identify which elements are present and their quantities.

XRF testing was conducted on specimens with an Optimum Asphalt Content (OAC) of 5.00% that had already undergone Marshall testing. Five specimens were used, each with varying LDPE plastic contents of 0%, 0.25%, 0.50%, 0.75%, and 1%. The samples were powdered to pass a No. 200 sieve. This XRF testing was part of the characterization of asphalt samples modified with LDPE at different concentrations. The test aimed to analyze the elemental composition and evaluate the effect of LDPE addition on the distribution of elements within the asphalt matrix. The XRF analysis was conducted at the UPA Integrated Laboratory, Tadulako University.

G. Analysis of Elemental Composition from XRF Testing

Table 12. Elemental Composition of AC-WC Asphalt Mixtures with Various LDPE Additions

Element	**LDPE Plastic Addition (%)**				
	0	**0,25**	**0,50**	**0,75**	**1**
Light Element	54,1	59,3	58,2	56,9	55,9
Si	13,1	11,0	11,1	11,9	12,4
Fe	11,3	11,0	10,6	10,5	10,5
Ca	9,9	9,9	9,7	9,9	10,0
Al	5,2	4,4	4,4	4,6	4,8
Mg	4,0	2,0	3,9	4,0	4,0
Ti	0,6	0,6	0,6	0,6	0,6
K	0,5	0,4	0,4	0,4	0,4
S	0,2	0,4	0,4	0,4	0,4
Mn	0,2	0,2	0,2	0,2	0,2
P	0,1	0,1	0,1	0,1	0,1

The dominant element detected is the light element, which increases from 54.1% in the sample without LDPE to 59.3% at 0.25% LDPE, then gradually decreases to 55.9% at 1% LDPE, reflecting the characteristics of LDPE, which is rich in light elements such as carbon and hydrogen. Si decreases at 0.25% LDPE and then stabilizes in the range of 11.0–12.4%, while Al, Ca, and Fe remain relatively stable with minor variations, indicating that LDPE addition does not significantly affect the distribution of major minerals. Mg shows fluctuations, dropping from 4.0% to 2.0% and then returning to 4.0%, suggesting effects of dilution and re-homogenization during mixing. Minor elements such as S, Ti, K, P, and Mn remain stable with very small variations. Overall, adding LDPE up to 1% does not significantly alter the profile of the main mineral elements, but it increases the light element content at low concentrations and stabilizes at higher concentrations, indicating that asphalt modification with LDPE can enhance chemical characteristics without disturbing the mineral balance of the mixture.

H. Analysis of Oxide Content from XRF Testing

Table 13. Oxide Content of AC-WC Asphalt Mixtures with Various LDPE Additions

Oxide	LDPE Plastic Addition (%)				
	0	0,25	0,50	0,75	1
SiO_2	35,5	29,4	30,3	32,3	33,8
Light Element	13,0	16,2	22,0	18,5	15,9
Al_2O_3	15,5	12,9	13,1	13,8	14,5
MgO	15,3	7,8	14,4	15,0	15,3
CaO	9,8	9,9	9,6	9,8	10,0
Fe_2O_3	8,4	8,4	7,8	7,7	7,8
SO_3	0,5	1,0	1,1	1,1	1,0
TiO_2	0,6	0,6	0,6	0,6	0,6
K_2O	0,5	0,5	0,4	0,4	0,4
P_2O_5	0,4	0,3	0,3	0,3	0,3
MnO	0,2	0,2	0,1	0,1	0,1

The addition of LDPE also shows a significant effect on the light element content, which increases from 13.0% (0% LDPE) to a peak of 22.0% at 0.50% LDPE, then decreases again. This indicates that the light elements from LDPE begin to dominate as the concentration increases, but interactions with the aggregate and filler matrix occur beyond a certain point. MgO decreases sharply to 7.8% at 0.25% LDPE but returns to its initial level of 15.3% at 1.00% LDPE, suggesting that LDPE can influence the dissolution or distribution of magnesium in a non-linear manner.

Meanwhile, the contents of other metal oxides such as Fe_2O_3 and CaO remain relatively stable, showing only minor decreases or small fluctuations across the range of LDPE additions. The contents of SO_3, TiO_2, K_2O, P_2O_5, and MnO remain low and exhibit no significant variation, indicating that LDPE has minimal impact on minor and trace elements.

Overall, adding LDPE to AC-WC asphalt mixtures has a noticeable impact on the chemical composition, particularly on light elements, SiO_2, Al_2O_3, and MgO. These changes can affect the mechanical and thermal properties of the asphalt mixture. Furthermore, the light elements are closely associated with the presence of C, H, and O from LDPE, which act as additional binding agents and enhance cohesion between aggregate particles.

CONCLUSIONS

Based on the research results and discussion, the addition of LDPE to asphalt mixtures has a significant impact on the mechanical properties, microstructure, and chemical composition of the mixture. Mechanically, increasing the LDPE content and heating temperature resulted in a substantial increase in stability, from 985.87 kg for conventional asphalt up to 2236.09 kg for 1% LDPE at an optimal temperature of 180°C, all meeting the Bina Marga 2018 Revision 2 specifications. However, SEM results indicate that high stability does not always correlate with superior microstructural quality. The optimal microstructure was observed at 0.25% LDPE, exhibiting a more homogeneous and compact texture, whereas higher concentrations such as 0.75% and 1% caused agglomeration and imperfect bonding despite increased stability. XRF analysis confirmed chemical composition changes, particularly the increase in light elements due to the dominance of organic components from LDPE, while the main mineral elements such as Si, Fe, Ca, and Al remained stable. Oxides like SiO_2, Al_2O_3, and MgO showed variations indicating adjustments in the mineral matrix during the modification process. Overall, 0.25% LDPE is considered the optimal content for balancing enhanced stability with good microstructural quality, thereby supporting long-term durability in pavement applications.

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