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Study of the Effect of Mixing Temperature of LDPE-Modified AC-WC on Mixture Voids Using SEM and XRF Analysis

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Abstract: The demand for high-quality and sufficient quantities of road construction materials must be fulfilled to ensure optimal performance. Asphalt is one of the primary materials in road construction. The use of plastic waste as an additive in AC-WC mixtures is a promising alternative expected to enhance structural and functional performance, particularly with appropriate mixing temperatures. This study aims to evaluate the effect of adding Low-Density Polyethylene (LDPE) plastic on the void content of AC-WC asphalt mixtures, as well as their microstructural and chemical characteristics, using Scanning Electron Microscopy (SEM) and X-Ray Fluorescence (XRF) analyses. The wet mixing method was used with LDPE content variations of 0%, 0.25%, 0.5%, 0.75%, and 1%. The test results showed that LDPE addition increased the values of Void in Mixture (VIM), Void in Mineral Aggregate (VMA), and Void Filled Bitumen (VFB) compared to conventional mixtures. The highest values were obtained at 0.75% LDPE for VIM (4.77%) and VMA (16.50%), and at 0.25% LDPE for VFB (74.40%). SEM analysis revealed that LDPE content between 0.25% and 0.5% produced a more homogeneous mixture structure, while higher LDPE levels led to agglomeration that reduced void-filling effectiveness. Meanwhile, XRF results indicated that the main chemical components SiO_2, Al_2O_3, CaO, and Fe_2O_3 remained relatively stable, confirming that LDPE is inert and does not introduce new heavy metal contaminants, making it environmentally safe. This study concludes that the addition of LDPE, within optimal limits, can enhance the structural performance of AC-WC mixtures and serves as a sustainable solution for utilizing plastic waste in road infrastructure development.

Keywords: *AC-WC, LDPE, SEM, Voids, XRF.*

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I. INTRODUCTION

Indonesia is a developing country, and as a nation progresses, the burden of problems it must address also increases. Population growth, infrastructure development, and the expansion of various public facilities have had an impact on multiple aspects of life, one of which is the increasing rate of waste accumulation. In Indonesia, the potential for rising waste buildup is becoming more evident, and thus, waste management should be a matter of national concern, as it directly affects the well-being of its people. In daily life, waste is generated from various sectors, ranging from plastic waste and hazardous and toxic (B3) waste to household food waste. Among these, plastic waste draws significant attention due to its extremely slow decomposition process, which can take between 10 and 1,000 years depending on the type of plastic, before it fully degrades. Therefore, the issue of plastic waste must be addressed with appropriate waste management solutions. Indonesia ranks second in the world for the largest amount of mismanaged plastic waste, generating approximately 3.22 million tons. [1].

The Ministry of Public Works and Public Housing, through the Agency for Research and Development (Balitbang), has conducted research on the addition of plastic to asphalt mixtures as a potential solution to reduce waste- related issues. The development of a country also necessitates the advancement of infrastructure. In Indonesia, the construction of asphalt roads has continuously increased since 1957. The government has persistently pursued the development of paved roads to meet the growing demand for land transportation. Consequently, the demand for road construction materials, including asphalt, continues to rise. According to the Ministry of Public Works and Public Housing (as referenced in [2]), by 2023 Indonesia had a total of 550,735 kilometers of asphalt-paved roads. The annual demand for asphalt in Indonesia continues to increase in line with the expansion of road networks. Therefore, a solution is needed to reduce the yearly consumption of asphalt.

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A road is a land transportation infrastructure that serves as a transition area for people, vehicles, and other forms of traffic. This infrastructure includes auxiliary structures and facilities designed to support traffic flow. One of the factors contributing to road damage is the temperature of the asphalt mixture used in the field, which may not reach the appropriate level. During transportation, weather conditions may change such as light rain, heavy rain, or temperature fluctuations in certain areas causing a drop in the temperature of the asphalt mixture [3]. This ultimately results in a decrease in the temperature of the asphalt mixture, rendering it unsuitable for placement at the construction site. The asphalt mixture fails to meet the required temperature specifications for proper laying and compaction.

The type of asphalt mixture used is the asphalt concrete wearing course (AC-WC), which is a flexible pavement layer that comes into direct contact with vehicle wheels. It possesses high flexibility but is also susceptible to damage caused by high temperatures and heavy traffic loads [4]. One of the contributing factors to pavement damage is the mixing process carried out in the field at incorrect temperatures. This condition results in the asphalt mixture being unsuitable for placement at the road construction site, as its temperature does not meet the required standards for laying and compaction. Therefore, the mixing temperature significantly affects the Marshall parameters and the durability value of the AC-WC asphalt concrete mixture [5].

With the continuous growth of road construction in line with national development, the demand for key road construction materials must be met both in terms of quantity and quality. One of the primary materials used in road construction is asphalt. Plastic possesses advantageous properties such as strength, elasticity, temperature resistance, and adhesion, which can enhance the bonding capability between asphalt and aggregate. The use of plastic waste as an additive material represents an alternative solution to existing problems. The combination of plastic and asphalt is expected to improve the structural and functional performance of the pavement, provided that the appropriate mixing temperature is maintained. Thus, the increasing demand for road construction materials can be addressed more effectively.

Analysis is necessary to provide a detailed overview of the results of asphalt mixing at precise temperatures with the addition of LDPE (Low-Density Polyethylene) plastic, in order to strengthen and validate the quality of the asphalt mixture samples. Scanning Electron Microscopy (SEM) is a type of electron microscope capable of producing high-resolution images of a sample's surface. X-Ray Fluorescence (XRF) is a spectroscopic technique used to analyze the elemental composition of a material.

Based on the explanation above, the objective of this study is to investigate the effect of AC-WC mixing temperature on the void content of asphalt mixtures with the addition of LDPE plastic, and to examine the impact of incorporating LDPE plastic waste into pavement mixtures using SEM and X-Ray Fluorescence (XRF) analysis. This research is expected to contribute to the development of innovative and practical solutions for addressing the increasing demand for road construction materials through the modification of plastic waste. Furthermore, studies on plastic waste processing can serve as a valuable source of knowledge to support the development of plastic waste management industries, transforming waste into useful alternative materials.

II. LITERATURE REVIEW

A. Asphalt Concrete Wearing Course (AC-WC)

Asphalt concrete (AC) is a mixture of continuously graded aggregates and asphalt, mixed, laid, and compacted while hot at a specific temperature. The minimum nominal thickness of AC-WC is 4 cm [6]. The Asphalt Concrete Wearing Course (AC-WC) is the topmost layer of pavement, typically with a thickness of 5 cm, functioning as the wearing course and providing surface flexibility. AC-WC enhances pavement durability by resisting the degradation of underlying pavement layers. [3].

B. Constituent Materials

➢ *Asphalt*

Asphalt is a black or dark brown viscoelastic material used as a binder in road pavement. It is composed of hydrocarbons derived from petroleum, natural rock, or other organic materials. At room temperature, asphalt is solid to semi-solid in form and exhibits thermoplastic properties. It melts when heated to a certain temperature and solidifies again as the temperature drops. Along with aggregates, asphalt is one of the primary materials used in pavement mixtures [7].

➢ *Aggregates*

Aggregates are a collection of crushed stone, gravel, sand, or other mineral particles, either naturally occurring or manufactured. The properties of aggregates are a key factor in determining the pavement's ability to bear traffic loads and resist weathering. Based on sieve size, aggregates are classified into three types: coarse aggregate, fine aggregate, and filler [8][9].

C. LDPE Plastic

Plastic is a type of macromolecule formed through the process of polymerization. Polymerization is a chemical process in which several simple molecules (monomers) are combined to form large molecules (polymers or macromolecules). LDPE (Low-Density Polyethylene) is a type of plastic identified by the triangular recycling symbol with the code number 4. This type of plastic is commonly used for plastic wrap or packaging material for shipping goods or food, as well as for containers, plastic bags, and soft bottles [10].

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III. MATERIAL AND METHOD

A. *Research Design*

This study is an experimental research conducted in a laboratory setting to analyze the characteristics of asphalt mixtures modified with the addition of Low-Density Polyethylene (LDPE) plastic as an additive material. In this research, asphalt is mixed with varying percentages of LDPE to evaluate its effect on the void content of asphalt concrete. The study was carried out at the Transportation and Highway Laboratory, Faculty of Engineering, Tadulako University, which is equipped with standard testing instruments for asphalt mixture characterization.

B. *Data Collection*

Data collection in this study was conducted through a series of methods, including.

- Literature review, carried out by examining various relevant scientific sources. The data obtained from the literature were compared with the results of laboratory experiments.
- Laboratory sample testing, which included the following data: Aggregate Characteristic Test Data, Asphalt Characteristic Test Data without LDPE, Asphalt Characteristic Test Data with LDPE, Marshall Test Data, SEM Analysis Data, and XRF Analysis Data.

C. *Material Collection*

In this study, three types of materials were collected and tested for use, as follows.

- *Aggregates*

The aggregates used as the primary material in the asphalt mixture were obtained from the stone crusher machine at AMP PT. Sapta Unggul, sourced from Ex-Watusampu, Ulujadi District, Palu City. The mineral filler was sourced from river sand from the Palu River, while additional filler materials included Tonasa brand cement and stone dust, a by- product of the stone crusher at PT. Sapta Unggul.

- *Asphalt*

The asphalt used as the binder in the mixture was sourced from the materials available at the Transportation and Highway Laboratory, Faculty of Engineering, Tadulako University. The type of asphalt used in this research was 60/70 penetration grade asphalt, commonly used in road pavements in tropical climates due to its balanced flexibility and stiffness.

- *LDPE Plastic*

The LDPE plastic used in this study was collected plastic waste. The LDPE was shredded and passed through a No. 4 sieve. The LDPE plastic was added to the asphalt mixture in the following proportions by weight of asphalt: 0%, 0.25%, 0.5%, 0.75%, and 1%.

D. *Material Testing*

- *Asphalt Testing*

The asphalt used in this study was 60/70 penetration grade asphalt. It was tested to determine whether it met the required specifications. The types of asphalt tests and their procedures were conducted according to the following standards:

- Penetration test: SNI 2432-2011
- Specific gravity test: SNI 2441-2011
- Ductility test: SNI 2432-2011
- Viscosity test: SNI 7729-2011
- Flash and fire point test: SNI 2433-2011
- Softening point test: SNI 2434-2011
- Loss on heating test: SNI 06-2440-1991

- *Aggregate Testing*

The aggregates used in this study consisted of coarse and fine aggregates. These materials were tested to determine whether they met the required specifications. The types of aggregate tests and their procedures included:

- Sieve analysis test, using the combined aggregate gradation specifications for asphalt mixtures
- Specific gravity test for coarse aggregates according to SNI 1969-2008, and for fine aggregates according to SNI 1970-2008
- Aggregate abrasion test according to SNI 2417-2008

E. *Test Specimen Matrix for Determining Optimum Asphalt Content (OAC)*

In determining the Optimum Asphalt Content (OAC), the test specimens were prepared based on the planned mixing temperatures of asphalt modified with LDPE plastic, corresponding to each level of conventional asphalt content.

Table 1 Test Specimen Matrix for Determining the Optimum Asphalt Content (OAC)

No	Without Additive	OAC					Total
		4,0%	4,5%	5,0%	5,5%	6,0%	
1	Conventional Asphalt	3	3	3	3	3	15
Total							15

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Table 2 Test Specimen Matrix for OAC + LDPE

No	LDPE Content (%)	OAC + LDPE	Residual Marshall	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

F. *Testing of Asphalt Concrete + LDPE at Optimum Asphalt Content (OAC) Conditions*

Before mixing, the aggregate gradation must first be determined. The method used to determine gradation is based on sieve size distribution. The proportioning of aggregates is not based on the percentage of each aggregate fraction in the combined gradation, but rather determined according to sieve sizes.

G. *Testing of Asphalt Concrete + LDPE at Mixing Temperatures*

This test was conducted using a mixing temperature that meets asphalt specification requirements, with an asphalt content of 5.0%. For each asphalt content, three specimens were prepared at each mixing temperature. Mix design is a critical aspect in the preparation of Optimum Asphalt Content (OAC). The materials used in this study were selected to comply with the specifications for AC-WC mixtures.

The determination of the composition between coarse aggregate, fine aggregate, and filler aims to achieve a gradation that produces a surface layer with good inter-particle bonding. The AC-WC mix design used in this research was based on the Marshall method. This method allows for the determination of the appropriate asphalt content, ensuring an optimal mixture composition between asphalt and aggregates that meets the technical requirements for pavement construction.

H. *Marshall Characteristics Testing*

Marshall characteristics values were obtained by analyzing the data from laboratory experiments using the guidelines of SNI 06-2489-1991. The Marshall characteristic tests include the following parameters:

- *Stability*
- VMA (*Void in Mineral Aggregate*)

- VIM (*Voin in The Mix*)
- VFB (*Void Filled with Bitumen*)
- *Flow*
- *Density*
- *Marshall Quotient*

I. *SEM (Scanning Electron Microscope) Testing*

The SEM testing was conducted at the Integrated Laboratory of Tadulako University. The research was carried out over a period of 14 working days. With the aid of SEM, researchers were able to examine the sample surfaces and visually observe them by scanning the surface with a focused beam of electrons at various magnification scales. The electrons interact with the atoms in the sample, generating signals that provide information about the surface topography and the sample's composition. In this study, using the SEM- EDX (Energy Dispersive X-ray) combination, researchers were able to capture images from three different points, or one sample point with three optimal magnification scales. The application of SEM–EDS techniques can be summarized as follows:

- Topography, Analyzing surface texture (e.g., roughness, reflectivity)
- Morphology, Analyzing the shape and size of the sample
- Composition, Analyzing the surface composition of the sample both quantitatively and qualitatively

J. *XRF (X-Ray Fluorescence) Testing*

The XRF testing was conducted at the Integrated Laboratory of Tadulako University over a period of 14 working days. The use of XRF equipment enables the acquisition of semi-quantitative elemental composition data. Although the results are semi-quantitative, they are sufficiently close to quantitative values. XRF is an analytical tool used for the qualitative and quantitative analysis of the elements contained within a material.

K. *AC-WC Volumetric Data Analysis of AC-WC Mixtures*

Data analysis was conducted on the Marshall characteristic parameters of asphalt mixtures with and without the addition of LDPE plastic at concentrations of 0%, 0.25%, 0.5%, 0.75%, and 1%. The results are presented in the form of graphical relationships between asphalt content and the corresponding Marshall parameters. Data analysis from SEM and XRF testing in this study was conducted to evaluate the microstructure and chemical composition of the asphalt mixtures modified with LDPE. SEM test data were analyzed by observing surface morphology, the distribution of LDPE within the asphalt matrix, and the presence of cracks or voids between materials. Meanwhile, XRF test results were used to identify the elements and chemical compounds within the mixture, particularly to detect any changes in elemental composition due to the addition of LDPE.

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The results of both analyses were then compared with those of conventional asphalt to assess any improvements or changes in characteristics resulting from the LDPE modification. Data interpretation was carried out both qualitatively and quantitatively to understand the extent to which LDPE can enhance the performance of asphalt in pavement applications.

IV. RESULTS & DISCUSSION

A. Aggregate Examination

Table 3 Results of Specific Gravity and Aggregate Absorption Tests

Coarse Aggregate Fraction 3/4"				
No.	**Type of Test**	**Result**	**Specification**	**Remarks**
1	Bulk Specific Gravity	2,79	>2	Meets Requirement
2	SSD (Saturated Surface Dry) SG	2,81	>2.5	
3	Apparent Specific Gravity	2,86	>2.5	
4	Water Absorption (%)	0,90	<3	
Coarse Aggregate Fraction 3/8"				
No.	**Type of Test**	**Result**	**Specification**	**Remarks**
1	Bulk Specific Gravity	2,76	>2	Meets Requirement
2	SSD (Saturated Surface Dry) SG	2,79	>2.5	
3	Apparent Specific Gravity	2,83	>2.5	
4	Water Absorption (%)	0,89	<3	
Fine Aggregate – Stone Dust				
No.	**Type of Test**	**Result**	**Specification**	**Remarks**
1	Bulk Specific Gravity	2,68	>2	Meets Requirement
2	SSD (Saturated Surface Dry) SG	2,75	>2.5	
3	Apparent Specific Gravity	2,89	>2.5	
4	Water Absorption (%)	2,73	<3	

Table 4 Results of No. 200 Sieve Passing Test

No.	Material Type	Result (%)	Specification	Remarks
1	Coarse Aggregate 3/4" Fraction	0,398	<10	Meets Requirement
2	Coarse Aggregate 3/8" Fraction	0,930	<10	
3	Fine Aggregate (Stone Dust)	9,017	<10	

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Table 5 Results of Aggregate Material Abrasion Test

No.	Type of Test	Number of Rotations	Result (%)	Spesifications	Remarks
1	Abrasion Using LA Machine	500 Rotations	15.49	<40	Meets Requirement

Based on the results of the specific gravity and absorption test, the No. 200 sieve passing test, and the aggregate abrasion test, it can be concluded that the aggregate material used in this study meets the requirements for use in asphalt mixture design and implementation.

B. Asphalt Characteristic Testing

This study used 60/70 penetration grade asphalt as the main binder material. The following table presents the results of the conventional asphalt characteristic tests.

Table 6 Results of Conventional Asphalt Characteristic Tests

No.	Type of Test	Test Result	General Specification 2018		Remarks
			Min	Max	
1	Penetration (0.1 mm)	65,0	60	70	Meets Requirement
2	Specific Gravity	1,045	1	-	Meets Requirement
3	Softening Point (°C)	48	48	-	Meets Requirement
4	Ductility (cm/sec)	152,57	100	-	Meets Requirement
5	Weight Loss (%)	0,13959	-	0.8	Meets Requirement
6	Flash Point (°C)	325	232	-	Meets Requirement
7	Viscosity (°C)	1468,48	300	-	Meets Requirement

C. Modified Asphalt Characteristics Testing

The testing of modified asphalt characteristics in this study was carried out by adding LDPE plastic at percentages of 0.25%, 0.5%, 0.75%, and 1% by weight of asphalt. The modified asphalt tests include penetration test, specific gravity test, softening point test, ductility test, and viscosity test. The following table presents the test results of the modified asphalt.

Table 7 Test Results of Modified Asphalt Characteristics

No.	Type of Test	Test Results				Spec	Unit
		0,25	0,5	0,75	1		
1	Penetration (0.1 mm)	52.1	40.4	32.5	30.8	-	mm
2	Specific Gravity	1.250	1.69	1.75	2.023	-	-
3	Softening Point (°C)	49	51	67	68	-	°C
4	Ductility (cm/sec)	152.57	150.67	6.27	5.79	-	cm
5	Viscosity (°C)	2820.85	4173.22	5525.59	6000.67	≥300	cSt

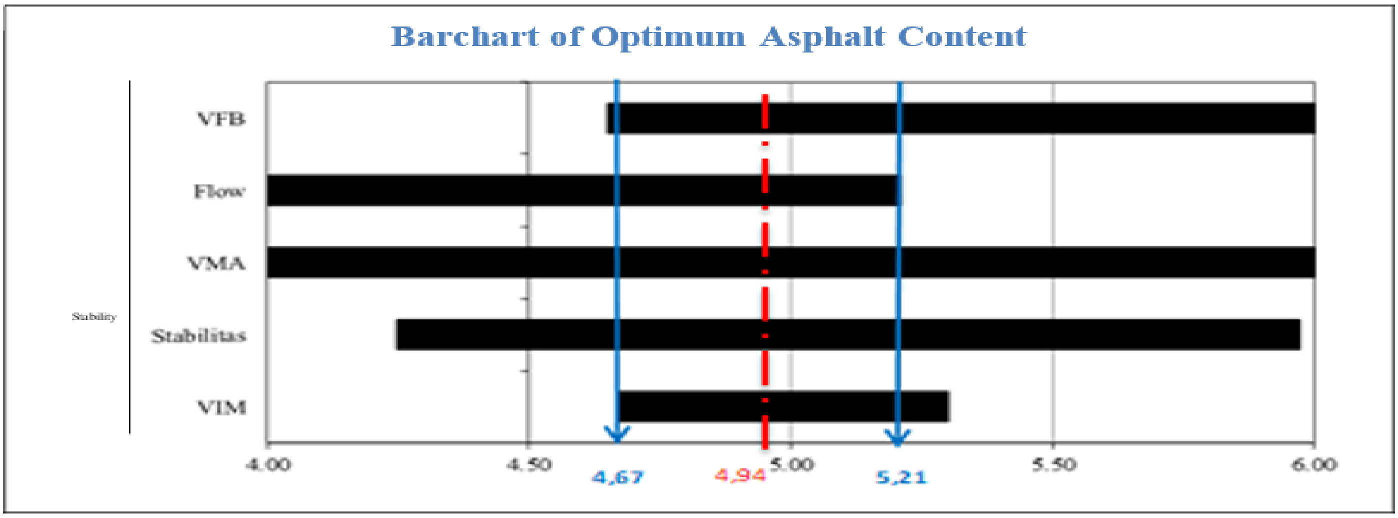

Fig 1 Barchart of Optimum Asphalt Content

D. AC-WC Determination of Aggregate Composition for AC-WC Mixture

The determination of aggregate composition for the AC-WC mixture in this study used the by Portion method, in which aggregates are grouped based on their fraction into coarse and fine aggregates. The composition determination is illustrated in Figure 2 as follows.

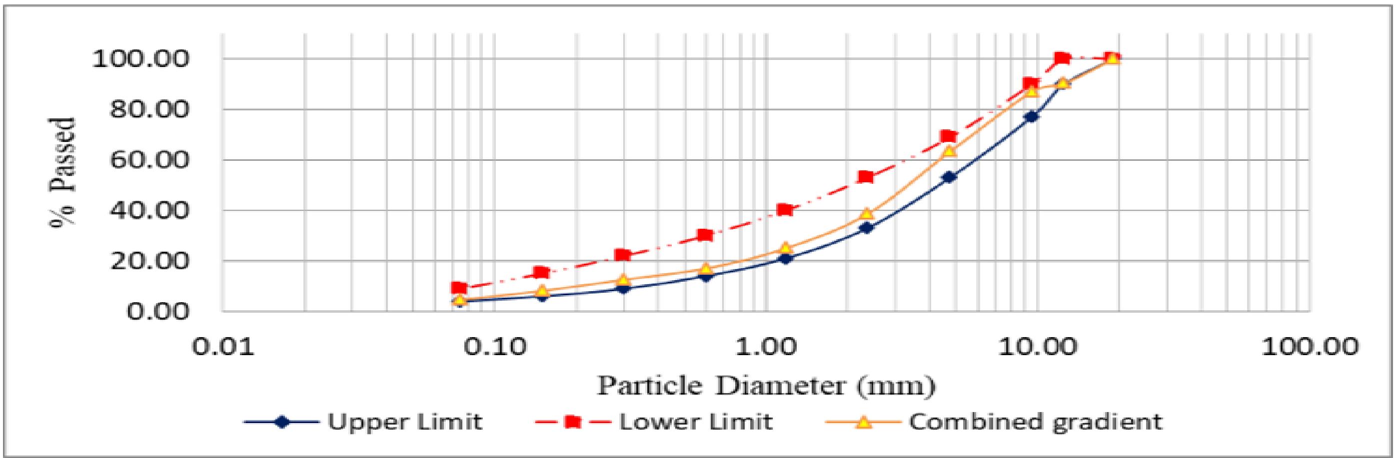

Fig 2 Combined Gradation Graph of AC-WC Asphalt Concrete Mixture

E. Determination of Optimum Asphalt Content (OAC) Using Marshall Test

The specimens, which were prepared based on the determined aggregate composition and estimated optimum asphalt content, were left to rest for ±24 hours. Subsequently, the specimens were immersed in a water bath at a temperature of 60°C for 30 minutes, and then tested using the Marshall press apparatus. The results of the Marshall test can be seen in the following table and graph.

Table 8 Marshall Test Results for Determination of Optimum Asphalt Content (OAC)

Type of Test	Unit	Test Results by Asphalt Content (%)					Specification
		4	4.5	5	5.5	6	
Density	(gr/cm3)	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	Min 15
VFB	(%)	49.57	63.11	73.76	80.13	86.06	Min 65
Stability	(Kg)	711.54	942.21	1017.68	918.30	905.89	Min 800 kg
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	Min 250

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Figure 3. Barchart of Optimum Asphalt Content (OAC) Determination from the figure above, the asphalt content range for AC-WC is found to be 4.67% – 5.21%. Therefore, the value of OAC (Optimum Asphalt Content) is determined as follows.

$$OAC = \frac{A+B}{2} + \frac{4{,}67+5{,}21}{2} = 4{,}94 \approx 5{,}0\%$$

Based on the results obtained, the asphalt content is determined to be 5%. This OAC (Optimum Asphalt Content) value is then used for testing the asphalt modified with LDPE.

F. LDPE Marshall Testing of AC-WC + LDPE Mixtures

The Marshall testing for the asphalt mixtures with LDPE was conducted using an optimum asphalt content (OAC) of 5% and LDPE content variations of 0.25%, 0.5%, 0.75%, and 1%. The mixing temperatures for each LDPE content level varied and were determined based on viscosity testing. The corresponding mixing temperatures used for each LDPE content are shown below.

Table 9 Mixing Temperature Based on LDPE Content

No.	LDPE Content (%)	Mixing Temperature (°C)
1	0	173
2	0,25	207
3	0,5	210
4	0,75	214
5	1	228

G. Analysis Results of Marshall Parameters for Asphalt + LDPE

The calculation of Marshall parameters for asphalt- plastic mixtures follows the same procedure as for conventional asphalt mixtures. The results of the testing conducted are presented below.

Table 10 Marshall Test Results for Asphalt + LDPE

Marshall Parameter	Unit	Test Results by Asphalt Content (%)					Specification.
		0%	0.25	0.5	0.75	1	
Density	(gr/cm3)	2.46	2.47	2.46	2.45	2.46	
VIM	(%)	4.35	4.07	4.42	4.77	4.34	3 - 5 %
VMA	(%)	16.13	15.89	16.20	16.50	16.13	Min 15
VFB	(%)	73.08	74.40	72.78	71.12	73.09	Min 65
Stability	(Kg)	1030.56	1642.10	1752.88	1902.17	2228.11	Min 800 kg
Flow	(mm)	3.58	3.53	3.62	3.26	3.15	2 - 4
MQ	(Kg/mm)	288.49	465.01	497.24	584.16	708.41	Min 250

Based on the table above, graphs were then created to show the relationship between the asphalt content and each Marshall test parameter, as follows.

- *Density*

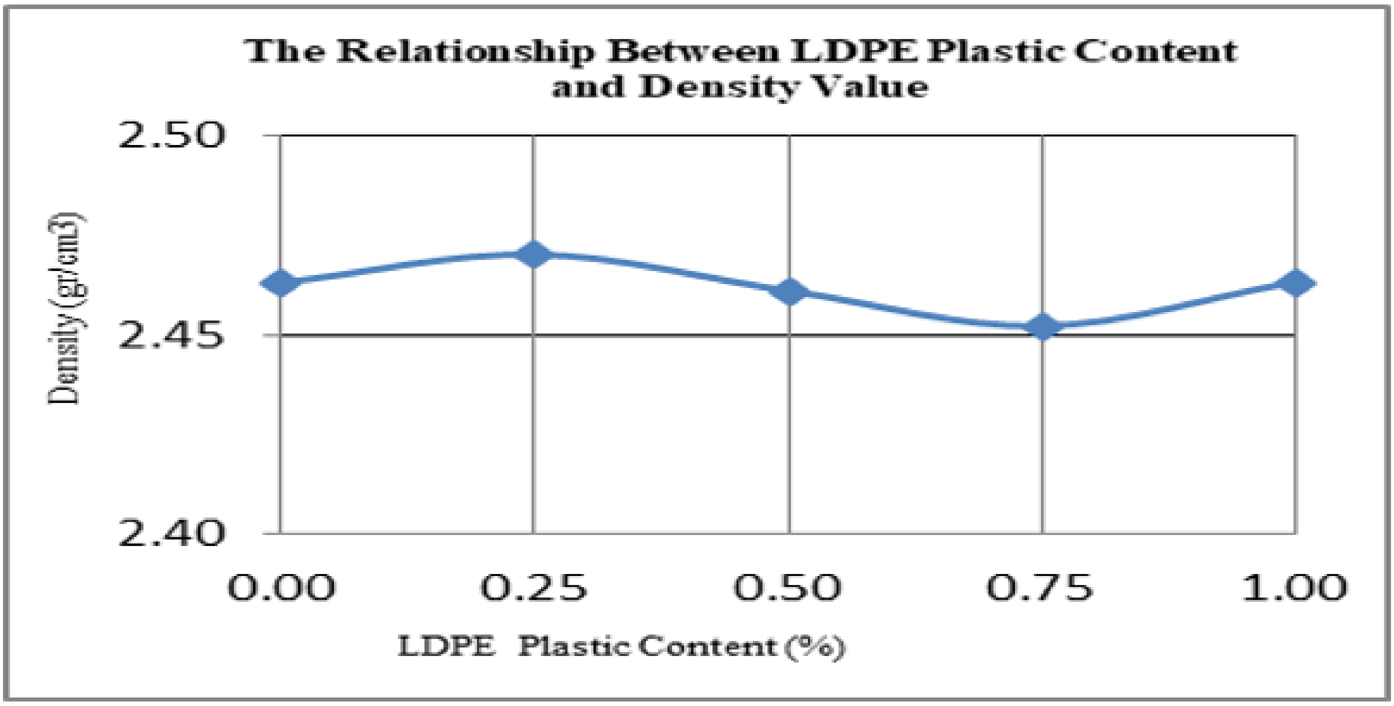


Fig 3 Graph of the Relationship Between LDPE Plastic Content and Density Value

From the figure above, it can be seen that the density graph corresponding to the addition of LDPE plastic content at levels of 0%, 0.25%, 0.5%, 0.75%, and 1%, using 60/70 penetration asphalt, shows fluctuating results. The test results obtained through the wet mixing method indicate inconsistent density values with each increment of LDPE content. Although the values are not stable or show fluctuation, all the density results for 0%, 0.25%, 0.5%, 0.75%, and 1% meet the minimum requirement specified in the 2018 General Specifications, which is at least 2 g/cm³. The fewer the voids filled with asphalt, the higher the porosity within the mixture. As a result, asphalt mixtures with LDPE tend to be less dense compared to those without LDPE.

- *VIM (Void in Mixture)*

To cause deformation or structural issues such as rutting or cracking.

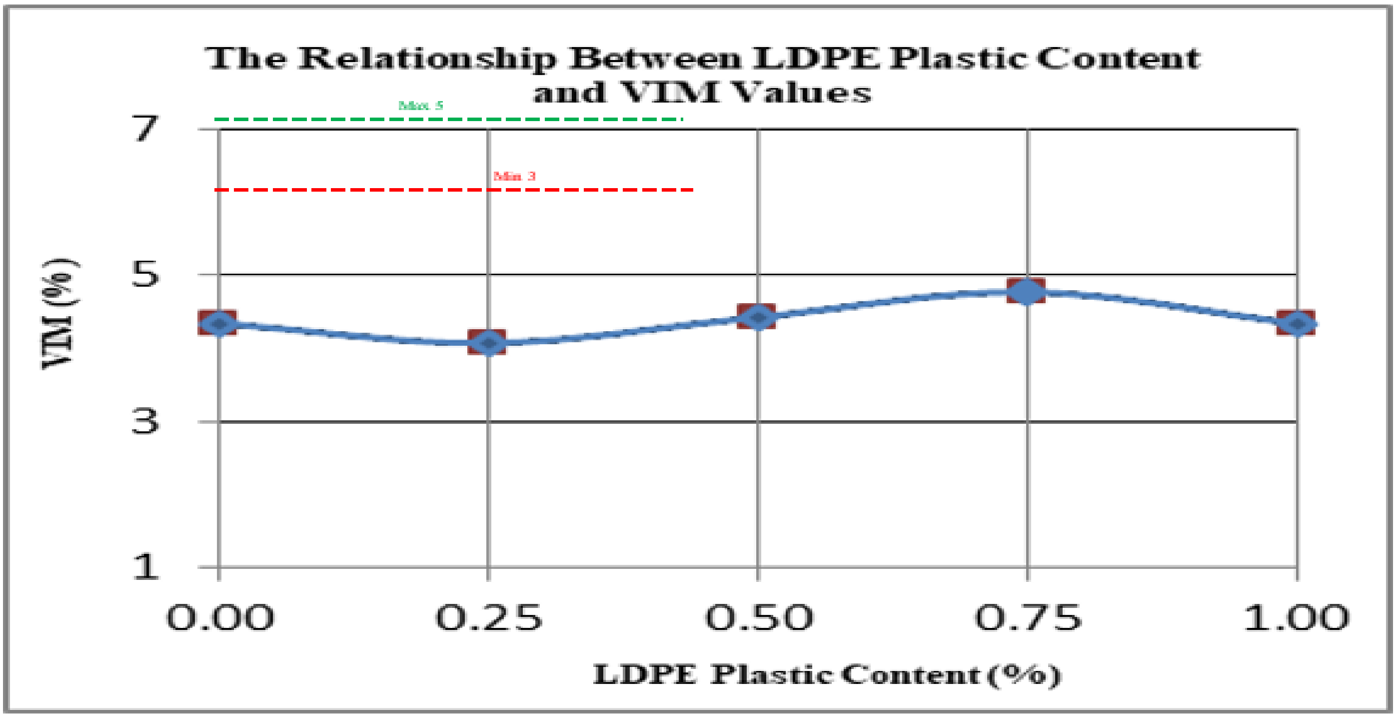


Fig 4 The Relationship Between LDPE Plastic Content and VIM Values

➢ *VMA (Void In Mineral Aggreggate)*

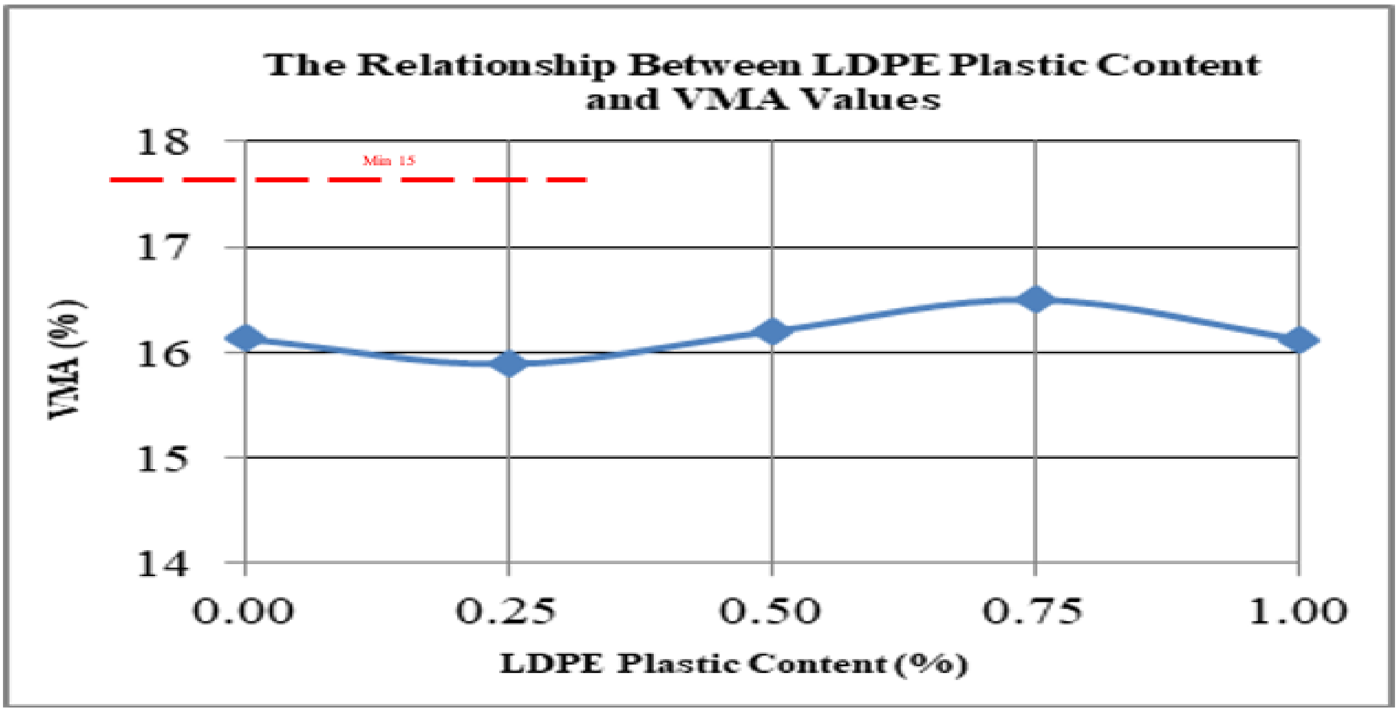


Fig 5 Graph of the Relationship Between LDPE Plastic Content and VMA Values

From the figure above, the graph shows the relationship between the voids in mineral aggregate (VMA) and the percentage of LDPE plastic content added, at levels of 0%, 0.25%, 0.5%, 0.75%, and 1%. The test results using the wet mixing method exhibit fluctuating VMA values with each increment of LDPE plastic content. Although the results are not entirely consistent or linear, all VMA values obtained at 0%, 0.25%, 0.5%, 0.75%, and 1% LDPE content with 60/70 penetration asphalt meet the 2018 General Specifications requirement, which states that the minimum acceptable VMA value is 15%. Therefore, the addition of LDPE plastic within this range in flexible pavement construction is not expected to cause adverse effects such as plastic deformation.

➢ *VFB (Void Filled Bitumen)*

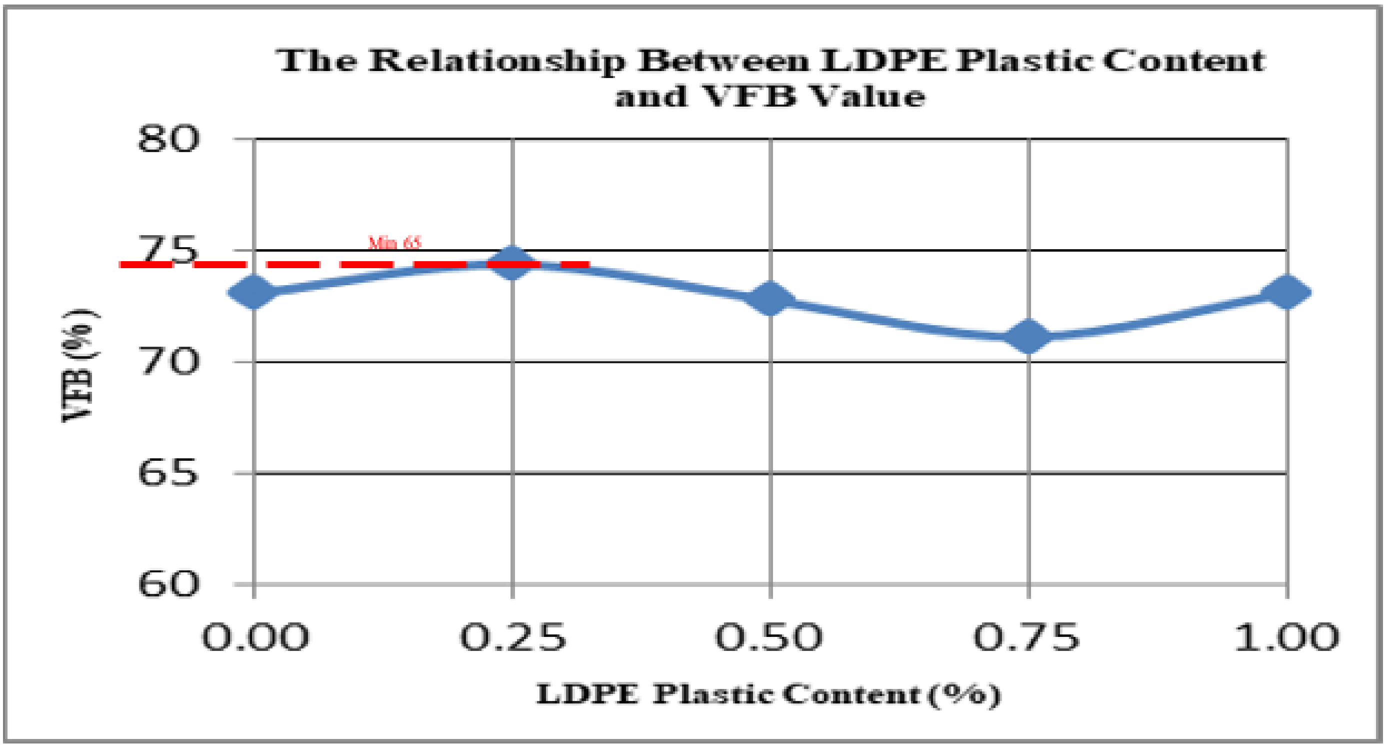


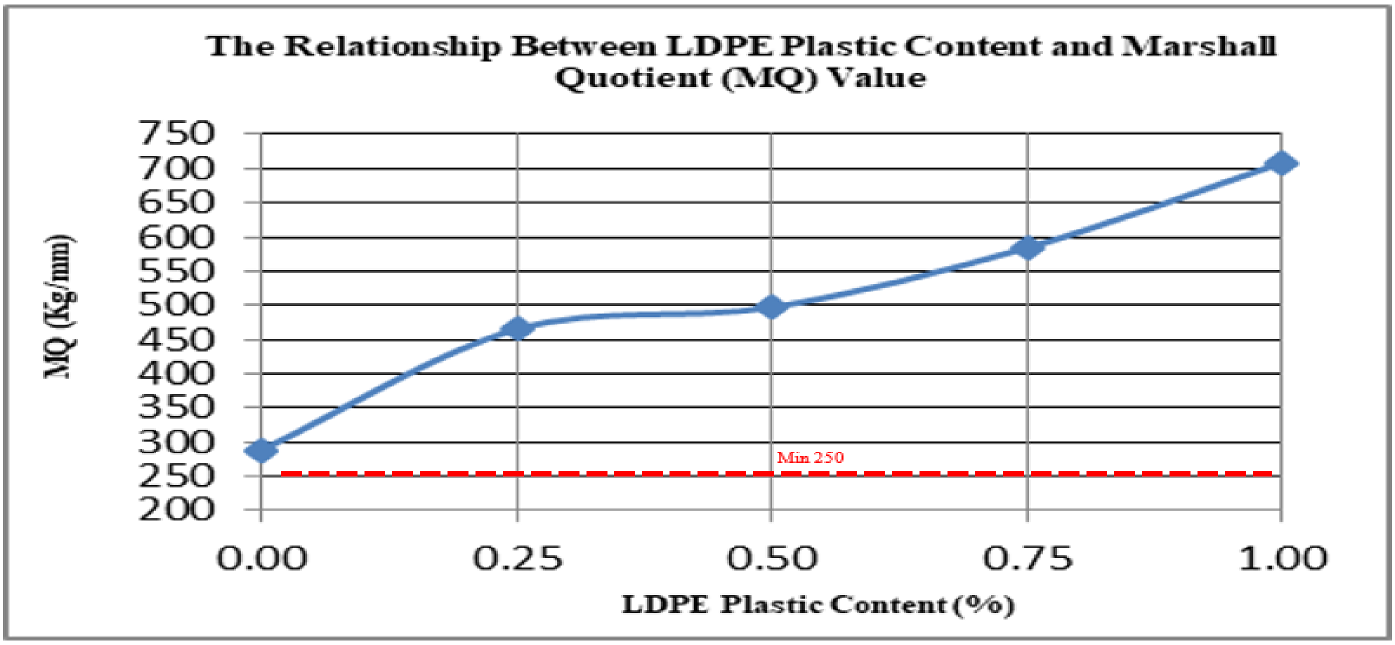
Fig 6 Graph of the Relationship Between LDPE Plastic Content and VFB Value

From the figure above, the graph illustrates the relationship between the voids in the mixture (VIM) and the percentage of LDPE plastic content added, at levels of 0%, 0.25%, 0.5%, 0.75%, and 1%. The test results using the wet mixing method show fluctuating VIM values with each addition of LDPE plastic content. Although the results are not consistent and exhibit some fluctuations, all VIM values obtained with 0%, 0.25%, 0.5%, 0.75%, and 1% LDPE content with 60/70 penetration asphalt meet the 2018 General Specifications requirement, which states that the VIM value must be between 3% and 5%. Therefore, the use of LDPE plastic within this range in flexible pavement is not expected

From the figure above, the graph shows the relationship between Void Filled with Bitumen (VFB) and the addition of LDPE plastic at concentrations of 0%, 0.25%, 0.5%, 0.75%, and 1%. The test results using the wet mixing method exhibit fluctuating VFB values as the percentage of LDPE plastic increases. The decrease in VFB values is attributed to the plastic not fully melting during mixing, remaining in fibrous form and getting coated with bitumen. This reduces the amount of bitumen available to fill the voids, leading to lower VFB values. Despite these fluctuations, all VFB values obtained at 0%, 0.25%, 0.5%, 0.75%, and 1% LDPE content with 60/70 penetration asphalt still meet the 2018 General Specifications, which require a minimum VFB of 65%. Therefore, the addition of LDPE plastic at these levels in flexible pavement construction is not expected to cause adverse effects such as plastic deformation.

➢ Stability

Plastic at these levels in flexible pavement construction is not expected to cause adverse effects such as plastic deformation.



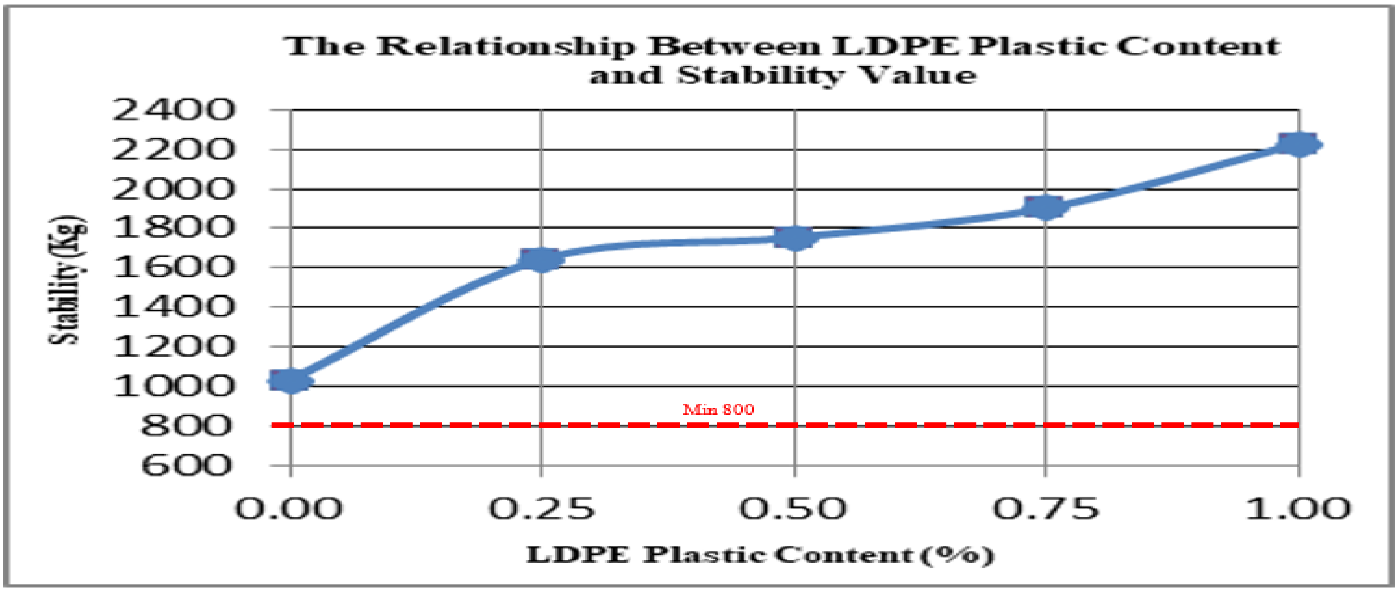


Fig 7 Graph of the Relationship Between LDPE Plastic Content and Stability Value

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From the test results using the wet mixing method and the designated temperatures for each LDPE content, it was found that the stability value tends to increase as the LDPE plastic content increases. This occurs because the plastic makes the asphalt mixture harder, thereby enhancing the stability of the asphalt mixture.

➢ *Flow*

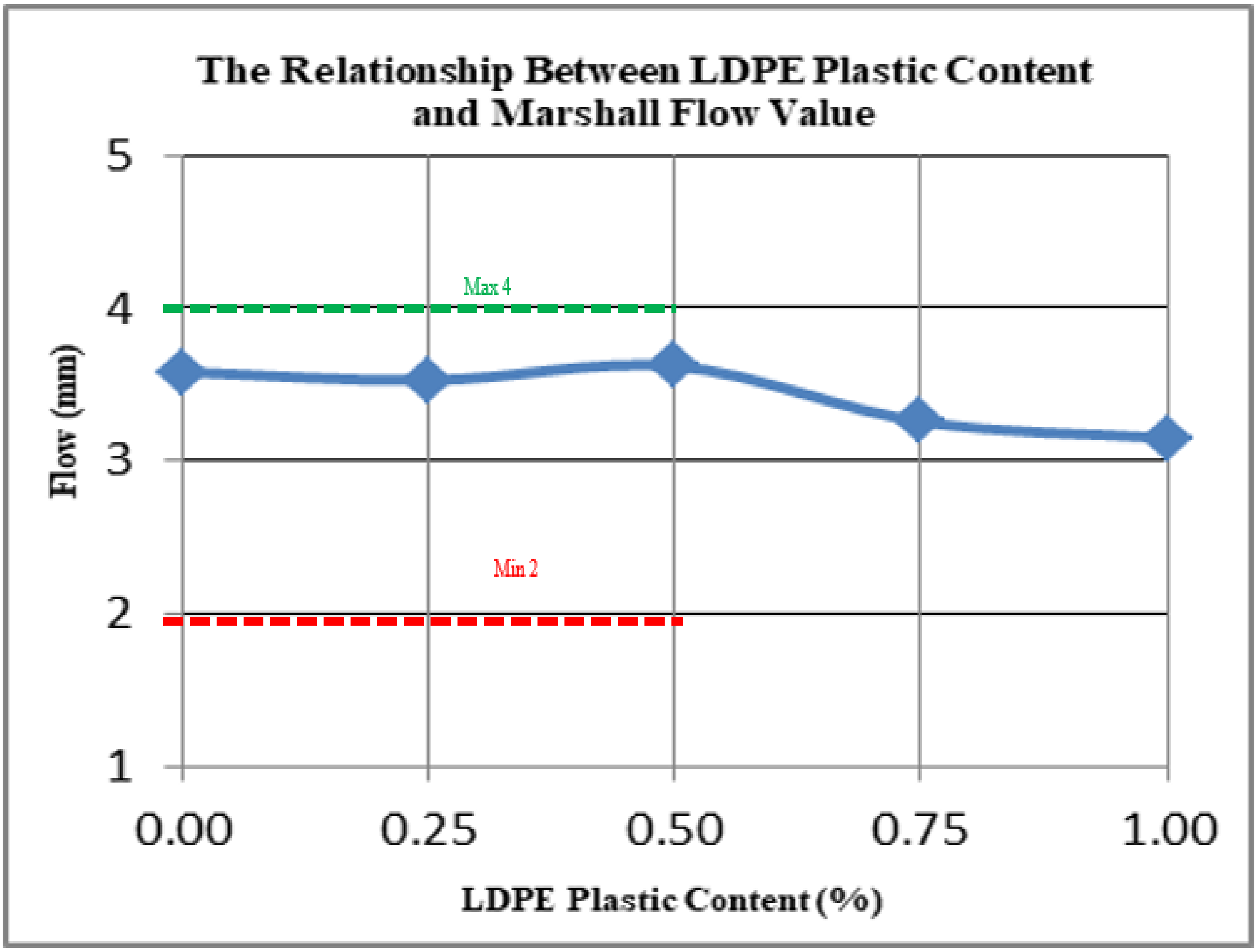

Fig 8 Graph of the Relationship Between LDPE Plastic Content and Marshall Flow Value

From the test results using the wet mixing method, the flow values show fluctuating results with each increment of LDPE plastic content. Although the outcomes are not consistent or stable, all flow values obtained at 0%, 0.25%, 0.5%, 0.75%, and 1% LDPE content with 60/70 penetration asphalt meet the 2018 general specification requirements, which is a minimum of 2 mm and a maximum of 4 mm. Therefore, the addition of LDPE plastic to flexible pavement does not cause deformation or plastic flow in the asphalt mixture.

➢ *MQ (Marshall Quetient)*

From the test results using the wet mixing method, the Marshall Quotient (MQ) values increase with the addition of LDPE plastic content. This indicates that the higher the plastic content added to the mixture, the stiffer and more brittle the asphalt mixture becomes. All MQ values obtained from the tests meet the 2018 General Specification requirement, where the minimum MQ value is 250 kg/mm.

H. XRF (X-Ray Fluorescence) Analysis Results of AC- WC Mixture

The results of the XRF analysis are presented to determine the chemical composition of the AC-WC mixture with the addition of LDPE at concentrations of 0%, 0.25%, 0.5%, 0.75%, and 1%. This analysis provides information on the elemental and chemical compound content, which can be used to better understand the chemical properties and structure of the sample.

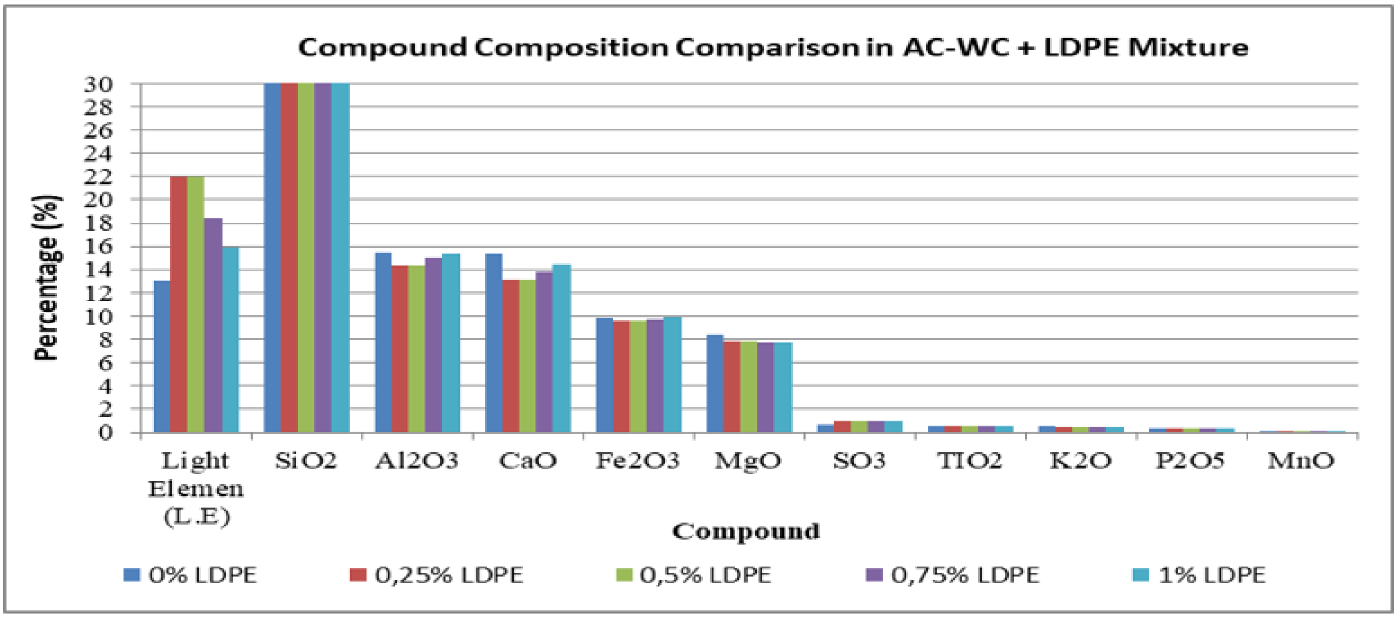

Fig 9 Graph of Compound Composition Comparison in AC-WC + LDPE Mixture

The graph above shows the main compound composition in all LDPE concentration samples based on XRF results, with SiO_2 being the dominant component, followed by Al_2O_3, CaO, Fe_2O_3, and others. From the compound analysis results in the Asphalt + LDPE mixture, the data is then correlated with the void parameters in the AC-WC mixture, namely VIM, VMA, and VFB. These volumetric parameters are significantly influenced by the mineral composition of the aggregate.

I. SEM (Scanning Electron Microscope) Analysis Results of AC-WC Mixture

The SEM analysis results are presented to identify the surface morphology of the AC-WC mixture modified with LDPE at concentrations of 0%, 0.25%, 0.5%, 0.75%, and 1%.

- *Conventional Asphalt without Additives (LDPE 0%)*

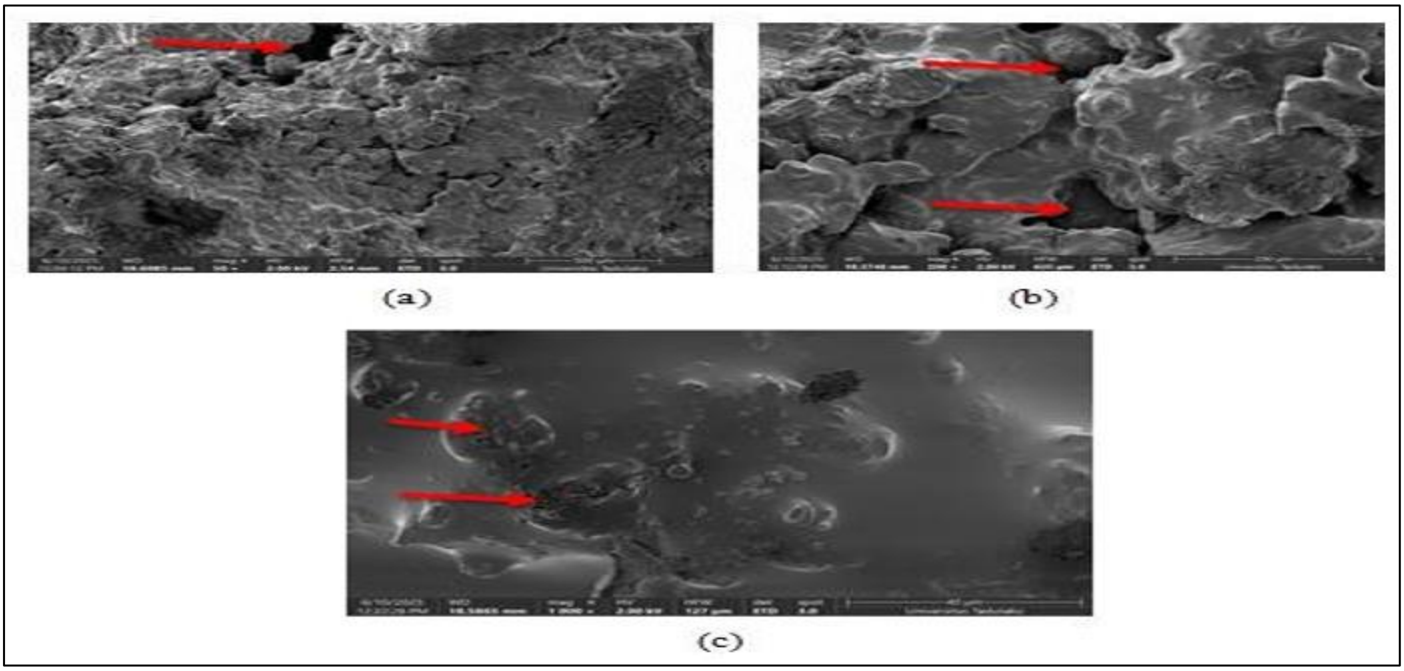

Fig 10 SEM Test Results of AC-WC Asphalt Without LDPE Additive at Magnifications: (a) 50x, (b) 200x, (c) 1000x

The SEM images of AC-WC asphalt without the addition of LDPE are shown at three different magnifications: 50x, 200x, and 1000x. The BSE-SEM images in (a) and (b) reveal a rough surface texture, micro- voids, fine cracks, and imperfect bonding between aggregate particles and asphalt. In image (c), the morphology of AC- WC asphalt appears smoother, although clumps are visible due to uneven distribution of filler particles.

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➢ *Asphalt with LDPE Additive 0.25%*

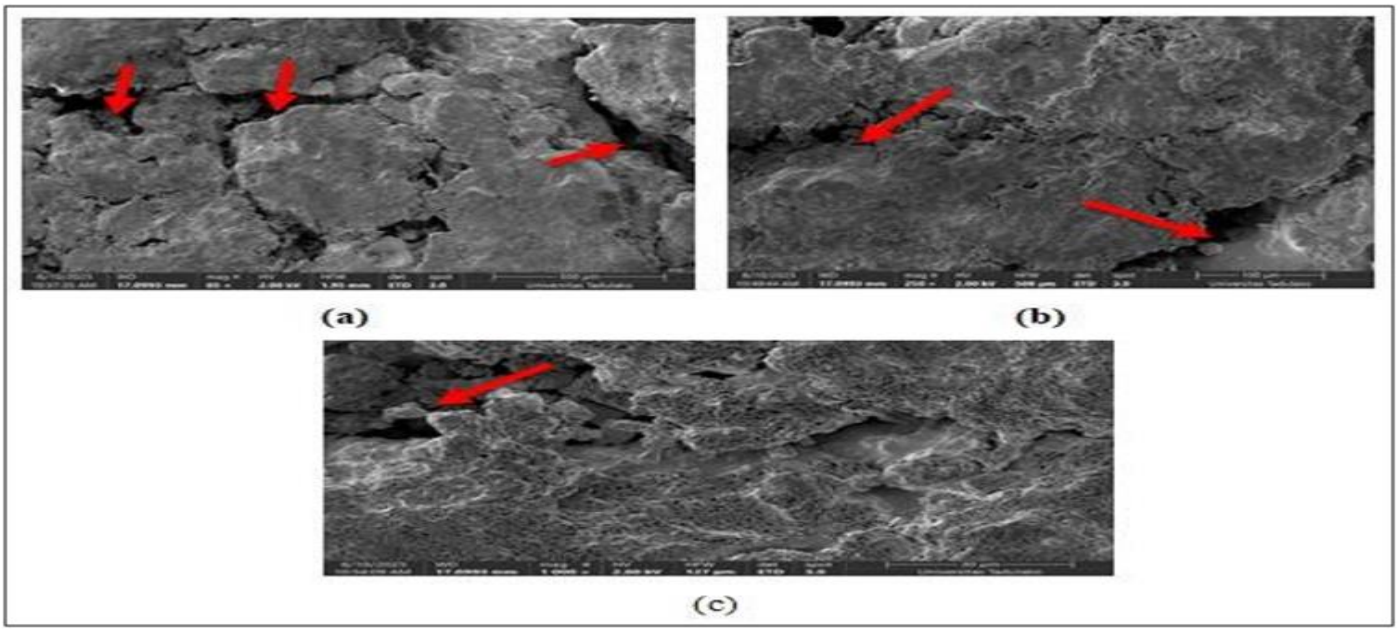

Fig 11 SEM Test Results of AC-WC Asphalt with 0.25% LDPE Additive at Magnifications: (a) 65x, (b) 250x, (c) 1000x

The SEM images of AC-WC asphalt with 0.25% LDPE additive are presented at three different magnifications: 65x, 250x, and 1000x. The BSE SEM images in (a) and (b) still show the presence of small voids and micro-cracks, but these are reduced compared to the mix without LDPE. The surface appears more homogeneous. In image (c), the voids are noticeably smaller and further reduced compared to (a) and (b). This is due to the added LDPE starting to function as a void filler, improving the mixture's density and the bonding strength between aggregates.

➢ *Asphalt with LDPE Additive 0.50%*

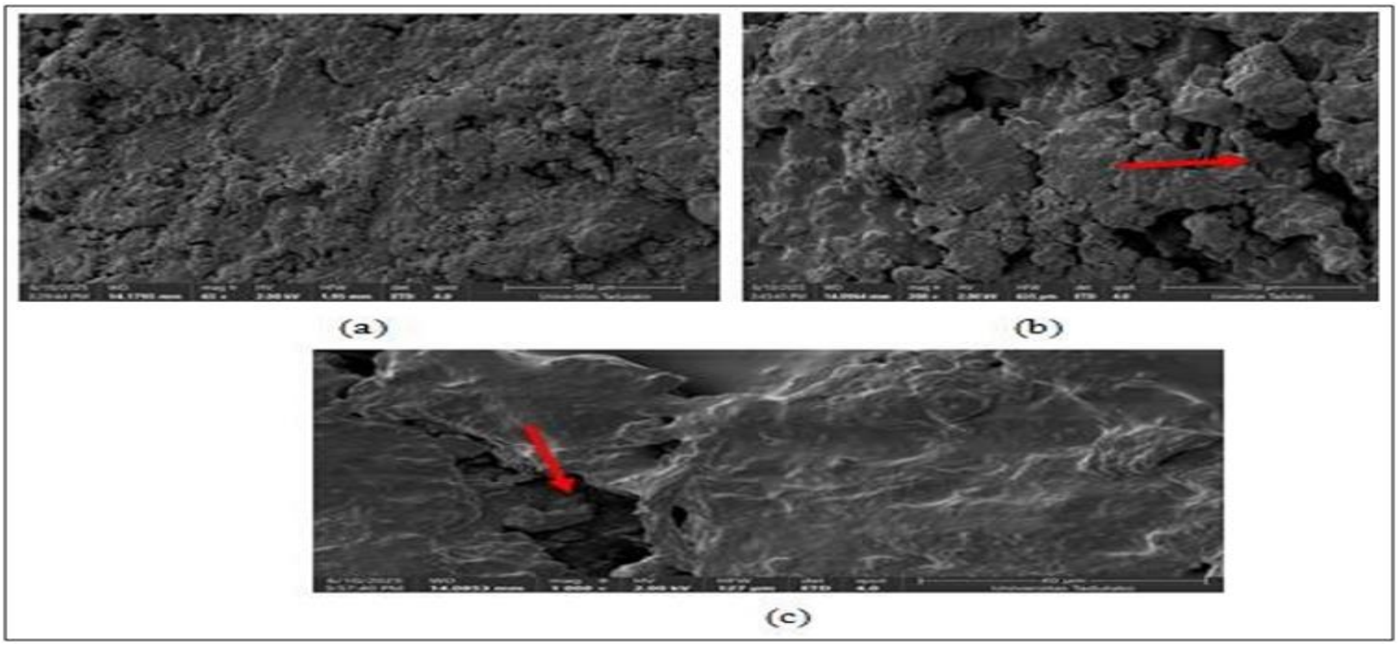

Fig 12 SEM Test Results of AC-WC Asphalt with 0.50% LDPE Additive at Magnifications: (a) 65x, (b) 200x, (c) 1000x

The SEM images of the AC-WC asphalt with 0.50% LDPE additive are shown at three different magnifications: 65x, 200x, and 1000x. In image (a), BSE SEM visualization reveals that no significant cracks are present, although small voids are still visible. In images (b) and (c), the surface appears more homogeneous, with asphalt and LDPE coating the aggregate, though the texture of the aggregate remains partially visible. Visually, the addition of 0.50% LDPE tends to increase the microstructural density. The structure appears more compact and uniform, indicating an improvement in the binding and filling capabilities of the mixture.

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- *Asphalt with LDPE Additive 0.75%*

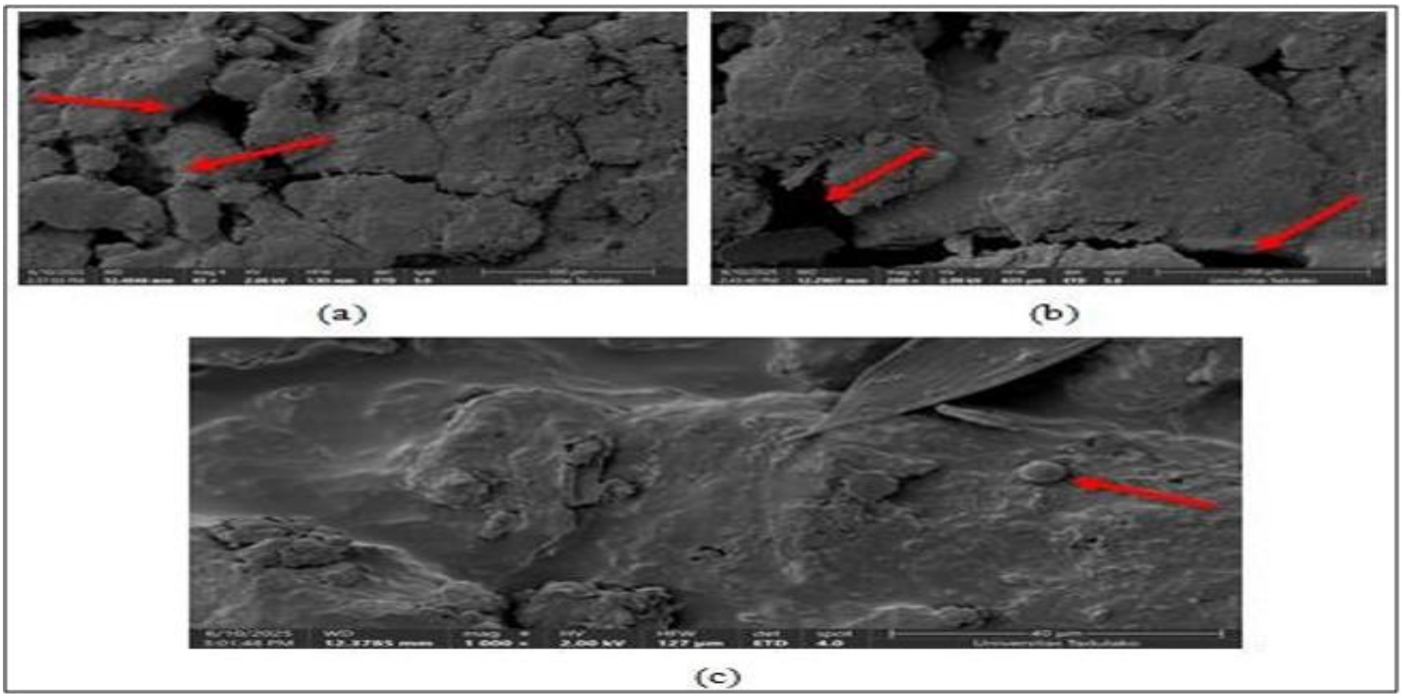

Fig 13 SEM Test Results of AC-WC Asphalt with 0.75% LDPE Additive at Magnifications: (a) 65x, (b) 200x, (c) 1000x

The SEM images of AC-WC asphalt with 0.75% LDPE additive are shown at three different magnifications: 65x, 200x, and 1000x. In images (a) and (b), the BSE SEM visuals reveal a rougher surface compared to the mixture with 0.50% LDPE. Micro-cracks and small voids are more noticeable at these magnifications. The aggregate appears less homogeneously coated by the asphalt matrix than in the 0.50% sample. Image (c) displays a dense structure but shows clumps of LDPE within the asphalt, which may indicate incomplete mixing during the blending of LDPE and asphalt.

- *Asphalt with LDPE Additive 1%*

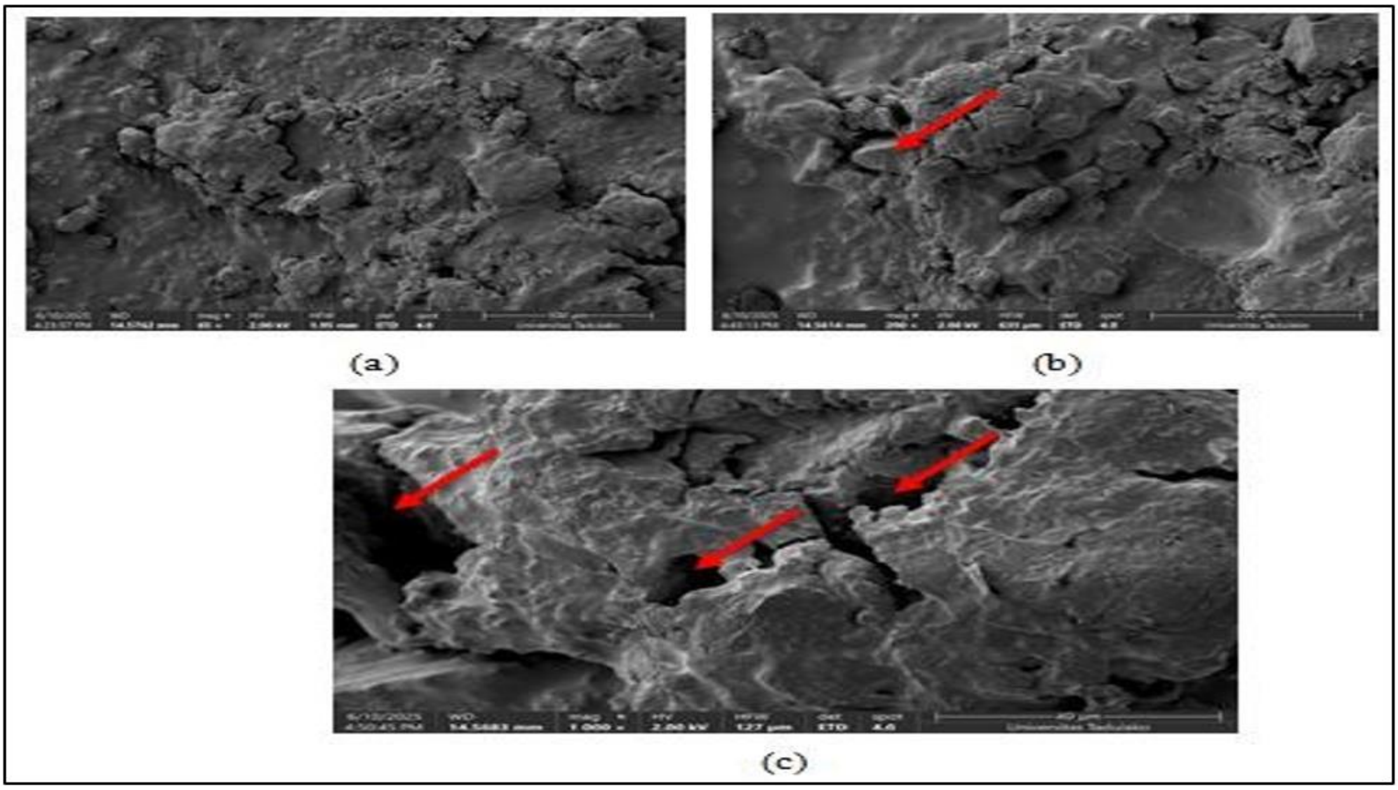

Fig 14 SEM Test Results of AC-WC Asphalt with 1% LDPE Additive at Magnifications: (a) 65x, (b) 200x, (c) 1000x

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The SEM (Scanning Electron Microscope) images for AC-WC asphalt with 1% LDPE additive are presented at three different magnifications: 65x, 200x, and 1000x. The BSE SEM images in (a) and (b) show a dense and homogeneous structure, with a reduction in large pores. The surface appears well-coated by the thermoplastic matrix, indicating very strong microstructural bonding. However, in image (c), macro-voids and cracks are visible. This may be attributed to the excessive stiffness introduced by the 1% LDPE content, which can lead to over-rigid asphalt and increase the risk of cracking. Overall, the SEM visuals suggest a decline in compaction effectiveness and reduced void-filling capability of the asphalt as LDPE content increases to 1%.

V. CONCLUSION

Based on the results of the research and data analysis that have been conducted, it can be concluded that the AC-WC mixture added with LDPE plastic shows an increase in void values, namely VIM, VMA, and VFB, when compared to conventional asphalt mixtures. The highest VIM value is found at 0.75% LDPE content, amounting to 4.77% of the asphalt. The highest VMA value is also at 0.75% LDPE content, amounting to 16.50% of the asphalt. The highest VFB value is found at 0.25% LDPE content, amounting to 74.40% of the asphalt. The results of the XRF test on both conventional asphalt and modified asphalt indicate that the main contents such as SiO_2 (silica), Al_2O_3 (alumina), Fe_2O_3 (iron oxide), CaO (calcium oxide), and MgO (magnesium oxide) are detected in all samples. Some minor elements such as P_2O_5, K_2O, and TiO_2 show small fluctuations between LDPE levels, but they are not technically significant. Meanwhile, from the SEM test results, it can be seen that the surface condition of the asphalt shows that the optimal effectiveness of LDPE occurs around 0.25–0.50%. At this range, the voids begin to close and the structure becomes more homogeneous. This is because the LDPE melts during the heating process. LDPE content that is too high causes agglomeration and a decrease in the bonding between aggregates.

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