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Study of the Effect of Adding LDPE (Low Density Polyethylene) Plastic on the Stability Value of AC-WC Mixtures Using SEM and XRF (X-Ray Fluorescence) Analysis

Chielcia Meidy Salsabilla[1];Syamsul Arifin[2];Novita Pradani[3]

[1,2,3]Department of Civil Engineering, Faculty of Engineering, Tadulako University, Central Sulawesi, Indonesia

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Abstract: The use of asphalt, especially AC-WC, still dominates the construction of road transportation facilities in Indonesia. One way to improve the quality of highways is by adding additives, such as the use of LDPE plastic into the asphalt mixture, which not only reduces waste but also produces stronger and more durable materials. This is followed by analysis using SEM and XRF, which allows researchers to study the microstructure and chemical composition of the AC-WC mixture. The aim of this research is to determine the effect of varying LDPE plastic mixture content on the Marshall stability of asphalt concrete mixtures and to understand the microstructure from the addition of LDPE plastic through SEM and XRF testing. This research was conducted with 5 variations of plastic content: 0.00%, 0.25%, 0.50%, 0.75%, and 1.00%. The results of this study indicate that with the addition of a higher plastic content, the structure produced in the SEM readings becomes very dense and homogeneous with cracks that are almost invisible. For the XRF test, three main components were identified, namely: SiO_2, Al_2O_3, and MgO. These three main components are the contents of the aggregates that affect the strength, elasticity, and optimal adhesion, thus enhancing the Marshall stability values.

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

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I. INTRODUCTION

The development of road infrastructure as a primary means of transportation in Indonesia has significantly increased in recent years. Roads serve as essential facilities for connecting goods and people from one place to another. In Indonesia, asphalt remains the dominant material used in road pavement construction. Natural asphalt found in Indonesia commonly known as Asbuton originates specifically from Buton Island in Southeast Sulawesi. One method to improve the quality of road pavement is by incorporating additive materials [1]. The addition of plastic waste can be utilized as a filler or additive material in the construction of road pavement structures. The inclusion of plastic in the asphalt mixture can increase the softening point, indicating that plastic modified asphalt is more resistant to extreme weather conditions. Deformation in asphalt mixtures is prone to occur in road pavements due to factors such as overloaded vehicles, moisture, and cracking caused by high temperatures.

Filler is a component in asphalt mixtures that functions to reduce temperature sensitivity and decrease air voids within the mixture, thereby minimizing the risk of cracking and plastic deformation in the asphalt pavement [2]. Low Density Polyethylene (LDPE) plastic can be used as an additive to strengthen the asphalt layer on aggregates, functioning as a filler in asphalt mixtures. LDPE plastic, commonly used as packaging wrap, is chosen as an alternative binder material in asphalt mixtures because it helps reduce plastic waste and is readily available. The use of LDPE plastic as an alternative aggregate binder to replace asphalt is expected not only to provide technical and economic benefits but also to serve as a potential solution for reducing the vast amount of LDPE waste on Earth. This is especially relevant considering that LDPE is currently used on a relatively small scale, such as in containers or plastic bags, which often have lower quality and limited reuse potential [3].

Analysis using Scanning Electron Microscopy (SEM) and X-Ray Fluorescence (XRF) allows researchers to examine the microstructure and chemical composition of

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asphalt mixtures. SEM provides a detailed visualization of the morphology and material distribution within the mixture, while XRF offers information on the elemental composition. In this study, SEM is expected to help identify the interactions between asphalt components and LDPE plastic particles, as well as determine their influence on the physical stability of the mixture. By understanding the microstructure, it becomes possible to evaluate how LDPE contributes to the enhanced performance of asphalt mixtures. XRF, as a non destructive chemical analysis method, will offer deeper insight into the elemental composition of the asphalt mixture. By analyzing the present elements, researchers can better understand how the addition of LDPE affects the chemical and physical properties of the asphalt. Integrating plastic waste into asphalt mixtures not only helps reduce plastic pollution but also results in a stronger and more durable materialcreating opportunities for innovation in the construction industry.

Based on the aforementioned background, the objective of this study is to determine the effect of varying LDPE plastic content on the Marshall stability of asphalt concrete mixtures, as well as to examine the microscopic structure resulting from the addition of LDPE plastic through SEM and XRF analysis. This research is expected to provide insights into methods for improving the quality of road pavements through the use of additive materials, thereby supporting future implementation in road construction across Indonesia

II. LITERATURE STUDY

➢ *Asphalt Concrete:*

- *Definition of Asphalt Concrete:*

Asphalt concrete, commonly referred to as asphalt, is a construction material composed of a mixture of aggregates and binder, typically used for the construction of road surfaces, sidewalks, and parking areas [4].

- *Constituent Materials:*

✓ Asphalt is a dark brown to black solid material composed of hydrocarbon compounds. It exhibits viscoelastic properties, meaning it softens when heated and hardens under cooler conditions [5].
✓ Aggregates are collections of mineral particles used as a component in various types of mixtures. They serve as the primary load-bearing material in asphalt concrete and are also used in road base layers, backfill materials, and other construction applications [6].

➢ *Asphalt and Aggregate Testing:*

The purpose of asphalt and aggregate testing is to determine whether the asphalt used in this study meets the specified standards and to ensure that the aggregates prepared for use conform to the required specifications. The tests conducted in this study include:

- Ductility, Ductility testing measures the tensile strength between particles of the same type. The point at which the asphalt and its particles separate is referred to as the breaking condition. This test is conducted at a standard room temperature of 25°C..
- Penetration, The penetration test aims to determine the hardness level of asphalt. It is performed by applying a standard load onto the surface of the prepared test specimen. The specimen, consisting of heated asphalt, is poured into a mold and then immersed in a water bath for 1 to 1.5 hours. The penetration value is expressed in units multiplied by 0.1 mm.
- Flash Point, The flash point test identifies the temperature at which a brief flame (lasting less than 5 seconds) appears at a specific point above the asphalt surface.
- Softening Point, The softening point test is conducted to determine the temperature at which asphalt softens, typically ranging from 30°C to 200°C. The test measures the time and temperature required for a steel ball with a diameter of 9.35 mm to push softened asphalt through a brass ring until it touches the base plate.
- Specific Gravity, This test determines the specific gravity of asphalt, which is essential for further calculations during the execution of construction work. According to standard specifications, the minimum acceptable specific gravity value is above 1.0 g/cc.
- Viscosity, Viscosity refers to the thickness or flow resistance of asphalt material, which is a critical factor in asphalt mix design. Asphalt viscosity is closely related to temperature. At room temperature (±25°C), asphalt typically exhibits high viscosity, making it difficult to mix with other materials—resulting in low workability.
- Loss on Heating, This test aims to measure the loss of volatile components in asphalt due to repeated heating and to assess performance changes caused by weight loss during the heating process.
- Sieve Analysis, Sieve analysis is used to classify the aggregate gradation, which is essential for determining the composition and proportioning of the test specimens.
- Aggregate Specific Gravity, This test is conducted to determine the mass-to-volume ratio of aggregates and serves as a reference in mix design. It is defined as the ratio between the volume of aggregate and the volume of water.
- Abrasion, The abrasion test is used to determine the resistance of coarse aggregates to wear, using the Los Angeles Abrasion Machine. Abrasion resistance is expressed as the percentage ratio of the weight of material passing through the No. 12 sieve to the original sample weight.

➢ *Determination of Volumetric Properties of Asphalt Concrete Mixtures Using the Marshall Test:*

According to ref [7], the determination of volumetric properties in asphalt concrete mixtures is useful for identifying the characteristics of compacted asphalt concrete, whether prepared in the laboratory or obtained from field coring samples.

- Void in Mineral Aggregate (VMA). VMA refers to the volume of air voids between aggregate particles in a compacted asphalt mixture..

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- Void in Mix (VIM), VIM represents the air pockets within the asphalt mixture, located between aggregate particles coated with asphalt.
- Voids Filled with Bitumen (VFB), VFB is the portion of VMA that is filled with effective asphalt, expressed as the percentage ratio of (VMA – VIM) to VMA.
- Effective Asphalt Content (Pbe), The effective asphalt content is the total asphalt content minus the amount absorbed by the aggregate. This effective asphalt forms a coating on the outer surface of the aggregate particles and significantly affects the performance of the asphalt mix.
- Absorbed Asphalt (Pbabs): This is the amount of asphalt absorbed by the aggregate, typically expressed as a percentage by weight of the total aggregate, not the total mixture.
- Maximum Theoretical Specific Gravity (Gmm): Gmm represents the theoretical maximum specific gravity of the asphalt mixture, assuming zero air voids in the mix.

➢ *Plastic:*

- *Definition of Plastic:*

Plastic is a polymer material known for its advantages, particularly its low cost and wide availability. It has become an integral part of daily life, as many tools and products are made from plastic [8].

- *Low Density Polyethylene (LDPE) Platic:*

LDPE is a type of plastic derived from petroleum and is highly moldable when heated. It is a type of resin that is durable, strong, and chemically resistant. LDPE exhibits excellent chemical resistance and does not dissolve at room temperature due to its crystalline properties. It is characterized by its slightly cloudy appearance, flexibility, thinness, and ease of forming when heated [9].

III. MATERIALS AND METHOD

➢ *Type of Research:*

This research is an experimental study conducted in a laboratory using available laboratory equipment, following scientific principles and systematic procedures to achieve verifiable results. The research was carried out in stages, applying both theoretical and practical procedures, including sampling, examination, and testing, to obtain data relevant to the research objectives. This study was conducted at the Transportation and Highway Laboratory, Faculty of Engineering, Tadulako University.

➢ *Material Collection:*

- *Asphalt:*

The asphalt used in this study is penetration grade 60/70, which was readily available at the laboratory where the research was conducted. The selection of 60/70 penetration asphalt is based on the climatic conditions in Central Sulawesi, Indonesia, where high ambient temperatures make this grade more suitable and commonly used. The collection of asphalt material must be carried out carefully to preserve its original properties. Furthermore, a series of tests were conducted to ensure that the asphalt meets national standards and is suitable for use. The asphalt tests conducted in this study include penetration, softening point, ductility, flash point and fire point, specific gravity, loss on heating, and viscosity.

- *Agregat:*

The aggregates used in this study consist of coarse and fine aggregates sourced from Ex Watusampu, Ulujadi District, Palu City, and stockpiled in Tinggede Village, Sigi Regency. These aggregates were processed using a stone crusher machine. The mineral filler was obtained from river sand from the Palu River, while additional fillers were sourced from Tonasa brand cement and stone dust, a by-product of the stone crushing process. Materials were collected from various stockpile points and included crushed stone with grain sizes of 3/4", 3/8", and stone dust. These sampling practices were designed to represent the overall population of aggregate materials.

To ensure that the aggregate materials meet the requirements of the Indonesian National Standard (SNI), several tests were performed to assess aggregate quality. The testing procedures followed the standards set by the Ministry of Public Works, Directorate General of Highways (Bina Marga), and included:

✓ Specific gravity and water absorption tests for both coarse and fine aggregates
✓ Sieve analysis for aggregate gradation
✓ Abrasion resistance test (Los Angeles Abrasion Test)

➢ *Determination of Optimum Asphalt Content (OAC):*

In the determination of the Optimum Asphalt Content (OAC), test specimens were prepared at the designated mixing temperature using asphalt modified with LDPE plastic, corresponding to each planned level of conventional asphalt content.

➢ *Testing of Asphalt Concrete + LDPE at Optimum Asphalt Content (OAC):*

In asphalt concrete mixtures, the determination of the composition of coarse aggregates, fine aggregates, and filler materials aims to produce a well-balanced mix that meets specifications and ensures strong interparticle bonding and effective interlocking among the aggregates. Before mixing, the aggregate gradation must be established. The method used for determining the gradation is the sieve analysis method, based on particle size distribution. The proportioning of aggregates is not based on the percentage of each aggregate fraction in the combined gradation but rather determined by the sieve size.

➢ *Testing of Asphalt Concrete + LDPE:*

Mix design plays a critical role in determining the Optimum Asphalt Content (OAC). The materials used in this research were selected to comply with the specifications for Asphalt Concrete Wearing Course (AC-WC). The determination of the mixture composition comprising coarse aggregates, fine aggregates, and filler is aimed at achieving a gradation that meets the required standards, resulting in a surface layer with strong inter-particle bonding and effective

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aggregate interlock. The AC-WC mix design employed in this study follows the Marshall Method**,** which enables the determination of the optimum asphalt content required to produce a well-balanced mixture of asphalt and aggregates in accordance with technical specifications for road pavement.

- *Marshall Characteristics and Volumetric Properties Testing of AC-WC Mixtures:*

The Marshall characteristics are obtained by analyzing data from laboratory experiments, including Stability, Flow, VIM (Void in Mixture), VMA (Void in Mineral Aggregate), VFB (Void Filled with Bitumen), Density, and MQ (Marshall Quotient).

- *SEM (Scanning Electron Microscopy) Testing:*

Scanning Electron Microscopy (SEM) is a type of electron microscope that creates images of a specimen by scanning it with a high-energy electron beam in a raster pattern. The electrons interact with the atoms in the specimen, producing signals that contain information about the specimen's surface topography, composition, and other properties such as electrical conductivity. The types of signals generated by SEM include secondary electrons, backscattered electrons (BSE), characteristic X-rays, and photons each detected by specialized detectors. These signals result from the interaction between the electron beam and atoms near the specimen surface. The most commonly used imaging mode is Secondary Electron Imaging (SEI), which allows SEM to produce extremely high-resolution images of the specimen surface often with detail less than 1 nanometer. Due to the narrow electron beam, SEM images have significant depth of field, providing a pseudo-3D view of the surface structure.

SEM allows for magnification ranging from approximately 10x (comparable to a hand lens) up to over 500,000x, which is about 250 times greater than that of conventional optical microscopes. Backscattered electrons (BSE) are those that are elastically scattered and reflected back from the specimen. BSE imaging is commonly used in SEM analysis alongside characteristic X-ray spectra. Since BSE signal intensity is strongly related to the atomic number (Z) of the elements present, BSE images can provide information about the distribution of different elements in the specimen.

BSE can visualize immuno-gold labels with diameters of 5 or 10 nanometers, which are often difficult or impossible to detect using secondary electron imaging in biological samples. Characteristic X-rays are emitted when the electron beam displaces an inner-shell electron from an atom, causing a higher-energy electron to fill the vacancy and release energy in the form of X-rays. These X-rays are used to identify the elemental composition and quantify the abundance of elements in the specimen.

- *X-Ray Fluorescence (XRF) Testing:*

X-Ray Fluorescence (XRF) testing is an analytical method used to determine the elemental composition of a material. The general stages involved in XRF analysis begin with sample preparation, followed by instrument calibration and parameter setup, such as analysis time and X-ray energy. Once the equipment is properly configured, the sample is irradiated with X-rays. The elements within the sample emit secondary (fluorescent) X-rays in response, which are then detected and measured by the instrument's detector. The resulting data is then analyzed to identify the types and concentrations of elements present in the sample. This analysis is typically performed using specialized software integrated with the XRF device. The output is presented in a report that includes elemental composition, concentrations, and may include graphical or tabular visualizations. For quality assurance, validation of the results is recommended often by comparison with other analytical methods if necessary.

IV. DATA ANALYSIS

Data analysis is conducted on the Marshall parameters of asphalt mixtures, both with and without the addition of LDPE plastic at varying contents (0.25%, 0.50%, 0.75%, and 1.00%). The results of this analysis will be presented in the form of comparative graphs. The SEM and XRF methods are employed to examine the microstructure and chemical composition of the modified asphalt mixture. SEM test results are analyzed by observing surface morphology, the distribution of LDPE within the asphalt matrix, and the presence of cracks or voids between materials. Meanwhile, the XRF test results are used to determine the elements and chemical compounds present in the mixture, and to evaluate how these elements and compounds are affected by the addition of LDPE plastic.

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V. RESULTS AND DISCUSSION

➢ *Aggregate Quality Test Results:*

Table 1 Specific Gravity Test Results of Coarse and Fine Aggregates

No.	Type of Test	Requirement	Result		Unit	Remarks
	Coarse Aggregate Fraction		3/4	3/8		
1	Bulk Specific Gravity	> 2.5	2.79	2.76		
2	Saturated Surface Dry (SSD) Specific Gravity	> 2.5	2.81	2.79	%	Meets Requirement
3	Apparent Specific Gravity	> 2.5	2.86	2.83		
4	Water Absorption	< 3	0.90	0.89		
Fine Aggregate (Stone Dust)						
1	Bulk Specific Gravity	> 2.5	2.68			
2	Saturated Surface Dry (SSD) Specific Gravity	> 2.5	2.75		%	Meets Requirement
3	Apparent Specific Gravity	> 2.5	2.89			
4	Water Absorption	< 3	2.73			

Table 2 Results of the No. 200 Sieve Passing Test

No.	Type of Material	Test Result	Requirement	Descriptiom
Coarse Aggregate				
1.	Fraction 3/4	0,398	<1%	Meets requirement
2.	Fraction 3/8	0,930		
Fine Aggregate				
1.	Stone Ash	9,017	<10%	Meets requirement

Table 3 Abrasion Test Results

No.	Type of Test	Requirement	Result	Unit	Remarks
1.	Abrasion (500 Revolutions)	< 30	16,45	%	Meets Requirement

Based on the results of the specific gravity and absorption tests of coarse and fine aggregates, sieve analysis, and abrasion tests on the aggregate materials, it can be concluded that the aggregates used in this study have met the required standards.

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➤ *Results of Asphalt Quality Testing:*

Table 4 Test Results of 60/70 Penetration Asphalt Characteristics

No.	Type of Test	Test Result	Requirement	Unit	Remarks
1	Penetration (25°C, 5 sec	65	60 – 70	mm	Meets Requirement
2	Softening Point	48	≥ 48	°C	
3	Ductility (25°C, 5 cm/sec)	153,43	≥ 100	cm	
4	Flash Point	325,00	≥ 230	°C	
5	Specific Gravity (25°C)	1,04	≥ 1,0	-	
6	Asphalt Weight Loss (25°C)	0,0014	≤ 0,8	%	
7	Viscosity (135°C)	434,88	≥ 300	cSt	

Table 5 Test Results of 60/70 Penetration Asphalt Characteristics with LDPE Addition

No.	Type of Test	Test Result				Requirement	Unit
		0,25%	0,50%	0,75%	1,00%		
1	Penetration	52,1	40,4	32,5	30,80	-	mm
2	Softening Point	49	51	67	68	-	°C
3	Ductility	152,57	150,67	6,27	5,70	-	cm
4	Flash Point	1,25	1,69	1,75	2,03	-	-
5	Viscosity	2820,85	4173,22	5525,59	6000,67	≥ 300	cSt

Based on the test results of asphalt without and with the addition of LDPE plastic at concentrations of 0.25%, 0.50%, 0.75%, and 1.00%, it was observed that the asphalt becomes increasingly hard and brittle, as indicated by the increase in softening point, specific gravity, and viscosity values. It can therefore be concluded that the addition of LDPE plastic affects both the density and the viscosity of the asphalt.

➤ *Determination of Aggregate Composition in the Mixture:*

The aggregate composition design for the asphalt mixture uses the by portion method, which employs aggregate fractions for the asphalt mixture. The determination of this aggregate composition can be represented in Figure 1, which illustrates the gradation curve used in the Asphalt AC-WC layer mixture, namely a continuous gradation.

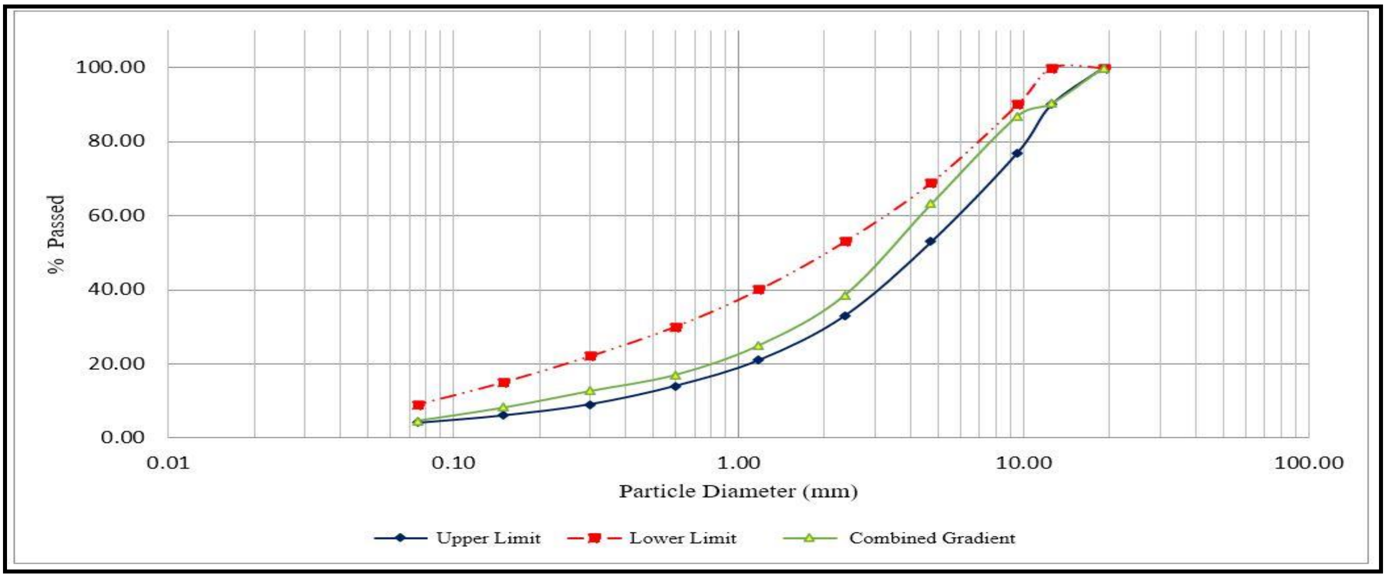

Fig 1 Combined Aggregate Gradation Curve of LASTON AC-WC Mixture

➢ *Marshall Test Results for Determining Optimum Asphalt Content (OAC):*

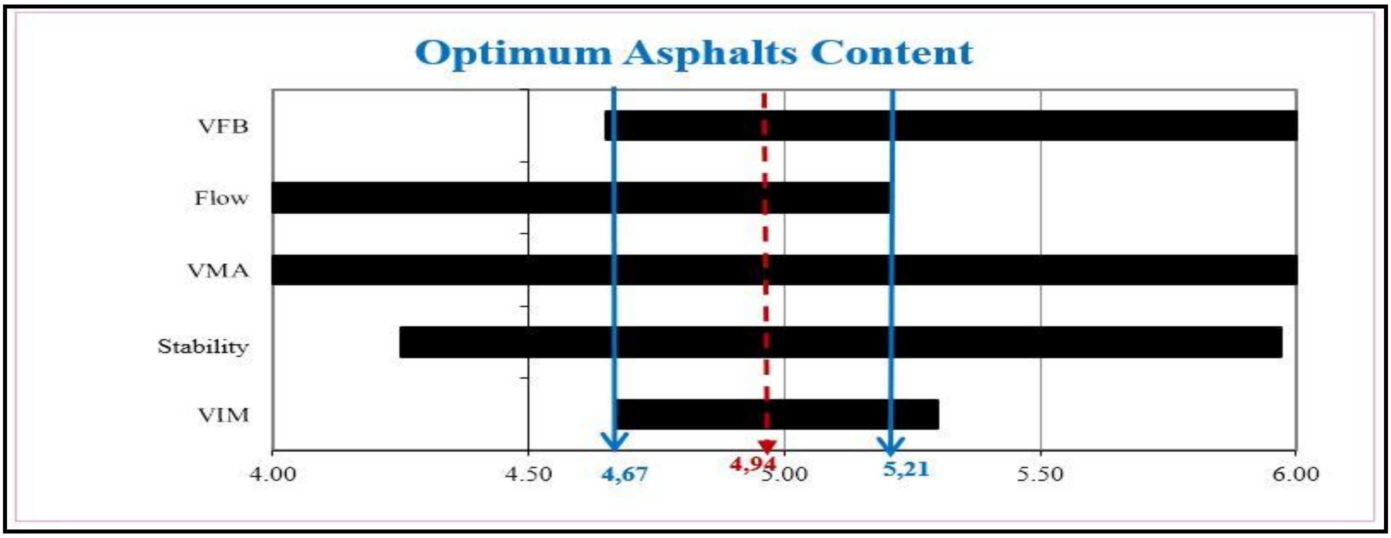

Fig 2 Barchart Determination of KAO

z 2, the range of asphalt content for AC-WC is found to be 4.67% – 5.21%. Therefore, the Optimum Asphalt Content (OAC) is determined as follows.

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

➢ *Marshall Test Results After Determining the Optimum Asphalt Content (OAC):*

Tabel 6 Marshall Test Results for Conventional Asphalt Penetration Grade 60/70

Marshall Parameter	Unit	Test Result	Specification
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/cm^3	2,47	-

Table 7 Marshall Test Results for LDPE-Modified Asphalt

M: ll Parameter	Satuan	Test Result					Specification
		Design 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	711,54	942,21	1017,68	918,30	905,89	>800
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

➢ *Analysis of Marshall Characteristics Data:*

In this study, the test specimens were prepared using variations of LDPE plastic content at 0.00%, 0.25%, 0.50%, 0.75%, and 1.00%. The analysis of the test results for the mixtures is as follows.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul326

- *Effect of Stability on LDPE Content:*

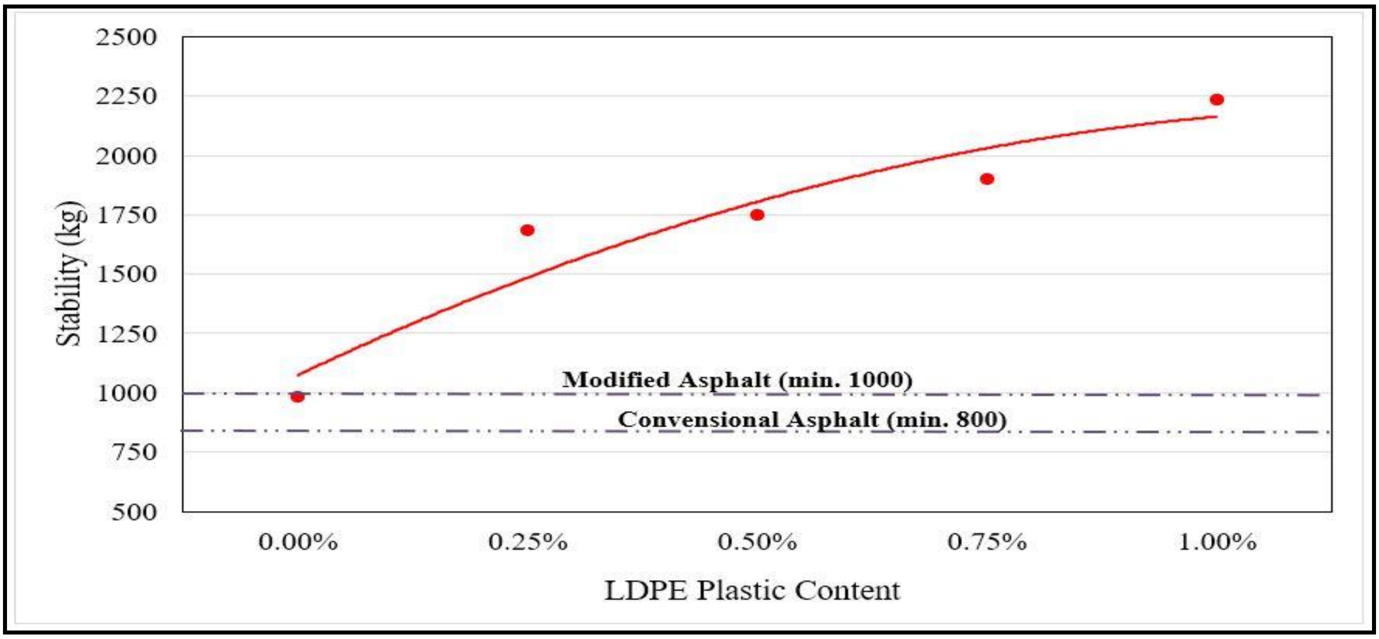

Fig 3 Relationship Between Stability Value and LDPE Plastic Content

Based on Figure 3, it can be observed that the stability value increases proportionally with the increase in LDPE plastic content. This indicates that higher plastic content enhances the pavement's ability to withstand loads until deformation occurs, thereby potentially reducing road damage.

- *Effect of Flow on LDPE Content:*

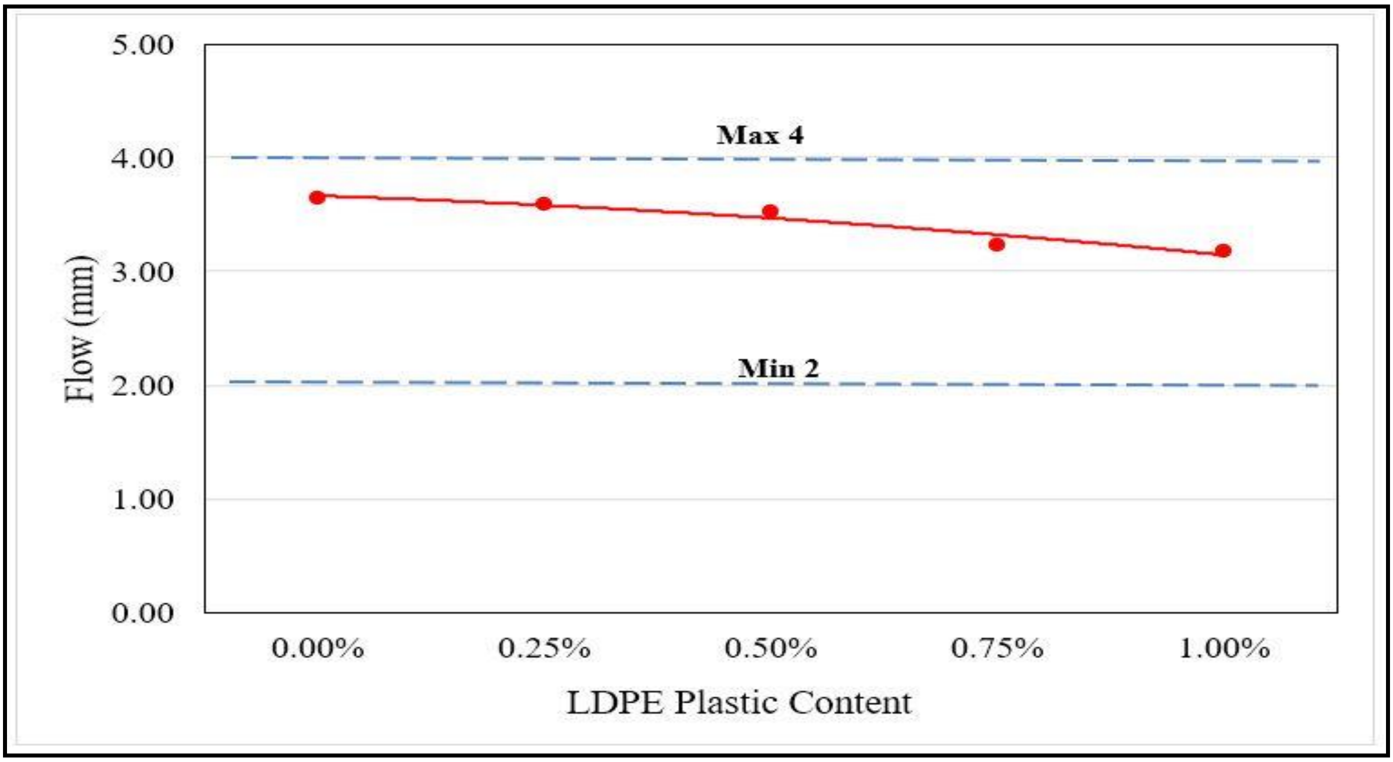

Fig 4 Relationship Between Flow Value and LDPE Plastic Content

Based on Figure 4, the flow values for both conventional asphalt and asphalt with the addition of LDPE plastic fall within the specification range of 2-4 mm. Unlike the stability values, where higher plastic content leads to increased stiffness and brittleness of the asphalt mixture, it is observed that increasing the LDPE content results in lower flow values as recorded by the Marshall apparatus. This suggests that the mixture becomes less deformable under load as more plastic is added.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul326

- *Effect of VIM on LDPE Content:*

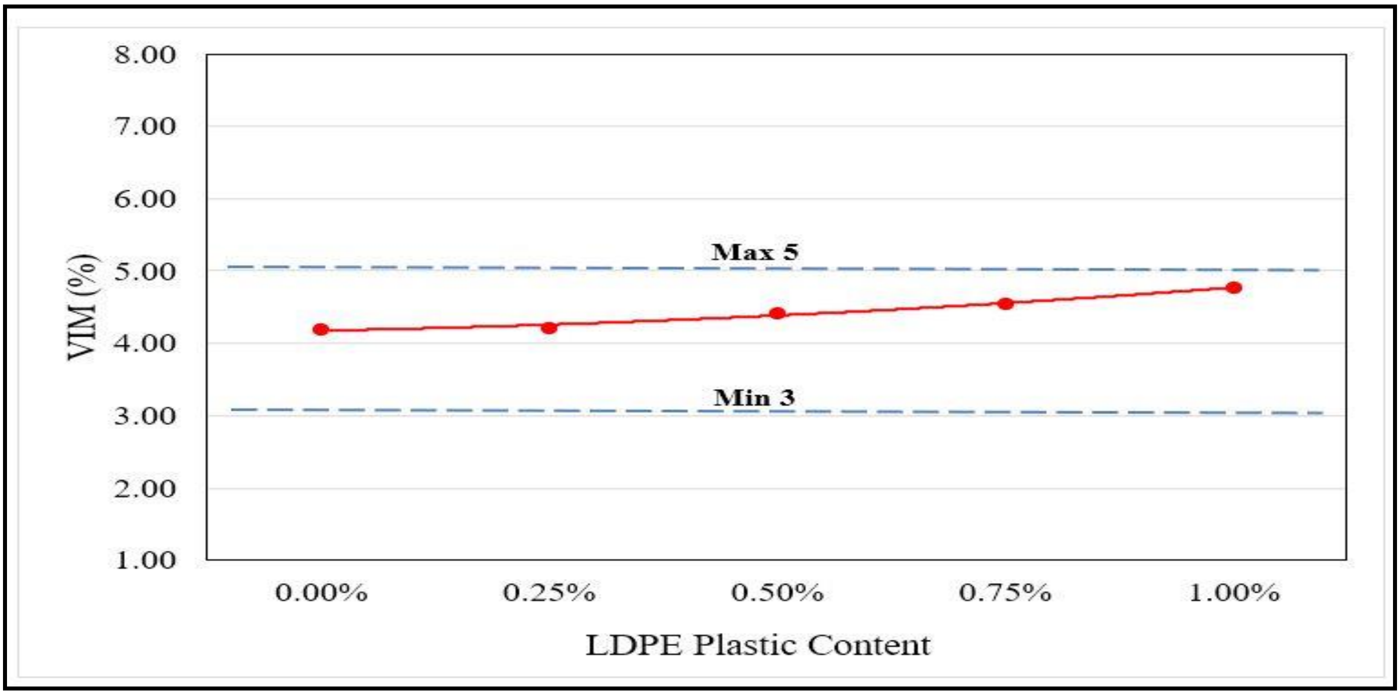

Figure 5. Relationship Between VIM Value and LDPE Plastic Content

Based on Figure 5, the VIM values of asphalt mixtures with and without LDPE addition fall within the specification range of 3–5%. The LDPE plastic content in the mixture influences the VIM value, as higher LDPE content tends to make the modified asphalt stiffer and more brittle. This results in an increase in VIM values because the air voids in the mixture become more difficult to fill, leading to a less compact structure.

- *Effect of VIM on LDPE Content:*

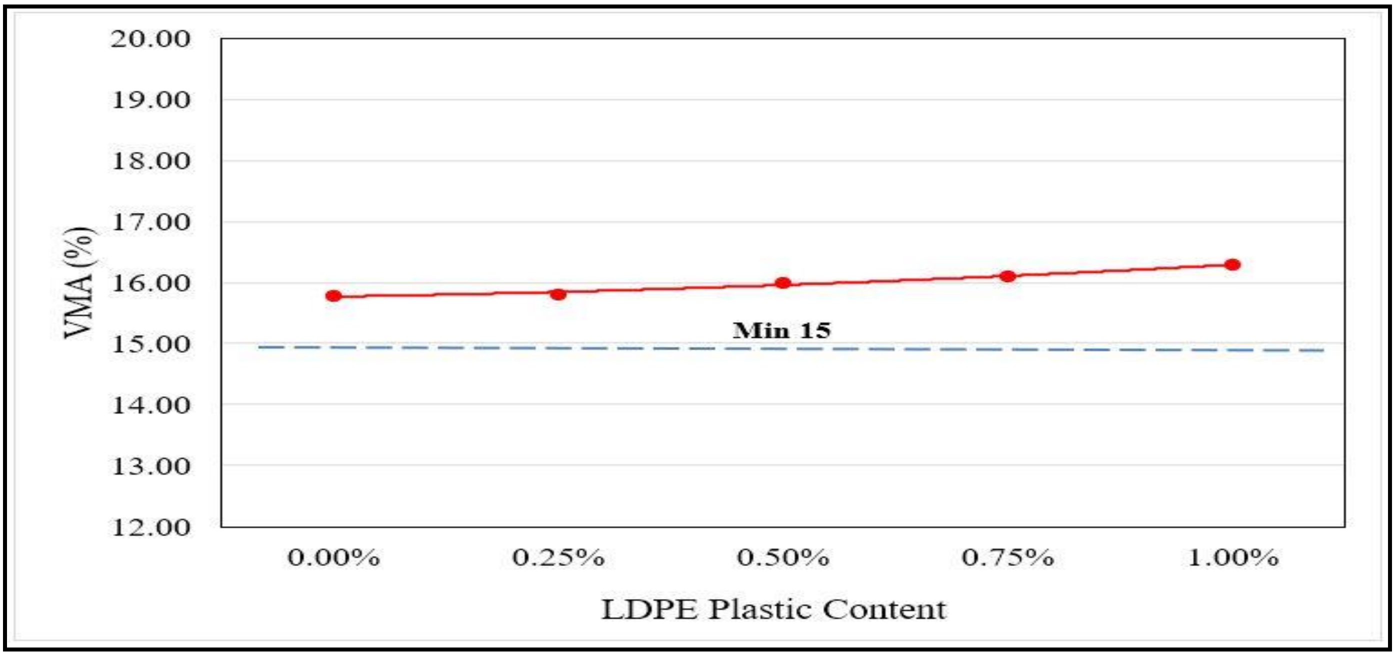

Fig 6 Relationship Between VMA Values and LDPE Plastic Content

The VMA values of asphalt mixtures, both without and with the addition of LDPE plastic, as shown in Figure 6, all meet the specification requirement of being greater than 15%. The VMA value shows a direct relationship with the VIM value. The addition of LDPE plastic content also influences the VMA values—where the higher the LDPE content used in the mixture, the higher the resulting VMA value. This occurs because the asphalt modified with LDPE becomes stiffer and more brittle than conventional asphalt, making it more difficult to fill the voids within the mixture.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul326

- *Effect of VFB on LDPE Content:*

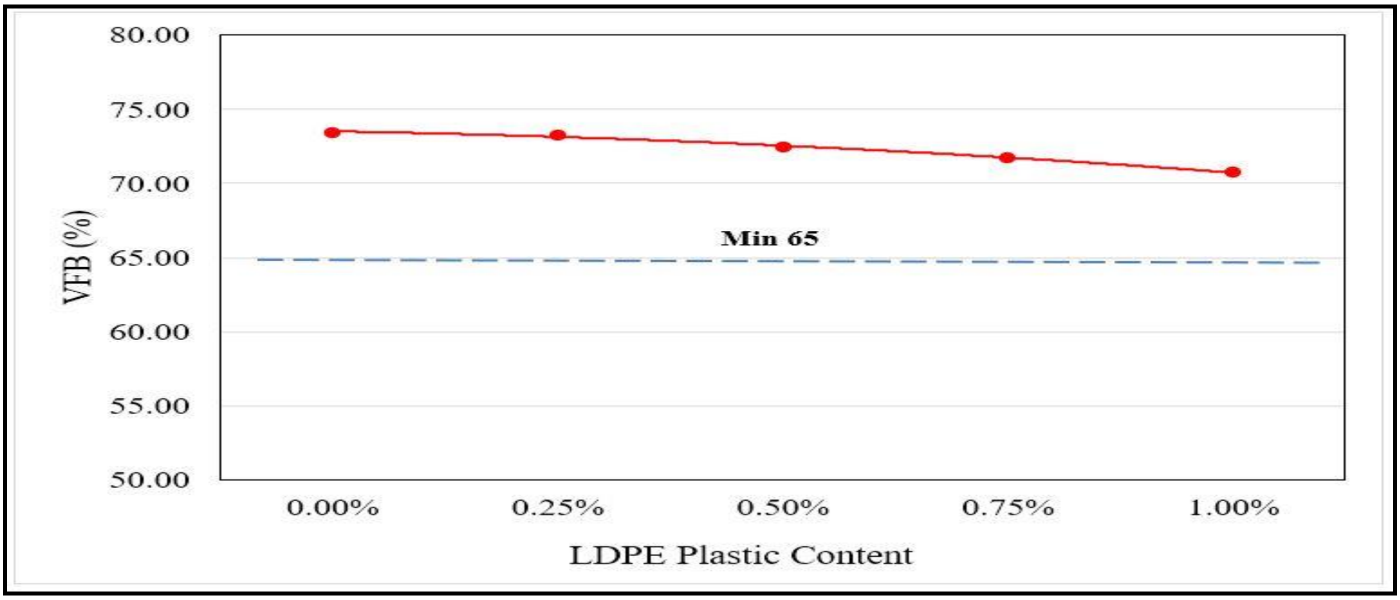

Fig 7 Relationship Between VFB Value and LDPE Content

From Figure 7, it is observed that the VFB values, both with and without the addition of LDPE plastic, meet the specification requirement of being greater than 65%. As the LDPE content increases, the resulting VFB values decrease, which is inversely proportional to the VIM and VMA values. A higher VFB value indicates that a greater proportion of voids have been filled with asphalt. At 0.00% LDPE content, the VFB value is higher compared to LDPE contents of 0.25%, 0.50%, 0.75%, and 1.00%, due to the use of conventional asphalt that is more fluid than modified asphalt. As the LDPE content increases in the modified asphalt mixture, the asphalt becomes more viscous and brittle, making it more difficult for the binder to fill the voids within the mixture due to its stiffer and more rigid characteristics.

- *Effect of Density on LDPE Content:*

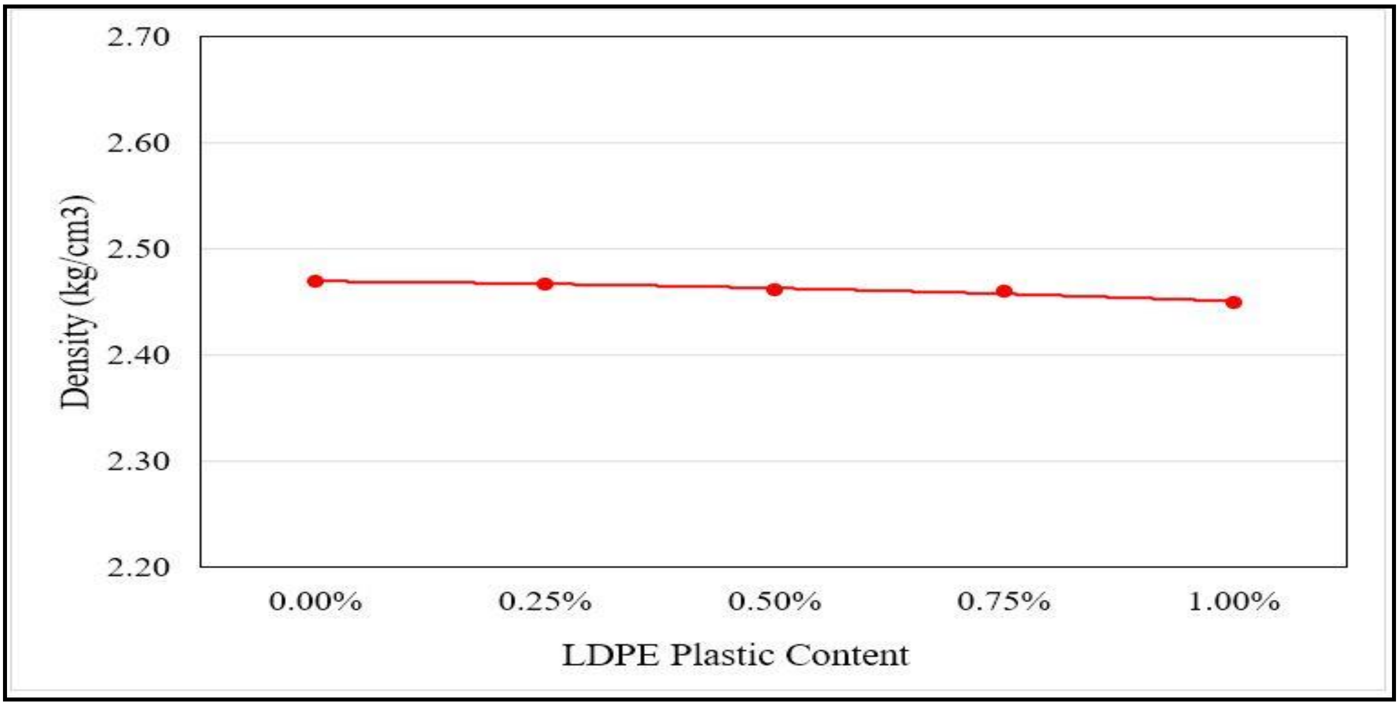

Fig 8 Relationship Between Density Value and LDPE Content

Based on Figure 8, it can be seen that the density values obtained with respect to the content of LDPE plastic are not much different, where the higher the amount of LDPE plastic added, the lower the density values obtained.

- *Effect of Marshall Quotient (MQ) on LDPE Content:*

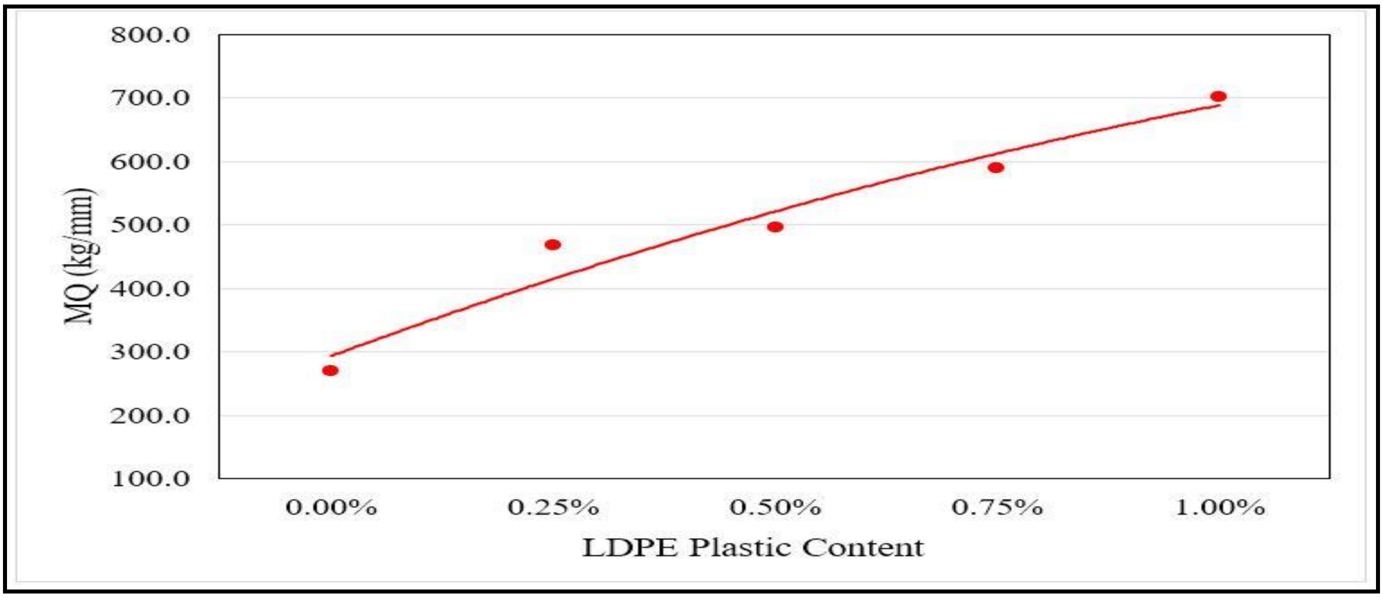

Fig 8 Relationship Between Marshall Quotient (MQ) Value and LDPE Plastic Content

In Figure 8, it can be observed that the Marshall Quotient (MQ) values increase with the addition of LDPE plastic at percentages of 0%, 0.25%, 0.5%, 0.75%, and 1%. The test results indicate that as the LDPE content increases, the stiffness of the asphalt mixture also increases, resulting in a more brittle mixture. All obtained MQ values meet the 2018 General Specifications, which require a minimum MQ value of 250 kg/mm.

- *Results of Scanning Electron Microscopy (SEM) Testing on AC-WC Mixture:*

In the SEM testing, the sample used was taken from the asphalt mixture with an optimum asphalt content (OAC) of 5.00% and had undergone Marshall testing with a soaking time of 30 minutes. The SEM analysis results are presented to identify the surface morphology of the AC-WC mixture with the addition of LDPE at levels of 0.00%, 0.25%, 0.50%, 0.75%, and 1.00%. The results of the SEM testing are displayed in the form of scanned images to facilitate the analysis, as follows.

- *AC-WC Asphalt Without LDPE Additive:*

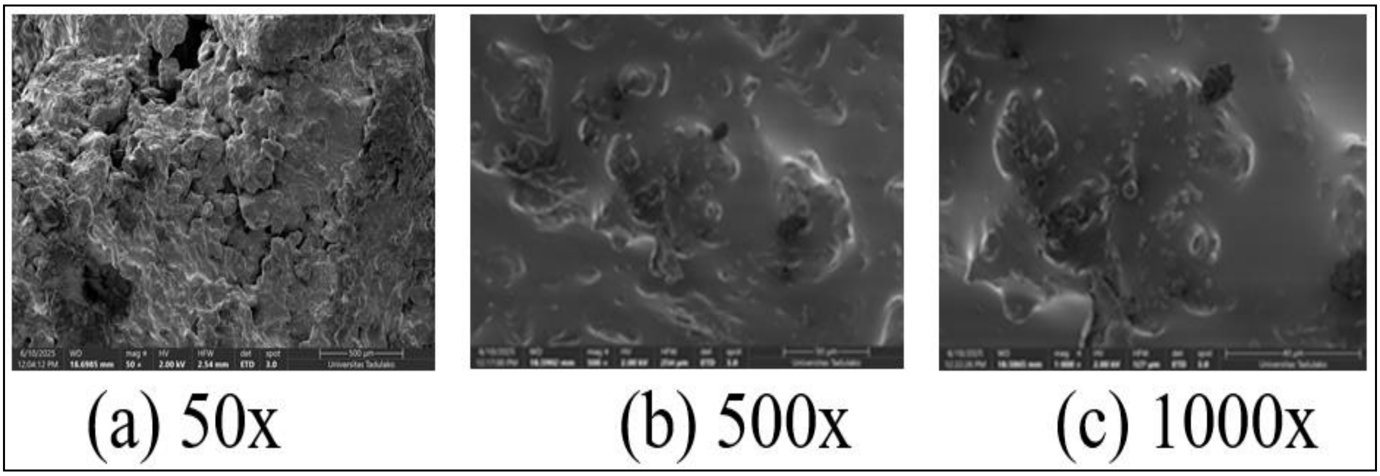

Fig 9 SEM Test Results Without LDPE Additive

Fig 9 shows the BSE-SEM images of the AC-WC asphalt sample without LDPE addition (0%) at different magnifications: 50x, 500x, and 1000x. The BSE-SEM image at 50x magnification reveals a rough surface morphology, uneven aggregate distribution, and the presence of air voids within the asphalt–aggregate matrix, indicating weak adhesion.

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- *AC-WC Asphalt with 0.25% LDPE Additive:*

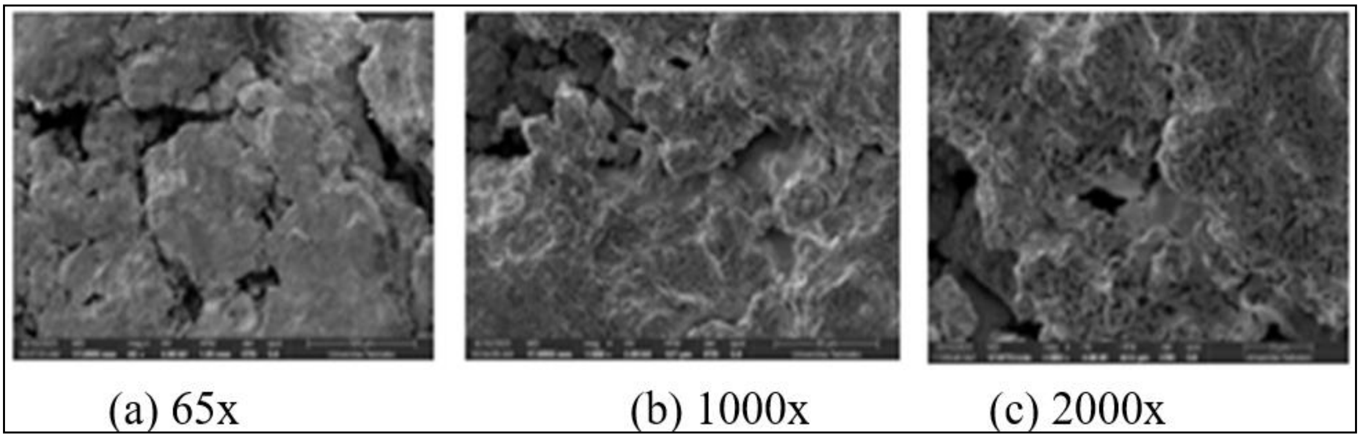

Fig 10 SEM Test Results for 0.25% LDPE Content

Based on Figure 10, the BSE SEM image of the asphalt sample with 0.25% LDPE content at different magnifications shows that the asphalt begins to exhibit increased homogeneity. Furthermore, the surface appears denser, and the bonding between particles is tighter.

- *AC-WC Asphalt with 0.50% LDPE Additive:*

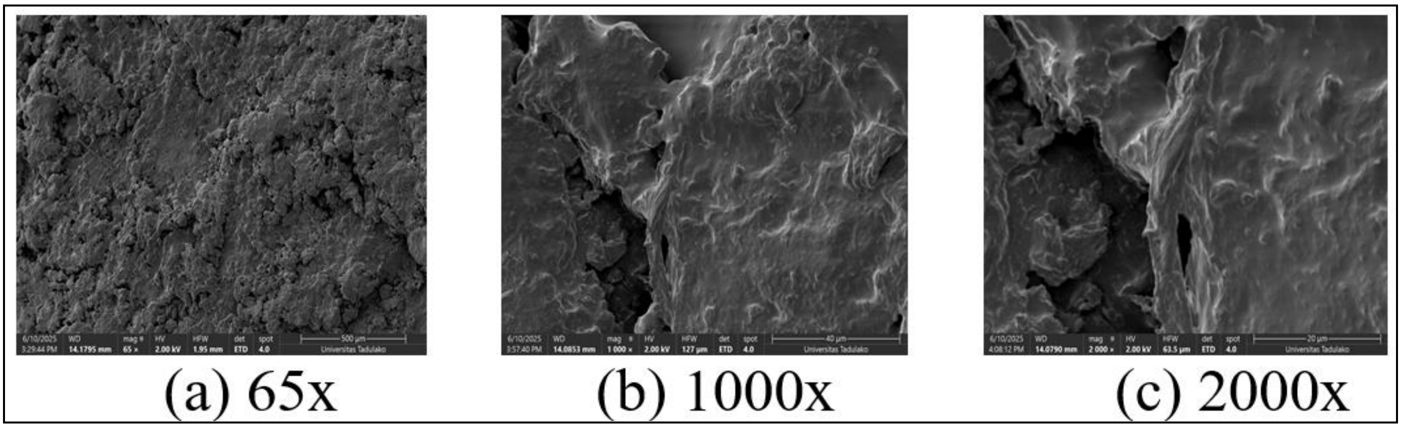

Fig 11 SEM Test Results for 0.50% LDPE Content

Figure 11 shows the BSE SEM image of the asphalt sample with 0.50% LDPE addition at various magnifications up to 2000×. Categories (a)-(c) illustrate a more compact and homogeneous morphology. The aggregates are more evenly distributed within the asphalt matrix. The asphalt mixture with 0.50% LDPE appears to coat the aggregates uniformly, resulting in a more stable and solid microstructure.

- *AC-WC Asphalt with 0.75% LDPE Additive*

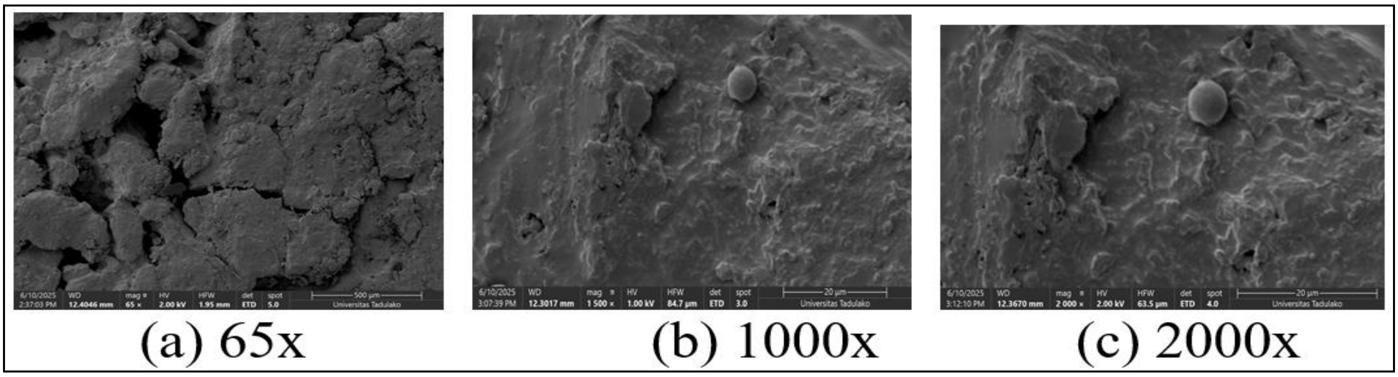

Fig 12 SEM Test Results for 0.75% LDPE

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Based on Figure 13, the BSE SEM image of the asphalt sample with 0.75% LDPE content at various magnifications shows a denser asphalt surface. At 65× magnification, the surface appears increasingly compact, and cracks are barely visible. This indicates improved cohesion and uniformity in the mixture, suggesting that the addition of 0.75% LDPE enhances the structural integrity and compactness of the asphalt matrix.

- *AC-WC Asphalt with 1.00% LDPE Additive:*

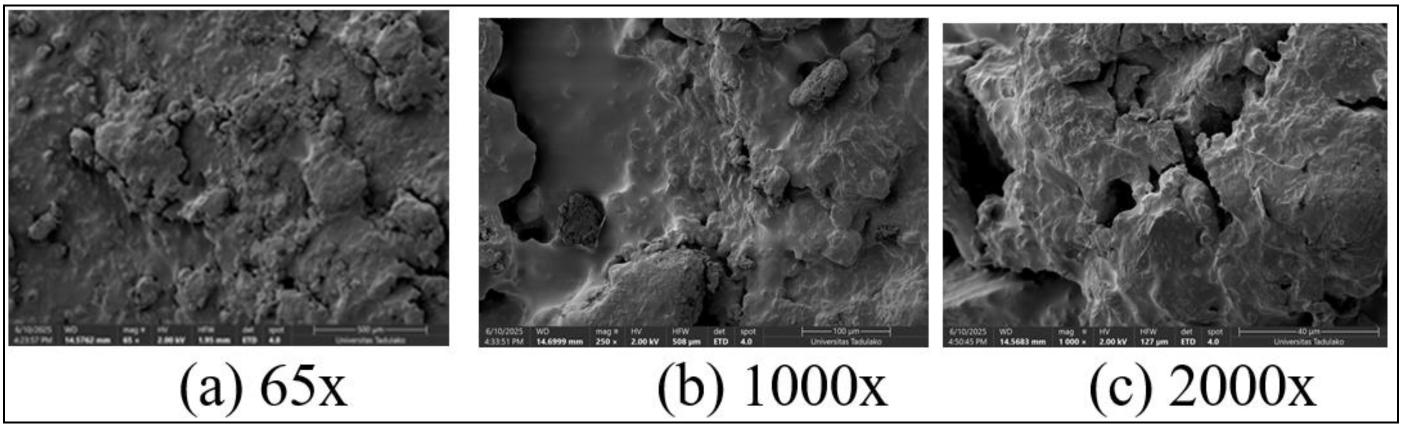

Fig 13 SEM Test Results for 1.00% LDPE

In Figure 13, the BSE SEM images of the asphalt sample with 1.00% LDPE addition at various magnifications up to 2000× show a highly dense and homogeneous structure. Criteria (a)–(c) reveal a surface that appears thoroughly coated by the thermoplastic matrix, exhibiting very strong microstructural bonding. This indicates that the incorporation of 1.00% LDPE significantly enhances the compactness and cohesion of the asphalt mixture at the microscopic level.

➢ *Correlation Between Stability Values and SEM Test Results at Various LDPE Content Levels:*

In general, SEM imagery of samples without LDPE addition shows that the mixture appears not fully homogeneous, indicating the presence of voids and weak interparticle bonding. This results in suboptimal cohesion, which negatively affects the sample's stability value. The incorporation of LDPE plastic, which integrates and bonds effectively within the asphalt matrix, increases stiffness and resistance, thereby contributing to the improvement of Marshall stability. A significant increase in stability values is observed with each increment of LDPE content, namely 1683.26 kg, 1752.88 kg, 1903.67 kg, and 2236.09 kg, indicating that the resulting microstructure strongly supports the mechanical performance of the AC-WC mixture. As shown by the SEM results, the higher the LDPE content, the denser and more homogeneous the structure becomes, with surface cracks becoming nearly invisible.

- *X-Ray Fluorescence (XRF) Test Results of AC-WC Mixture:*

The XRF test was conducted on test specimens with an Optimum Asphalt Content (OAC) of 5.00% that had previously undergone Marshall testing. The number of samples used in this test consisted of five specimens, each containing different LDPE plastic content, namely: 0.00%, 0.25%, 0.50%, 0.75%, and 1.00%.

- *AC-WC Asphalt Without LDPE Plastic Additive:*

The chemical element characteristics obtained from the XRF test on the AC-WC test sample without the addition of LDPE plastic consist of several elements, with the dominant elements and compounds being: Silicon Dioxide or Silica (SiO_2) at 35.482%, Alumina (Al_2O_3) at 15.495%, Magnesium Oxide (MgO) at 15.335%, Calcium Oxide (CaO) at 9.817%, and Ferric Oxide (Fe_2O_3) at 8.378%. The element with the highest percentage is Silicon Dioxide or Silica (SiO_2), which is commonly found in nature as sand or quartz, and in the cell walls of diatoms.

- *AC-WC Asphalt with 0,25% LDPE Plastic Additive:*

XRF testing to determine the characteristics of chemical elements in the AC-WC test sample with an LDPE plastic additive of 0.25% consists of several elements, with the dominating elements being: Silicon Dioxide or Silica (SiO_2) at 29.417%, Alumina (Al_2O_3) at 12.872%, Calcium Oxide (CaO) at 9.945%, Iron III Oxide (Fe_2O_3) at 8.394%, and Magnesium Oxide (MgO) at 7.786%. The element with the largest percentage is Silicon Dioxide or Silica (SiO_2). Silica is most commonly found in nature as sand or quartz, and in cell walls at the atomic level.

- *AC-WC Asphalt with 0.50% LDPE Plastic Additive:*

The chemical element characteristics were identified through XRF testing of the AC-WC test sample with 0.50% LDPE plastic additive. Several elements were detected, with the dominant elements being: Silicon Dioxide or Silica (SiO_2) at 30.296%, Magnesium Oxide (MgO) at 14.380%, Alumina (Al_2O_3) at 13.110%, Calcium Oxide (CaO) at 9.619%, and Ferric Oxide (Fe_2O_3) at 7.816%. The element with the highest percentage is Silicon Dioxide or Silica (SiO_2), which is most commonly found in nature as sand or quartz, and in the cell walls of diatoms.

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- *AC-WC Asphalt with 0.75% LDPE Plastic Additive:*

XRF testing was conducted to determine the chemical element characteristics in the AC-WC test sample with 0.75% LDPE plastic additive. The test revealed several elements present in the mixture, with the dominant ones being: Silicon Dioxide or Silica (SiO_2) at 32.293%, Magnesium Oxide (MgO) at 15.035%, Alumina (Al_2O_3) at 13.813%, Calcium Oxide (CaO) at 9.759%, and Ferric Oxide (Fe_2O_3) at 7.746%. The element with the highest percentage is Silicon Dioxide or Silica (SiO_2), which is commonly found in nature as sand or quartz, and in the cell walls of diatoms.

- *AC-WC Asphalt with 1.00% LDPE Plastic Additive:*

The chemical element characteristics obtained through XRF testing on the AC-WC test sample with 1.00% LDPE plastic additive revealed various elements present in the mixture. The dominant elements were: Silicon Dioxide or Silica (SiO_2) at 33.773%, Magnesium Oxide (MgO) at 15.309%, Alumina (Al_2O_3) at 14.465%, Calcium Oxide (CaO) at 9.978%, and Ferric Oxide (Fe_2O_3) at 7.754%. The element with the highest percentage is Silicon Dioxide or Silica (SiO_2), which is most commonly found in nature as sand or quartz, and in the cell walls of diatoms.

- *The Relationship Between Stability Values and XRF Test Results at Each LDPE Plastic Content:*

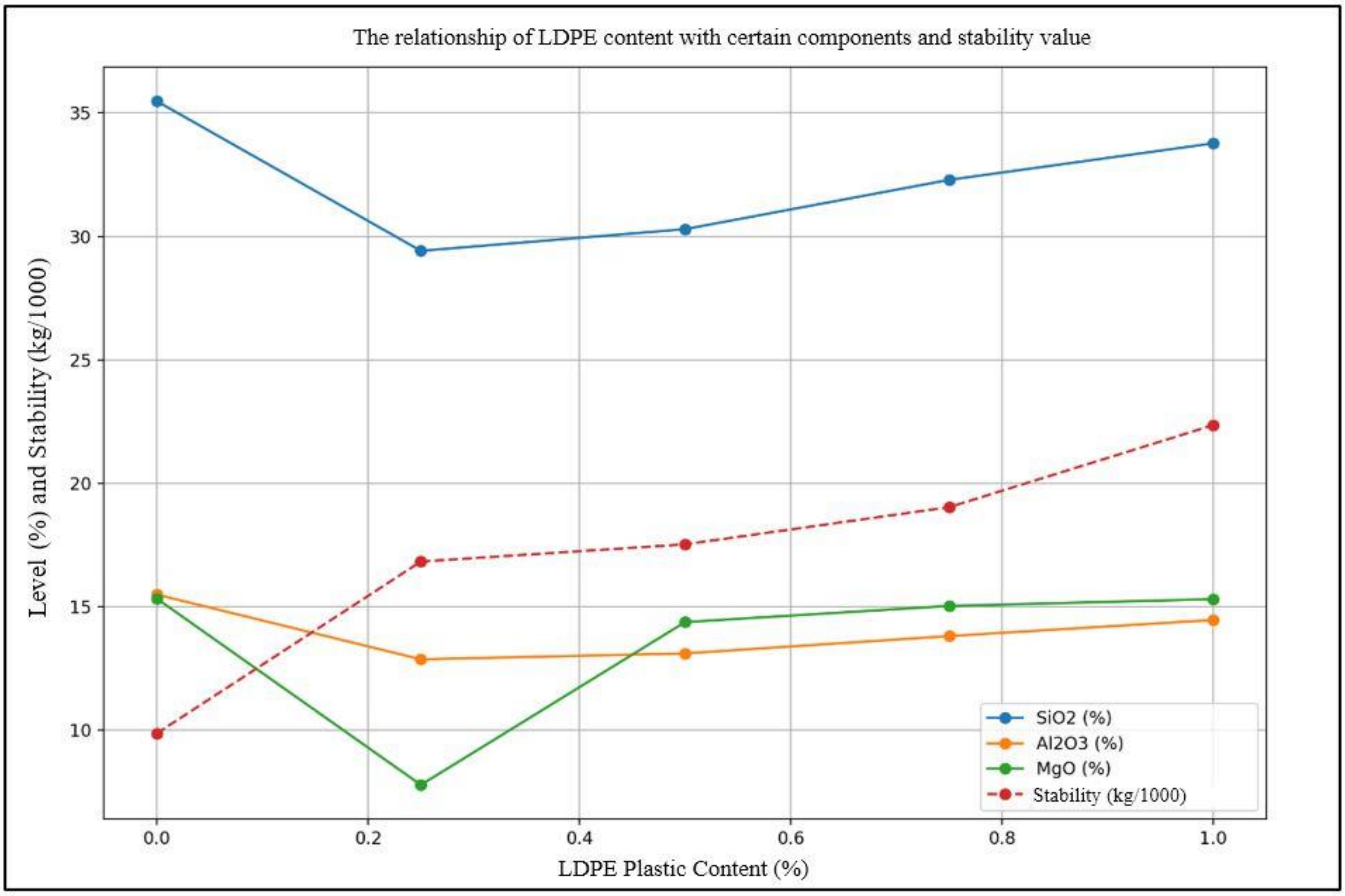

Fig 14 Relationship Between Stability Values and XRF Test Results at Each LDPE Plastic Content

In the graph above, it can be seen that the relationship between LDPE content consists of three main components from the XRF test results SiO_2, Al_2O_3, and MgO as well as the stability value (scaled down by 1/1000).

VI. CONCLUSION

Based on the test results and analysis conducted in this study, it can be concluded that the Marshall test results indicate all stability values meet the minimum specified requirements. The stability value increases proportionally with the increase in the plastic content used, indicating that a higher plastic content enhances the pavement's ability to withstand loads until deformation occurs, thereby reducing road damage. The addition of LDPE plastic, which is well-integrated and bonded within the asphalt matrix, increases stiffness and durability, contributing to the improvement of Marshall stability. The XRF test results for each sample with different LDPE plastic contents revealed three dominant chemical components: SiO_2, Al_2O_3, and MgO. These three components are constituents of aggregate materials that significantly influence strength, elasticity, and adhesion properties. Their presence contributes to an increase in Marshall stability, resulting in an asphalt mixture with improved resistance to traffic loads and weather conditions, as well as a longer service life.

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