



Permanent Deformation Analysis of Modified Asphalt Concrete Wearing Course Mixtures Using Wheel Tracking Machine

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Abstract

The issue of permanent deformation (rutting) on pavement layers, particularly in high-traffic load areas such as toll gates, is one of the main causes of premature damage to road infrastructure in Indonesia. This study aims to evaluate the performance of Asphalt Concrete Wearing Course (AC-WC) mixtures modified by the addition of Ethylene Vinyl Acetate (EVA) polymer, along with industrial waste materials such as fly ash as filler and bottom ash as fine aggregate. The method used is an experimental laboratory approach involving a series of tests, including material characterization, the Marshall Test to determine the Optimum Asphalt Content (OAC), and further testing using the Wheel Tracking Machine (WTM) to assess the asphalt mixture's resistance to repeated loading-induced deformation. The results show that the addition of EVA and FABA (fly ash and bottom ash) improves Marshall stability and reduces permanent deformation compared to conventional mixtures. The modified mixture demonstrates higher dynamic stability, indicating better rutting resistance at elevated temperatures. In addition to enhancing technical performance, the use of fly ash and bottom ash contributes to waste reduction and supports the application of sustainable development principles in civil engineering. Therefore, this combination of modified materials holds great potential as an alternative for stronger, more durable, and environmentally friendly pavement materials.

Introduction

In Indonesia, road construction generally uses hot mix asphalt-based pavement. This mixture is obtained from combining aggregate and asphalt, where asphalt serves as the main adhesive in the pavement structure (Sukarman, 2003). The heating process of this mixture is carried out at high temperatures, which has the potential to increase greenhouse gas emissions and accelerate global warming (Susanta & Sutjahjo, 2007). Therefore, innovations are needed in the formulation of asphalt mixtures that are environmentally friendly and able to utilize natural resources in a sustainable manner. In the pavement structure system, one of the layers that plays an important role is the Asphalt Concrete-Wearing Course (AC-WC). The AC-WC layer is responsible for withstanding the maximum load generated by vehicle traffic. In general, the constituent materials of AC-WC mixture include coarse aggregate, fine aggregate, filler, and asphalt as a binder (Wibowo et al., 2020; Salsabilla, 2024; Kantala et al., 2025).

In road construction, especially in the toll gate area, which is the point with the highest vehicle load, pavement materials that can withstand the load optimally are required. One potential solution is the use of a modified laston mixture with the addition of EVA+FABA, because this mixture is proven to have good performance against high temperatures and is able to

increase the durability of the pavement against heavy traffic loads. Structural improvements to road pavements are necessary because it is common to find pavement layers damaged by heavy-duty vehicles (Saliko & Erlingsson, 2021; Zhou et al., 2024). Asphalt pavement is often deformed so that there are vehicle wheel grooves in the asphalt pavement when Over Dimension Over Load (ODOL) vehicles pass and also when four-wheeled vehicles maneuver over the AC-WC layer (Mubarak, 2016). Many cases of permanent deformation occur on national roads and toll roads in Indonesia. Permanent deformation is a condition in which the pavement structure layer experiences a permanent decline and cannot return to its original form due to loads that are applied repeatedly (Prastyanto, 2018; Yang et al., 2025; Liu et al., 2023). One solution to overcome road damage due to high traffic volumes and excessive loads is to modify the asphalt, namely through the addition of polymeric materials and changes in the aggregate. One type of plastomer polymer that has been proven to improve asphalt performance is Ethylene Vinyl Acetate (EVA) (Suherman, 2013). and Fly ash Bottom ash has a tight gradation value so that it makes fewer air pores in the asphalt (Umboh et al., 2014). Permanent deformation can be overcome by modifying the asphalt mixture using EVA polymer additives to the asphalt and modifying the aggregate using FABA.

Fly ash and Bottom ash are solid residues from coal combustion that are formed due to thermal processes in the combustion chamber of a steam power plant (PLTU) (Rini et al., 2020; Wibowo et al., 2018; Pataras et al., 2023). Fly ash is carried out through the flue gas stream in the form of fine particles, while Bottom ash is left at the bottom of the combustion boiler. Both are classified as inorganic waste derived from mineral transformation due to high temperatures during the combustion process (Umboh et al., 2014). On the other hand, Ethylene Vinyl Acetate (EVA) plastomer polymers have characteristics that favor their use in asphalt modification, such as ease of mixing, stability at standard mixing temperatures, and the ability to interact effectively with bitumen (Suherman, 2013; Nizamuddin et al., 2021; Diab et al., 2022).

Some previous studies that were used as references in this study both related to the test objects used and the use of further testing equipment, one of which was in Suherman's research (2013) stated in his research that the mixture using EVA polymer modified asphalt showed a higher Marshall stability value, which was 1,634.57 kg, compared to 1,361.95 kg in the mixture without EVA modification. In addition, the mix with EVA polymer bitumen also produced a greater resilient modulus value. The smallest total deformation, 0.75 mm at 45°C, was also recorded in the mix modified with EVA polymer. Therefore, overall, it can be concluded that the use of EVA polymer modified bitumen is able to improve the performance of the mix, especially in reducing deformation.

In a study conducted by Suparma & Laos (2015) entitled "The Effect of Using EVA Modified Asphalt (EVA-MA) on the Design of Asphalt Concrete Mixtures", the main objective was to examine the characteristics of asphalt modified with Ethylene Vinyl Acetate (EVA-MA) and its impact on AC-WC and AC-BC mixtures, with variations in the use of EVA of 0%, 1%, 2%, 3%, and 4%. The results showed that the greater the EVA content in the asphalt will reduce the penetration value and increase the softening point, thus reducing the sensitivity to temperature changes. The effect of using EVA-MA on asphalt concrete mixtures shows that the higher the EVA content added, the optimum asphalt content in the mixture also increases (Yao et al., 2018; Siregar et al., 2023).

Previous research conducted by Faras et al. (2020) discussed the utilization of different sources of Fly ash and Bottom ash as fillers in flexible pavement mixtures. The results showed that the characteristics of the base material used met the requirements of the Indonesian National Standard (SNI). The addition of fillers from Fly ash and Bottom ash is generally able to increase the stability of the specimens, with an average increase in stability of 25% compared to specimens using fillers from stone ash.

Meanwhile, research conducted by Syarkawi et al. (2019) shows that marble waste used as filler is able to increase the deformation resistance of asphalt mixtures, as evidenced by testing using a Wheel Tracking Machine tool. With the addition of marble waste, the asphalt mixture becomes stronger in resisting traffic loads. To determine the level of deformation in the field, testing is carried out using the Wheel Tracking Test method, or often called the Dynamic Stability Test (Phan et al., 2022; Pan et al., 2023; Roy-Chowdhury et al., 2022). This method aims to measure how much deformation occurs in asphalt concrete samples by repeatedly passing certain loaded iron wheels over the sample surface. The results of this test are expressed in the number of passes required to produce a one-millimeter-deep groove.

Although various previous studies have shown that the addition of modified materials such as ethylene vinyl acetate (EVA), fly ash, and bottom ash can improve the quality of asphalt mixtures in terms of stability and resistance to deformation, the approaches taken are mostly partial and focused on one or two modified materials separately. There have not been many studies that comprehensively integrate the three materials in one Asphalt Concrete Wearing Course (AC-WC) mix formulation (Salsabilla, 2024; Arifin et al., 2024; Ramadhani et al., 2025). In addition, most studies still use conventional testing methods such as Marshall, while advanced testing with Wheel Tracking Machine (WTM) equipment that is more representative of heavy traffic and high temperature conditions in the field is still rarely applied, especially in the combination of EVA and fly ash-bottom ash (FABA) modified materials.

It is important to address this research gap given the high rate of premature deterioration of pavement layers in Indonesia, especially those caused by overloading from Over Dimension Over Load (ODOL) vehicles and extreme ambient temperatures (Hasrul et al., 2025; Miftahulkhair et al., 2024). The use of conventional AC-WC is increasingly inadequate in the face of complex and intensive traffic conditions such as at toll gates (Rahat, 2022). On the other hand, the increasing production of industrial waste, especially fly ash and bottom ash from steam power plants, demands sustainable and high-value utilization solutions. Therefore, this research becomes a relevant urgency to support the development of a more robust and environmentally friendly road infrastructure.

Based on this background, this research aims to evaluate the effect of EVA polymer addition as well as the utilization of fly ash as filler and bottom ash as fine aggregate substitution on the optimum asphalt content (KAO) and dynamic stability values of AC-WC mixtures. Tests were conducted through the Marshall method and continued with deformation tests using a Wheel Tracking Machine (WTM). Thus, this research not only contributes to improving the performance of asphalt mixtures against permanent deformation, but also provides alternative solutions in industrial waste management that are applicable in the field of road construction.

Methods

This research is an experimental study conducted in the laboratory with the aim of evaluating the effect of adding modified materials in the form of Ethylene Vinyl Acetate (EVA), fly ash, and bottom ash on the performance of Asphalt Concrete Wearing Course (AC-WC) mixtures, especially in terms of stability and permanent deformation (Yosevina, 2022). The research methodology is divided into several main stages that are structured and systematic to ensure the accuracy and reliability of the results obtained. (Adil et al., 2023)

The initial stage of the research began with a literature study, which aimed to review relevant theories, technical standards, and previous research results, both national and international, including the use of the PRISMA method in literature selection. This information became the basis for developing the mix design plan and determining the test parameters to be carried out.

Next came the preparation of materials and tools, which included: 1) Main equipment: Marshall test equipment, Wheel Tracking Machine (WTM), oven, digital scales, Marshall molds, and other laboratory equipment; 2) Materials: a) Asphalt 60/70 penetration as binder; b) Coarse and fine aggregates according to AC-WC gradation; c) Fly ash as filler; d) Bottom ash as fine aggregate substitution; e) EVA polymer as modification material.

At the mix design stage, Design Mix Formula (DMF) and Job Mix Formula (JMF) were used to determine the appropriate aggregate composition and asphalt content. The mixture was then made with variations in asphalt content and modification materials to obtain the Optimum Asphalt Content (KAO) through the Marshall Test method. This Marshall test aims to measure important parameters such as stability, flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Marshall Quotient.

After the optimum levels were determined, test specimens were made of modified mixtures with the addition of EVA, fly ash, and bottom ash at certain levels. These mixtures were then further tested using a Wheel Tracking Machine (WTM), which simulates repeated vehicle wheel loads on the road surface to evaluate the mixtures' resistance to permanent deformation (rutting). The test results are expressed in terms of rut depth and dynamic stability values (passes/mm).

The whole series of tests refers to the technical specifications set by the General Specifications of Bina Marga 2018 Revision 2, especially in section 6.3, as well as relevant laboratory testing standards such as SNI and ASTM. The final results of this study were analyzed quantitatively to compare the performance of standard and modified mixes in withstanding heavy traffic loads, with the aim of providing recommendations for optimal formulations in road pavements.

Results and Discussion

Marshall Test Results

The planning of asphalt mixtures is based on the gradation of aggregates that have been selected in accordance with technical specifications. Each type of mixture was tested using the Marshall method with variations in asphalt content determined based on the results of the estimated optimum asphalt content (Pb). In the process of determining the KAO, the optimum levels for mixtures with tight and open gradations were also calculated. The determination of KAO is done by making asphalt mixture samples with varying asphalt content, based on certain formula calculations. The asphalt content variations used in the Marshall test included 4%, 4.5%, 5%, 5.5%, 6%, 6.5%, and 7%, while for the absolute density test 5%, 5.5%, and 6% were used. The Optimum Asphalt Content (KAO) value is obtained by calculating the average of the minimum and maximum asphalt content that meets all criteria in the 2018 Bina Marga General Specifications, with a result of 5.65%. Full details of the test results using the Marshall method and KAO calculations can be seen in Table 1.

Table 1. Marshall Test Results

No.	Characteristics	Terms	Asphalt Content				
			4.5%	5%	5.5%	6%	6.5%
1	VMA	Min. 15	15,75	15,76	15,90	16,19	16,62
2			15,70	15,72	15,94	16,15	16,68
3			15,80	15,62	16,05	16,12	16,77
	Average		15.75	15.7	15.96	16.15	16.69
1	VFA	Min. 65	58,80	66,81	73,31	79,31	84,55
2			58,75	66,87	73,36	79,20	84,59
3			58,68	66,98	73,43	79,24	84,65

	Average		58.74	66.89	73.37	79.25	84.60
1	VIM		6,45	5,24	4,21	3,29	2,61
2		3-5	6,42	5,22	4,29	3,35	2,54
3			6,62	5,15	4,24	3,40	2,56
	Average		6.50	5.20	4.25	3.35	2.57
1	Stabilitas	Min. 800	1017	1056	1115	1115	1056
2			958	1095	1164	1089	1056
3			1014	1095	1154	1127	1115
	Average		996	1082	1144	1110	1076
1	Flow	Min. 2	3.20	3.30	3.40	3.60	3.80
2			3.10	3.10	3.60	3.80	3.70
3		Maks. 4	2.60	3.30	3.60	3.50	4.00
	Average		2.97	3.23	3.53	3.63	3.83
1	MQ		317.813	320	327.941	309.722	277.895
2		Min. 250	309.032	353.226	323.333	286.579	285.405
3			390	331.818	320.556	322	278.750
	Average		338.948	335.015	323.943	306.1	280.683

Source: Laboratory Testing Results PT. HKI

After all the Marshall test data for the standard Laston mixture (using 60/70 penetration asphalt) was recapitulated in tabular form, the data from various parameters were analyzed and presented in graphical form, as shown in the following figures.

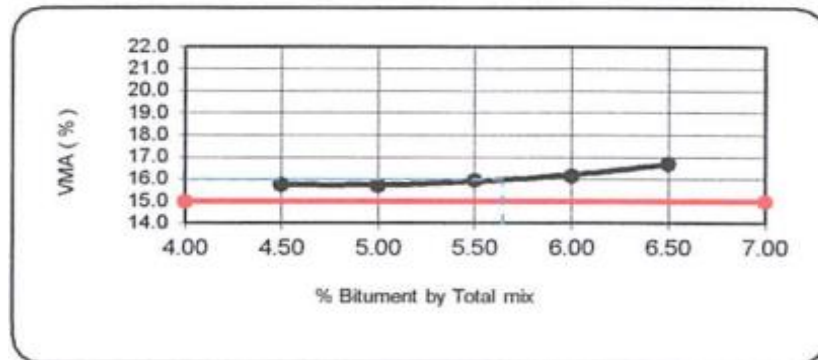


Figure 1. VMA Graph

Source: Laboratory Testing Results PT. HKI

Figure 1 shows the relationship between the Void in Mineral Aggregate (VMA) value and the planned asphalt content (KAR). From the graph, it can be seen that the VMA value increases as the asphalt content increases. Based on the provisions of the General Specifications of Bina Marga Division 6 Revision 1 of 2018, the VMA value for the AC-WC wear layer Laston mixture must be $\geq 15\%$.

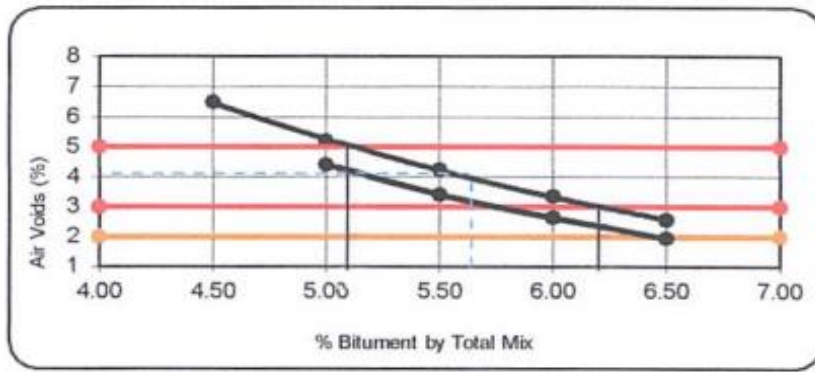


Figure 2. VIM Graph

Source: Laboratory Testing Results PT. HKI

Meanwhile, Figure 2 shows the graph between Void in Mix (VIM) and asphalt content. It can be seen that the higher the planned asphalt content (from 4.5% to 6.5%), the VIM value tends to decrease. VIM values at asphalt levels between 4.5% to 5.1%, as well as 6.2% to 6.5%, did not meet the specifications because they were outside the permitted range of 3%-5%. Qualified VIM values were obtained at asphalt levels between 5.12% and 6.19%, as shown by the trend line on the graph.

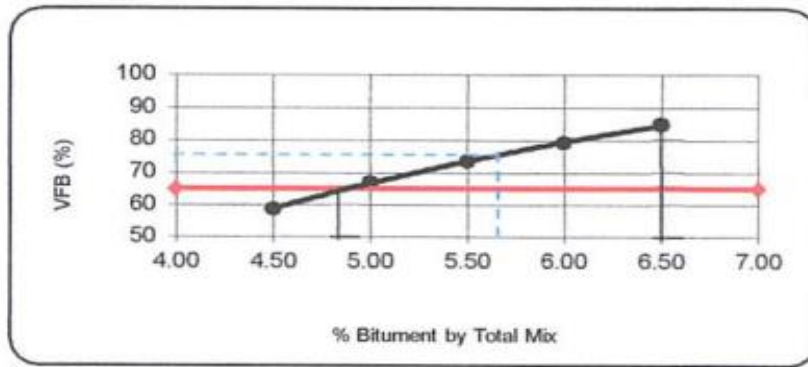


Figure 3. VFB Graph

Source: Laboratory Testing Results PT. HKI

In Figure 3, the graph of Void Filled with Bitumen (VFB) against asphalt content shows that the VFB value increases as the asphalt content increases from 4.5% to 6.5%. The VFB values were recorded at 58.74%, 66.89%, 73.37%, 79.25%, and 84.60%, respectively. Based on the Bina Marga Specification, the minimum requirement for VFB is 65%, so the asphalt content of 4.5% does not meet it because it produces values below this limit..

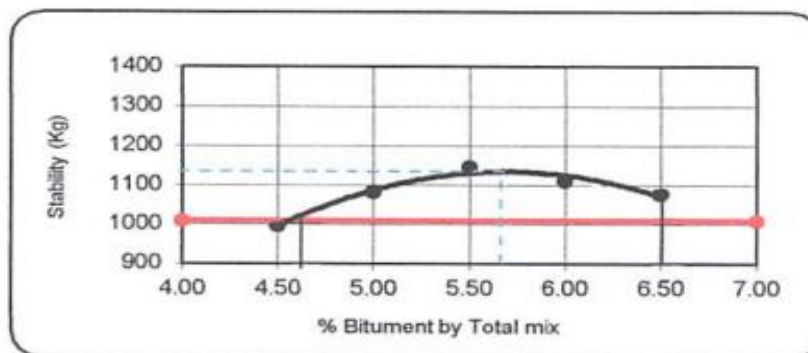


Figure 4. Stability graph

Source: Laboratory Testing Results PT. HKI

Figure 4 illustrates the graph of stability values against asphalt content. All test specimens at each asphalt content variation showed stability values that met the minimum requirements, which are ≥ 800 kg according to Bina Marga General Specifications, and ≥ 1000 kg for toll roads based on Technical Specifications Division 9. The highest stability value was achieved at 5.5% asphalt content, with a value of 1144 kg. It should be noted that these stability values were not obtained directly from the test equipment, but were calculated through corrections based on equipment calibration and test specimen thickness.

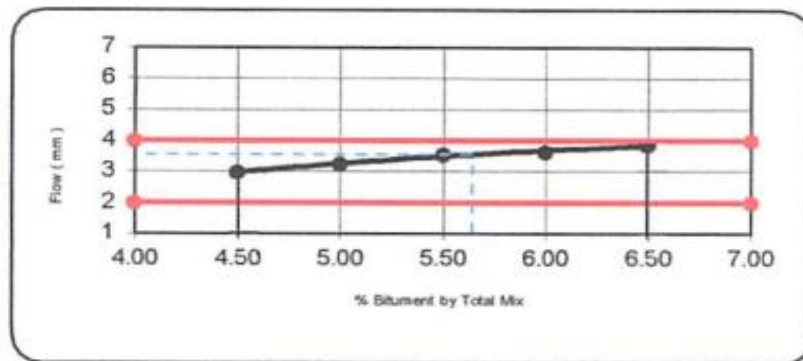


Figure 5. Flow Graph

Source: Laboratory Testing Results PT. HKI

In Figure 5, the graph of flow versus asphalt content shows an increasing trend. All flow values are still within the specified tolerance limits of 2%-4% for AC-WC mixes. The flow values of each asphalt content are 2.97%, 3.23%, 3.53%, 3.63%, and 3.83%.

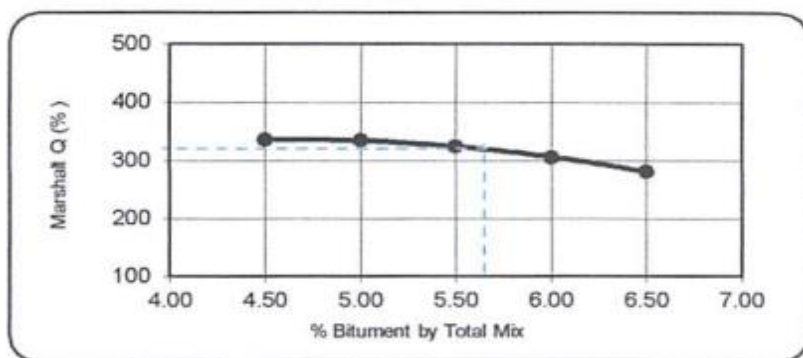


Figure 6. Grafik Marshall Quotient

Source: Laboratory Testing Results PT. HKI

The last parameter is shown in Figure 6, the Marshall Quotient (MQ) which is calculated by dividing the stability value by the flow value. The graph shows that all asphalt levels from 4.5% to 6.5% have MQ values that exceed the minimum limit of 250 kg/mm, in accordance with the General Specifications of Bina Marga. The MQ values for each asphalt content are 338.94 kg/mm, 335.01 kg/mm, 323.94 kg/mm, 306.10 kg/mm, and 280.68 kg/mm, respectively.

Determination of Optimum Asphalt Content (KAO) is done by calculating the average of the minimum and maximum asphalt content that meets all Marshall parameter requirements, as shown in Figure 7.

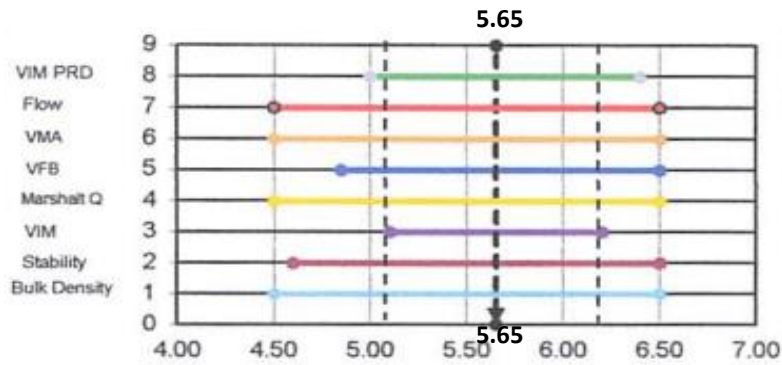


Figure 7. Optimum Asphalt Content (KAO) Determination Chart

Source: Laboratory Testing Results PT. HKI

The bar graph in Figure 7 shows that the asphalt content that met all criteria was in the range of 5.1% to 6.2%, with 5.1% being the lower limit and 6.2% the upper limit. From this range, the middle value was determined as the KAO, which was 5.65%, and was used as the optimum level for standard Laston mixes with 60/70 penetration asphalt.

Research conducted by Suparma (2015) shows that the addition of Ethylene Vinyl Acetate (EVA) to asphalt concrete mixtures of AC-WC and AC-BC types can significantly increase the Marshall stability value. The study used a variation of EVA content of 0% to 4%, and the results showed that the higher the EVA content, the stability value increased, along with a decrease in asphalt penetration value and an increase in the softening point. This suggests that EVA contributes to increasing the stiffness and bonding capacity of the mixture, making it more resistant to plastic deformation under load. These results support the findings in this study, where modified AC-WC mixes containing EVA, fly ash, and bottom ash showed higher Marshall stability values than standard mixes, indicating an improved structural ability to withstand traffic loads.

Marshall Testing Results of Modified Laston Mixture (AC-WC + EVA + Fly Ash + Bottom Ash)

The results of the marshall test for the modified laston mixture there are 4 variations with different percentages of added materials, namely the standard AC-WC mixture, AC-WC + EVA 1% + FA 0.25% + BA 0.75%, AC-WC + EVA 1% + FA 0.5% + BA 0.5%, and AC-WC + EVA 1% + FA 0.75% + BA 0.25%. The marshall test results can be seen in table 2.

Table 2. Modified Laston Marshall Test Results (AC-WC + EVA + Fly Ash + Bottom Ash)

No	Fly Ash + Bottom Ash Content	VIM	VMA	VFA	Stability	Fatigue	MQ
	%	%	%	%	Kg	mm	kg/mm
		3 – 5	Min. 15	Min.65	Min. 800	2 – 4	Min.250
1	0%	4.29	17.86	68.45	1268.2	3.6	352.29
2	0%	4.08	17.67	69.31	1249.2	3.7	337.62
3	0%	3.91	17.52	70.03	1260.2	3.5	360.07
Average		4.09	17.68	69.26	1259.2	3.6	349.99
1	FA 0,25% + BA 0,75%	3.79	17.43	70.51	1418	4	354.49
2	FA 0,25% + BA 0,75%	4.07	17.67	69.34	1348.7	3.7	364.51
3	FA 0,25% + BA 0,75%	3.83	17.46	70.35	1429.3	3.8	376.14
Average		3.90	17.52	70.07	1398.7	3.83	365.05
1	FA 0,5% + BA 0,5%	4.06	17.65	69.41	1504.2	3.95	380.81

2	FA 0,5% + BA 0,5%	3.37	17.06	72.33	1523.4	3.85	395.67
3	FA 0,5% + BA 0,5%	3.67	17.32	71.03	1514.5	3.75	403.87
Average		3.7	17.34	70.09	1514	3.85	393.45
1	FA 0,75% + BA 0,25%	2.87	16.63	74.57	1531.4	3.95	387.70
2	FA 0,75% + BA 0,25%	2.91	16.66	74.40	1580.8	3.90	405.34
3	FA 0,75% + BA 0,25%	2.84	16.61	74.67	1549.9	3.85	402.57
Average		2.87	16.64	74.55	1554	3.90	398.53

After all Marshall test data for the Modified Laston

(AC-WC + EVA + Fly ash + Bottom ash) is recapitulated into a table, then all data on several parameters above are made into graphical form, as follows:

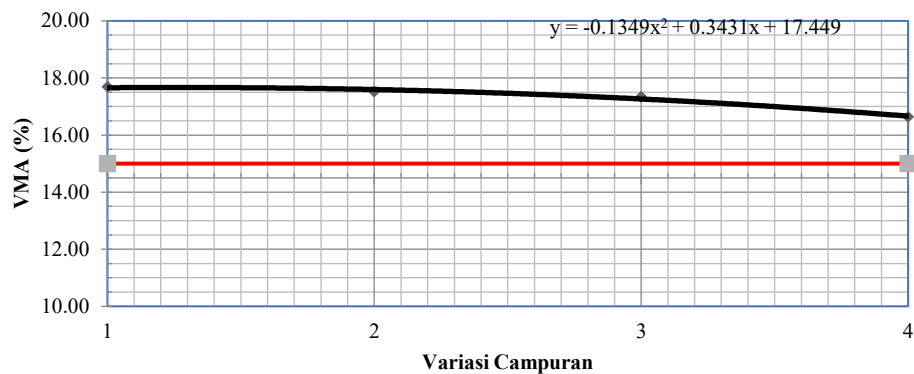


Figure 8. VMA Value Graph

Figure 8 shows the graph of VMA value against the percentage of Fly ash and bottom ash added material content. After recapitulation, it can be seen that the VMA value decreases towards the variation of the percentage content of Fly ash and bottom ash additives. Based on the General Specifications of Bina Marga Division 6 Revision 1 of 2018, the requirements for the appropriate VMA value for the AC-WC Wear Layer Laston mixture are $\geq 15\%$. If the VMA value is too small, the mixture can experience durability problems while a VMA value that is too high can cause mixture stability problems.

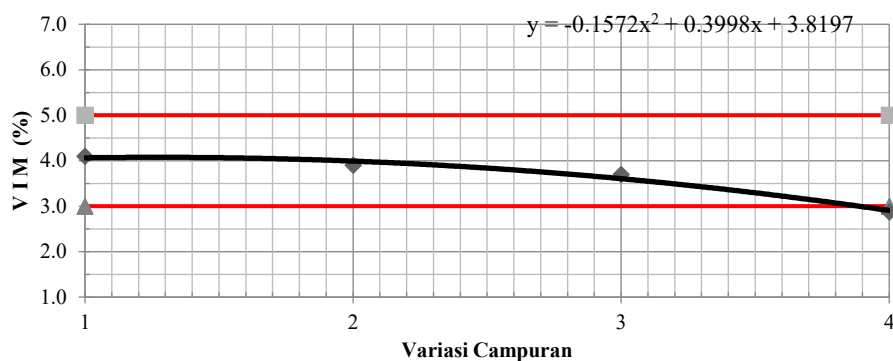


Figure 9. VIM Value Graph

The VIM value against the percentage content of Fly ash and Bottom ash additives is shown in Figure 9, from which it can be seen that the VIM value decreases when the percentage content of Fly ash additives is greater than bottom ash. The required range of Void in Mix (VIM) values is between 3% and 5%. Based on the trend line connecting the data on the graph, it is known that samples number 1 to 3 have VIM values that are in accordance with the provisions in the General Specifications of Bina Marga Division 6 Revision 1 of 2018 for the Wear Layer Laston mixture (AC-WC). The result of the analysis according to the definition

of VIM is that the smaller the VIM value, the smaller the voids in the mixture that can affect the durability of the asphalt aggregate mixture. In this study, the VIM value decreased so much that it did not make the mixture porous and made the mixture tighter.

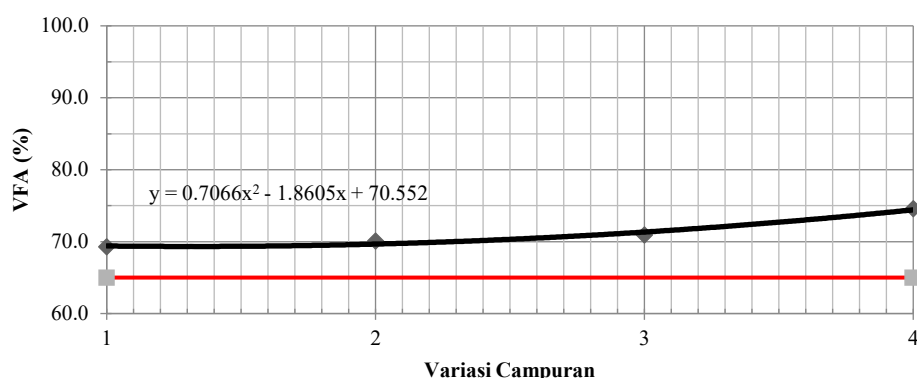


Figure 10. VFA Value Graph

Figure 10 shows a graph of the relationship between the VFA value and the percentage of FABA additive. It can be seen that an increase in fly ash content is followed by an increase in VFA value, and all values obtained are above the minimum specification limit. These VFA values have met the provisions according to the General Specifications of Bina Marga Division 6 Revision 1 of 2018 for the wear layer Laston mixture (AC-WC), which is at least 65%. The higher the VFA value, the more voids in the mixture are filled with asphalt which makes the asphalt water and air tight. Meanwhile, if the VFA value is low, the asphalt mixture becomes impermeable and cracks easily.

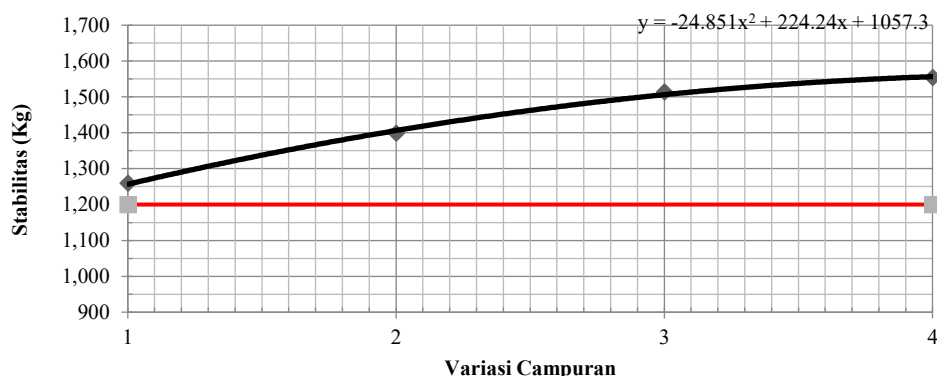


Figure 11. Stability Value Graph

There are four test specimens used to determine the stability value of the percentage of FABA added material content. The test specimens used the same material composition with different percentages of added material, this was done because it aims to get the best stability value from the four test specimens. Figure 11 shows the graph of the relationship between the stability value and the percentage of FABA added material content. Based on the graph, all the results of the four test specimens at each variation of the added material content show stability values that meet the minimum limit according to the General Specifications of Bina Marga Division 6 Revision 1 of 2018, which is ≥ 800 kg for the Wear Layer Laston mixture (AC-WC). It is important to note that the stability value results from the test need to be adjusted first through calibration using the test equipment correction factor, then multiplied by the correlation factor determined based on the thickness of the asphalt mixture specimen tested.

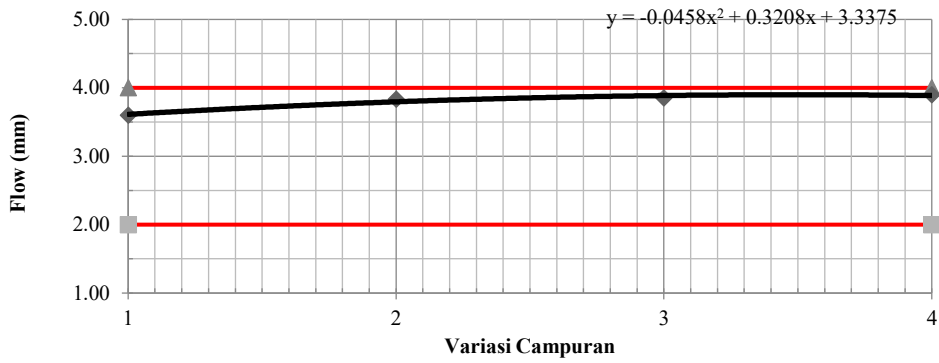


Figure 12. Flow Value Graph

The graph in Figure 12 illustrates the relationship between flow values and percentage of FABA additive. From the graph, it can be seen that the flow value increases as the additive content increases, following a similar pattern to other Marshall parameters. The test results show that the flow values are still within the limits set by the General Specifications of Bina Marga Division 6 Revision 1 Year 2018 for AC-WC wear layer Laston mixtures, which is between 2% and 4%. Mixtures with low flow values and high stability, will cause the mixture to tend to be stiff and brittle while if the flow value is high and stability is low, the mixture tends to be plastic and easily deformed when loaded.

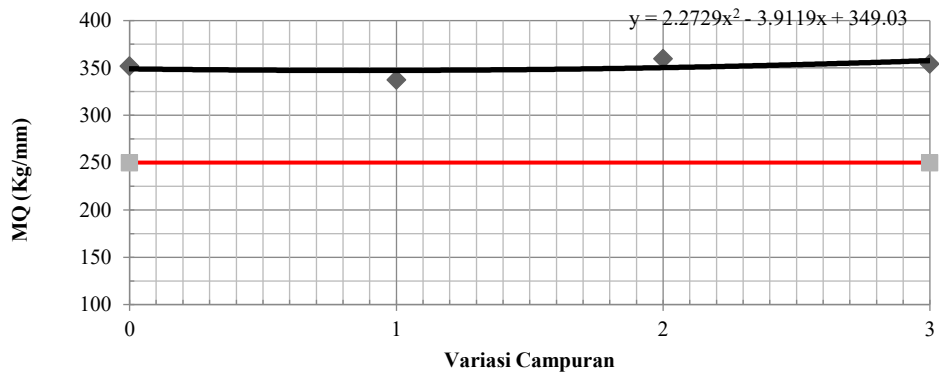


Figure 13. Marshall Quotient Graph

Based on Figure 13, it can be seen that the MQ value for all sample variations has met the requirements according to the General Specifications of Bina Marga Division 6 Revision 1 Year 2018 for AC-WC Wear Layer Laston mixes, which is ≥ 250 Kg/mm. The MQ value can be determined by comparing the stability value to the yield value.

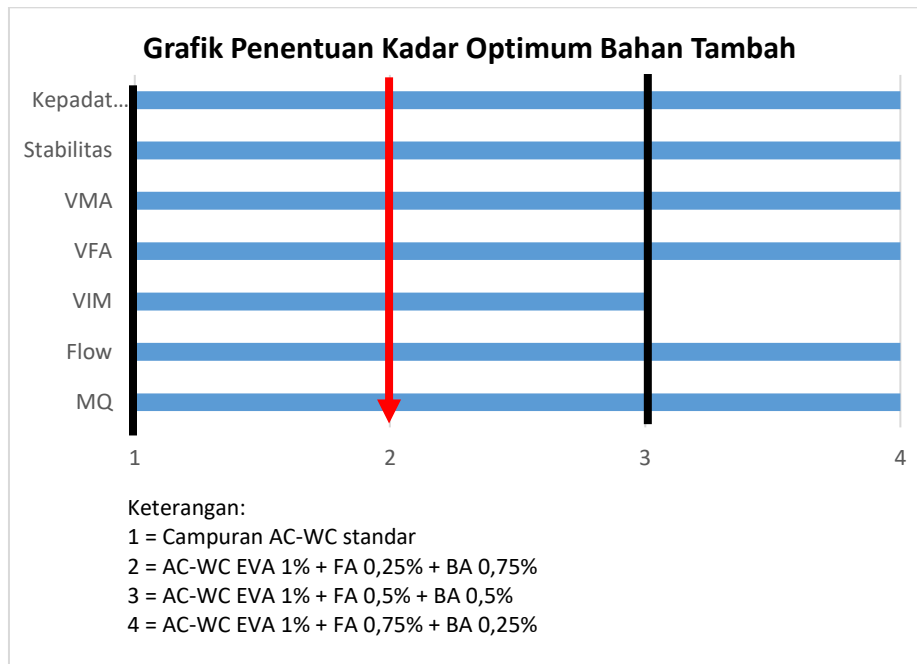


Figure 14. Graph of Determination of Optimum Level of Additives

Based on Figure 14, the Marshall parameter values that meet the overall requirements are from variations 1 to 3. Variation 1 becomes the lower limit while variation 3 becomes the upper limit to determine the optimum level of added material. The 4th variation does not meet the requirements because the VIM parameter test results do not meet Bina Marga specifications.

After obtaining the previous test results, the next step in determining the optimum levels of additional materials is to calculate the middle value of the range of limits obtained. Based on this process, the optimum composition for the modified asphalt concrete mix (AC-WC + EVA + Fly Ash + Bottom Ash) was found in the second variation, which contained 1% EVA, 0.25% Fly Ash, and 0.75% Bottom Ash.

As a result of the analysis, the samples taken in the 2nd variation have Marshall parameter values that meet the specifications and are better than the standard mix. In this mixture, the level of fly ash use is lower than bottom ash.

The VIM (Void in Mix) value is better than that of the standard mixture, which helps reduce air voids in the mix, thereby making the asphalt less porous and enhancing the durability of the asphalt mixture.

The VMA (Void in Mineral Aggregate) value in the second variation is better than the standard because it has a lower value, which can increase the mixture's stability. This is important considering field case studies, where asphalt often experiences permanent deformation caused by overloaded vehicles (ODOL).

The VFA (Void Filled with Asphalt) value in this mixture is higher than that of the standard mixture, meaning more voids are filled with asphalt, making the mixture more impermeable to water and air.

The stability value produced by the second variation of the mixture is significantly higher than that of the standard mixture.

As the Ethylene Vinyl Acetate (EVA) content increases, the asphalt penetration value decreases, while the ductility value increases. The maximum EVA content that meets the Bina

Marga 2018 specifications in this study is 1%; exceeding this amount may cause the asphalt to become too stiff due to EVA's elastomeric properties.

Fly ash and bottom ash have a silica (SiO₂) content greater than 50%, resulting in higher water absorption values compared to stone dust. This improves the water absorption performance of the asphalt mixture.

A study by Syarkawi et al. (2019), which utilized fly ash and bottom ash as fillers in flexible asphalt mixtures, showed an increase in Marshall stability by up to 25% compared to mixtures using only stone dust. The addition of fly ash and bottom ash fillers provided a denser structure in the mix, reduced air voids, and improved bonding between aggregate particles. These findings align with the Marshall test results in this study, where the use of EVA as a binder modifier and FABA as an additive significantly contributed to improvements in stability and other Marshall parameters such as VIM, VMA, and flow. The modified mixture demonstrated superior performance, particularly in its resistance to initial deformation and interparticle bonding strength under loading conditions.

Wheel Tracking Machine (WTM) Test Results of Modified Asphalt Concrete Wearing Course (AC-WC + EVA + Fly Ash + Bottom Ash)

Temperature has a significant impact on the rate of deformation, as the Wheel Tracking Machine (WTM) test in this study was conducted at 30°C to observe the influence of temperature on the performance of the asphalt mixture. The toughness of a material is highly affected by temperature conditions. At lower temperatures, the material tends to be more brittle due to the compact arrangement of particles, leaving little room for deformation. Conversely, at higher temperatures, the particles become more spaced out, resulting in lower dynamic stability and consequently higher rates of deformation. In this test, three variations of the modified AC-WC mixtures were evaluated with different percentages of additive materials: the standard AC-WC mixture as shown in Table 4.18, the mixture of AC-WC + 1% EVA + 0.25% fly ash + 0.75% bottom ash in Table 4.19, and the mixture of AC-WC + 1% EVA + 0.5% fly ash + 0.5% bottom ash in Table 3.

Table 3. Wheel Tracking Machine (WTM) Test Results of Modified Asphalt Concrete (AC-WC + 0% EVA + 0% Fly Ash + 0% Bottom Ash)

Type of Test	Method	Unit	Average Test Result	Remarks
Dynamic Stability	JRA (2005)	Passes/mm	5488,64	-
Dynamic Stability	JRA (2005)	Passes/mm	5486,18	-

Based on Table 3, the results of the dynamic stability test for the standard asphalt concrete mixture (AC-WC + 0% EVA + 0% Fly Ash + 0% Bottom Ash) at a temperature of 30°C showed values of 5488.64 passes/mm and 5486.18 passes/mm. The dynamic stability of the standard AC-WC mixture is naturally lower than that of the modified AC-WC mixture with the addition of EVA and FABA additives. Therefore, the ability of the modified mixture to resist deformation or the potential occurrence of permanent deformation (rutting) due to traffic loading is significantly higher.

Table 4. Wheel Tracking Machine (WTM) Test Results for Modified Asphalt Concrete Mixture (AC-WC + EVA + 0.25% Fly Ash + 0.75% Bottom Ash)

Type of Test	Method	Unit	Average Test Result	Remarks
Dynamic Stability	JRA (2005)	Passes/mm	15750,00	-
Dynamic Stability	JRA (2005)	Passes/mm	15751,04	-

Based on Table 4, the dynamic stability test results for the modified asphalt concrete mixture (AC-WC + EVA + 0.25% Fly Ash + 0.75% Bottom Ash) at a testing temperature of 30°C showed values of 15,750.00 passes/mm and 15,751.04 passes/mm. This indicates that the pavement using the modified mixture (AC-WC + EVA + 0.25% Fly Ash + 0.75% Bottom Ash) has a higher dynamic stability compared to both the unmodified mixture (0%) and the other modified mixture (AC-WC + EVA + 0.50% Fly Ash + 0.50% Bottom Ash). This variation also resulted in the lowest total deformation among all mixtures, which means the likelihood of permanent deformation (rutting) is minimal. Therefore, this modified asphalt concrete mixture is considered the best and most optimal option for use.

Table 5. Wheel Tracking Machine (WTM) Test Results for Modified Asphalt Concrete Mixture (AC-WC + EVA + 0.5% Fly Ash + 0.5% Bottom Ash)

Type of Test	Method	Unit	Average Test Result	Remarks
Dynamic Stability	JRA (2005)	Passes/mm	7875,00	-
Dynamic Stability	JRA (2005)	Passes/mm	7874,03	-

Based on Table 5, the dynamic stability test results for the modified asphalt concrete mixture (AC-WC + EVA + 0.50% Fly Ash + 0.50% Bottom Ash) at a test temperature of 30°C showed values of 7,875.00 passes/mm and 7,874.03 passes/mm. This modified mixture demonstrated higher dynamic stability than the standard AC-WC mixture but lower than the modified mixture (AC-WC + EVA + 0.25% Fly Ash + 0.75% Bottom Ash). Given its higher dynamic stability compared to the standard mixture, the resulting deformation will be lower, meaning that shape changes or damage due to traffic loading will be reduced. However, when compared to the modified mixture with 0.25% Fly Ash and 0.75% Bottom Ash, the likelihood of deformation is greater, which may lead to more rapid pavement deterioration.

Based on these test results, there are noticeable differences in performance following the addition of Ethylene Vinyl Acetate (EVA), Fly Ash, and Bottom Ash at various concentrations. The mixture without additives (0% EVA + 0% Fly Ash + 0% Bottom Ash) recorded 5,488.64 passes/mm and 5,486.18 passes/mm. The mixture with 1% EVA + 0.25% Fly Ash + 0.75% Bottom Ash showed the highest values at 15,750.00 passes/mm and 15,751.04 passes/mm. Meanwhile, the mixture with 1% EVA + 0.50% Fly Ash + 0.50% Bottom Ash yielded 7,875.00 passes/mm and 7,874.03 passes/mm. These results indicate that the modified asphalt concrete mixture (AC-WC + EVA + 0.25% Fly Ash + 0.75% Bottom Ash) achieved the highest dynamic stability, making it the most optimal and effective composition for use due to its superior resistance to deformation and high durability compared to the other mixtures.

The Wheel Tracking Machine (WTM) test results in this study align with the findings of Syarkawi (2019), who used marble waste as filler and demonstrated improved resistance to permanent deformation. Syarkawi's study showed that the modified mixture had a lower rut depth compared to the standard mixture, confirming enhanced dynamic stability. Similarly, in this research, the AC-WC mixture modified with EVA, fly ash, and bottom ash exhibited higher passes/mm values, indicating greater resistance to repeated loading under high-temperature conditions. This combination of materials has proven effective in minimizing rutting and enhancing the mixture's resistance to deformation under heavy traffic loads.

Conclusion

Based on the tests and analysis conducted on the Asphalt Concrete Wearing Course (AC-WC) mixture modified with the addition of Ethylene Vinyl Acetate (EVA), fly ash as filler, and bottom ash as fine aggregate, it can be concluded that this combination of modification materials has a positive impact on the performance of the asphalt mixture. The Marshall test

results showed an increase in stability and the Marshall Quotient in the modified mixture compared to the standard mixture, indicating improved structural strength and better resistance to initial deformation.

Furthermore, the results of the Wheel Tracking Machine (WTM) test demonstrated that the modified AC-WC mixture exhibited lower permanent deformation compared to the conventional mixture, especially under high-temperature conditions simulating repeated heavy vehicle loads. This indicates that the modified mixture is more effective in resisting rutting, making it more suitable for critical locations such as toll gate areas with high traffic intensity.

In addition, the utilization of industrial waste such as fly ash and bottom ash as partial substitutes for conventional aggregate not only improved the technical performance of the mixture but also provided a solution to environmental issues by reducing unused waste. Therefore, this study shows that modifying asphalt mixtures using EVA and FABA has significant potential to be applied in the development of longer-lasting, more economical, and environmentally friendly road infrastructure.

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