

MARSHALL CHARACTERISTICS OF A COMBINATION OF STONE DUST FILLER AND STYROFOAM IN ASPHALT CONCRETE WEARING COURSE (AC-WC) MIXTURE

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Abstract

Asphalt Concrete Wearing Course (AC-WC) pavement requires a mixture with good stability, durability, and resistance to traffic loads. One effort to improve the quality of asphalt mixtures is by utilizing alternative materials such as stone dust filler and styrofoam waste. This study aims to determine the effect of the combination of stone dust filler and styrofoam on the Marshall characteristics of AC-WC mixtures and to identify the most optimal mixture variation. The research method used was a laboratory experimental method by conducting Marshall tests on several variations of stone dust filler and styrofoam mixtures. The materials used consisted of coarse aggregate, fine aggregate, 60/70 penetration asphalt, stone dust, and styrofoam. The mixture variations studied included different proportions of stone dust and styrofoam at the same Optimum Asphalt Content (OAC), namely 5.90%. The tested parameters included Bulk Density, Void in Mix (VIM), Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), Stability, Flow, and Marshall Quotient (MQ). The results showed that the addition of styrofoam tended to increase the density of the mixture and the VFA value, while reducing the VIM and flow values. The highest stability value was obtained in the standard mixture at 1007.5 kg and was almost equal to the ABS-3 variation at 1004.6 kg. The highest Marshall Quotient (MQ) value was obtained in the ABS-3 mixture at 324.05 kg/mm, indicating the best combination of strength and stiffness. Overall, the ABS-3 mixture variation provided the most optimal Marshall characteristics compared to the other variations. Based on the research results, it can be concluded that the combination of stone dust filler and styrofoam affects the Marshall characteristics of AC-WC mixtures, and the ABS-3 variation has the potential to become an effective and environmentally friendly alternative pavement mixture through the utilization of styrofoam waste.

Keywords: AC-WC, stone dust, styrofoam, Marshall characteristics, filler, pavement.

1. Introduction

Road pavement is one of the most important transportation infrastructures in supporting community mobility and economic growth. One type of pavement layer commonly used in Indonesia is Asphalt Concrete Wearing Course (AC-WC), which is a surface layer directly subjected to traffic loads and weather effects. Therefore, AC-WC mixtures must possess good characteristics, such as high stability, durability, flexibility, and resistance to deformation and water damage. The quality of AC-WC mixtures is influenced by their constituent materials, especially aggregates, asphalt, and filler. Filler is a very fine material that functions to fill voids within the mixture, thereby increasing the density and strength of the asphalt mixture. One material that can be utilized as filler is stone dust because it has a fine texture and is easily obtained from stone crushing processes. The use of stone dust as filler is considered capable of improving the bond between aggregates and enhancing the Marshall characteristics of asphalt mixtures.

On the other hand, the increasing use of styrofoam in daily life has created environmental problems because styrofoam waste is difficult to decompose naturally. Styrofoam is classified as a non-biodegradable waste material which, if not properly managed, can pollute the environment. One effort to utilize styrofoam waste is by using it as an additive material in asphalt mixtures. Styrofoam has lightweight and waterproof properties and contains polymers that have the potential to improve adhesion and stability in asphalt mixtures. The utilization of a combination of stone dust filler and styrofoam in AC-WC mixtures is expected to improve Marshall characteristics, such as stability, flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). In addition, the use of styrofoam waste materials can become an innovative, environmentally friendly, and economical alternative in road pavement construction. Based on the above explanation, it is necessary to conduct research on the Marshall characteristics of a combination of stone dust filler and styrofoam in Asphalt Concrete Wearing Course (AC-WC) mixtures to determine their effect on the performance of asphalt mixtures and to identify the optimum composition that meets pavement specifications.

Several previous studies have examined the potential utilization of Styrofoam (Expanded Polystyrene/EPS) as an additive material or filler substitute in Asphalt Concrete Wearing Course (AC-WC) mixtures. In general, the objectives of these studies are to reduce the weight of the mixture, improve thermal insulation, and utilize styrofoam waste constructively, including the following:

1. Penelitian oleh Ujung et al. (2025) mengevaluasi karakteristik campuran AC-WC dengan penambahan Styrofoam sebanyak 3–5% dari berat aspal. Hasilnya menunjukkan bahwa penambahan Styrofoam dapat menurunkan densitas campuran tanpa mengubah kestabilan Marshall secara signifikan.
2. Fitriansyah et al. (2025) meneliti pengaruh suhu pencampuran dan variasi kadar Styrofoam terhadap karakteristik Marshall. Penelitian ini menekankan bahwa kombinasi suhu dan kadar Styrofoam berperan penting dalam stabilitas dan flow campuran, sehingga pemilihan kondisi pencampuran optimal sangat diperlukan.
3. Kinanti et al. (2024) fokus pada durabilitas campuran AC-WC dengan 1,5% Styrofoam melalui uji perendaman air dan pengukuran Indeks Kekuatan Sisa (IKS). Hasil menunjukkan bahwa campuran tetap memiliki ketahanan terhadap penetrasi air yang baik dan nilai IKS tetap memenuhi standar teknis.
4. Marbun et al. (2025) membandingkan AC-WC dengan aspal termodifikasi dan penambahan 1,5% Styrofoam, menunjukkan bahwa parameter Marshall seperti stabilitas, flow, dan void masih

memenuhi standar Bina Marga 2018, walaupun terdapat sedikit penurunan kekuatan tekan seiring meningkatnya proporsi Styrofoam.

5. Penelitian lain menggunakan Styrofoam dalam kombinasi dengan Reclaimed Asphalt Pavement (RAP) dan filler fly ash, seperti yang dilakukan oleh Kurniawan & Mahardi (2025). Studi ini menunjukkan bahwa penggunaan Styrofoam dalam kadar tertentu dapat menurunkan densitas campuran, meningkatkan isolasi termal, dan tetap mempertahankan karakteristik mekanik yang memadai.
6. Penelitian Arrahman et al. (2025) mengevaluasi pengaruh penggunaan abu batu sebagai filler terhadap karakteristik Marshall campuran AC-WC dengan variasi kadar 0%, 5%, dan 10%. Hasil uji Marshall menunjukkan perubahan parameter stabilitas dan flow pada setiap variasi kadar abu batu, yang mengindikasikan kemampuan abu batu untuk berkontribusi pada kinerja campuran aspal beton lapis aus.
7. Penelitian di Universitas Kadiri juga menguji pengaruh persentase filler abu batu terhadap parameter Marshall, dan hasilnya menunjukkan korelasi antara peningkatan persentase abu batu dengan karakteristik Marshall campuran.

2. Research Method

This study used a laboratory experimental method to determine the effect of the combination of stone dust filler and styrofoam on the Marshall characteristics of Asphalt Concrete Wearing Course (AC-WC) mixtures. The research was conducted at the asphalt testing laboratory owned by PT. Komba Mahaka Utama, located in Martapura, East OKU Regency. The fine aggregate used was obtained from the Asphalt Mixing Plant (AMP) of PT. Komba Mahaka Utama in East OKU, while the coarse aggregate and stone dust filler originated from natural stone that had undergone a crushing process using a crusher machine at the AMP facility. The experimental method was chosen because the study was carried out through direct testing of asphalt mixture specimens with specific composition variations, allowing the relationship between the use of stone dust filler and styrofoam and the values of stability, flow, VIM, VMA, VFA, and Marshall Quotient (MQ) to be determined. The entire research process was conducted in a civil engineering laboratory equipped with road pavement material testing facilities in accordance with applicable standards.

The research began with the preparation of materials and equipment. The main materials used consisted of coarse aggregate, fine aggregate, stone dust filler, 60/70 penetration asphalt, and styrofoam waste. Coarse and fine aggregates were used as the primary materials forming the structure of the AC-WC mixture, while stone dust was used as a filler to fill fine voids within the mixture. Styrofoam waste was utilized as an additive material with the aim of improving the quality of the mixture while simultaneously reducing environmental pollution caused by non-biodegradable waste. The 60/70 penetration asphalt was selected because it is commonly used in road construction in Indonesia and complies with flexible pavement specifications. Before being used in the mixture, all materials were first tested for their physical properties to ensure that they met the required specifications. Aggregate testing included sieve analysis, aggregate specific gravity, water absorption, Los Angeles abrasion test, and mud content test. Asphalt testing included penetration, softening point, flash point, ductility, and asphalt specific gravity tests. The fineness of the stone dust was also examined to ensure its suitability as a filler material. Meanwhile, the styrofoam waste was first cleaned of any attached impurities and then cut into small pieces to facilitate mixing into the hot asphalt mixture.

The next stage was the design of the AC-WC mixture based on applicable specifications, such as the General Specifications of Bina Marga. The aggregate gradation was designed to meet the gradation limits of AC-WC mixtures in order to produce a dense and stable mixture. After obtaining the aggregate gradation, the determination of the planned asphalt content was carried out using several variations of asphalt content to obtain the Optimum Asphalt Content (OAC). The determination of the optimum asphalt content was conducted using the Marshall method by considering the parameters of stability, flow, VIM, VMA, and VFA in accordance with the established specifications.

In this study, the mixture variations were prepared by adding combinations of stone dust filler and styrofoam at several percentages as follows:

1. 100% stone dust filler (Code AB100)
2. 75% stone dust filler and 25% styrofoam (Code ABS-1)
3. 50% stone dust filler and 50% styrofoam (Code ABS-2)
4. 25% stone dust filler and 75% styrofoam (Code ABS-3)

based on the total weight of the mixture. These variations were intended to determine the effect of changes in filler composition on the Marshall characteristics of AC-WC mixtures. Each mixture variation was prepared with the same number of specimens to ensure that the test results would be more accurate and objectively comparable. The specimens were made using standard Marshall molds with a diameter of 10.16 cm and a height of approximately 6.35 cm.

The mixing process was carried out by heating the aggregates and asphalt to a specific temperature until the appropriate mixing temperature was achieved. After the aggregates reached the predetermined temperature, the stone dust filler and styrofoam were evenly mixed into the hot aggregates. Subsequently, the hot asphalt was poured into the mixture and stirred until the entire surface of the aggregates was uniformly coated with asphalt. The mixture was then placed into Marshall molds and compacted using a Marshall compactor with the number of blows adjusted according to the standard requirements for AC-WC mixtures.

The compacted specimens were left at room temperature for approximately 24 hours before testing. After that, the specimens were immersed in a water bath at 60°C for about ± 30 minutes to prepare them for the Marshall test. The Marshall test was then conducted using a Marshall Testing machine to obtain the stability and flow values of each specimen. The stability value indicates the ability of the mixture to resist loads without undergoing deformation, while the flow value represents the degree of deformation or plasticity of the mixture when subjected to loading.

In addition to stability and flow testing, volumetric analysis of the mixture was also carried out, including the calculation of Void in Mix (VIM), Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), and Marshall Quotient (MQ). The VIM value is used to determine the percentage of air voids within the mixture, VMA represents the voids between aggregates in the compacted mixture, while VFA indicates the percentage of aggregate voids filled with asphalt. The Marshall Quotient is obtained from the ratio of stability to flow, which represents the stiffness of the mixture.

The test data were then analyzed using a quantitative descriptive method by comparing the Marshall characteristic values of each mixture variation against the applicable specifications. The analysis was conducted to determine the effect of adding styrofoam and stone dust filler on the performance of AC-WC mixtures and to identify the mixture variation that provides the most optimal results. The research results were presented in the form of tables, graphs, and discussions to facilitate data interpretation and conclusion drawing.

Through this research method, it is expected that information can be obtained regarding the effectiveness of using a combination of stone dust filler and styrofoam in improving the quality of Asphalt Concrete Wearing Course (AC-WC) mixtures. In addition to providing technical benefits in road construction, this study is also expected to serve as an alternative solution for utilizing styrofoam waste in a more environmentally friendly and economically valuable way.

3. Laboratory Research Results

The test data of the Asphalt Concrete Wearing Course (AC-WC) composite materials obtained in this study are presented in detail in the following table. The information illustrates the physical and mechanical characteristics of the mixture, which serve as the focus of evaluation in this study.

Table 1. Test Results of AC-WC Mixture Materials

No	Material	Hasil
1	Asphalt Properties - Penetration - Specific Gravity - Softening Point - Flash Point - Ductility	61,2 1,039 gram/cc 51,8 °C 358 °C 140
2	Fine Aggregate Properties - Bulk Specific Gravity - SSD (Saturated Surface Dry) Specific Gravity - Apparent Specific Gravity - Water Absorption	2,472 gram/cc 2,527 gram/cc 2,615 gram/cc 2,218 %
3	Stone Dust (Filler) Properties - Bulk Specific Gravity - SSD (Saturated Surface Dry) Specific Gravity - Apparent Specific Gravity - Water Absorption	2,503 gram/cc 2,554 gram/cc 2,638 gram/cc 2,051 %
4	Coarse Aggregate Crushed Stone 1/1 - Dry Bulk Specific Gravity (Sd) - SSD (Saturated Surface Dry) Bulk Specific Gravity (Ss) - Apparent Specific Gravity (Sa) - Water Absorption (Sw) Coarse Aggregate Crushed Stone 1/2 - Dry Bulk Specific Gravity (Sd) - SSD (Saturated Surface Dry) Bulk Specific Gravity (Ss) - Apparent Specific Gravity (Sa) - Water Absorption (Sw)	2,544 gram/cc 2,583 gram/cc 2,648 gram/cc 1,547 % 2,573 gram/cc 2,605 gram/cc 2,658 gram/cc 1,240 %

Source: DMF Laboratorium PT. KMU

Table 2. AC-WC Composition with Stone Dust and Styrofoam Combination

No	Material	Material Weight	Stone Dust	Styrofoam
1	Coarse Aggregate 1/2	94,08 gr	94,08 gr	94,08 gr
2	Coarse Aggregate 1/1	193,68 gr	193,68 gr	193,68 gr
3	Stone Dust	237,90 gr	237,90 gr	237,90 gr
4	Sand	27,66 gr	27,66 gr	27,66 gr
5	Asphalt	35,40 gr	35,40 gr	35,40 gr
6	Stone Dust Filler 100% (AB100)	11,28 gr	0	0
7	Stone Dust 75% + Styrofoam	0	8,46 gr	2,256 gr

	25% (ABS-1)			
8	Stone Dust 50% + Styrofoam 50% (ABS-2)	0	5,64 gr	5,64 gr
9	Stone Dust 25% + Styrofoam 75% (ABS-3)	0	2,82 gr	8,46 gr

Source: Analysis Results

Table 3. Test Results of Various Combinations of Stone Dust Filler and Styrofoam

No	Type of Test	Unit	DMF Standar (AB100)	Test Results		
				AB 75%+ Sty. 25% (ABS-1)	AB 50%+ Sty. 50% (ABS-2)	AB 25% +Sty.75% (ABS-3)
1	Optimum Asphalt Content	%	5,90	5,90	5,90	5,90
2	Standard Bulk Density	gr/cc	2,234	2,236	2,242	2,252
3	Standard VIM (Voids in Mix)	%	4,76	5,88	5,24	4,40
4	Voids in Mineral Aggregate (VMA)	%	16,59	16,61	16,46	16,14
5	Voids Filled with Asphalt (VFA)	%	71,30	64,59	68,18	72,75
6	Marshall Stability	kg	1007,5	939,8	956,0	1004,6
7	Flow (Deformation)	mm	3,17	3,50	3,30	3,10
8	Marshall Quotient (MQ)	kg/mm	318,15	268,50	289,68	324,05

Source: Analysis Results

4. Discussion

4.1 Stability Value

The Marshall stability value indicates the ability of the asphalt mixture to resist the maximum load before failure occurs. The higher the stability value obtained, the better the mixture's capability to withstand traffic loads. The stability values are presented in Table 4 below.

Table 4. Marshall Stability Values

No	DMF Type	Test Results (kg)	Specification 2018 Revisi 2 (kg)
1	AB100	1007,5	Min 800
2	ABS-1	939,8	
3	ABS-2	956,0	
4	ABS-3	1004,6	

Source: Analysis Results

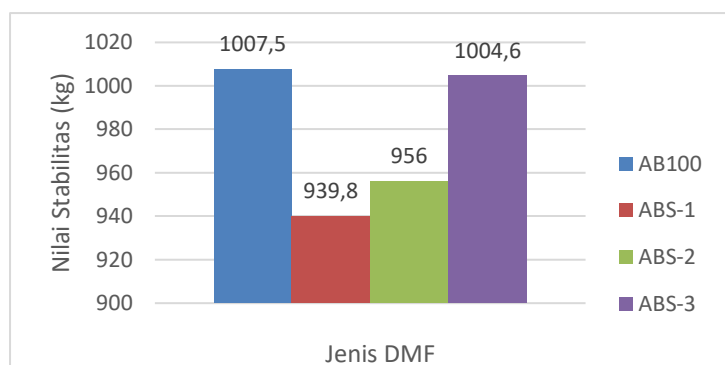


Figure 1. Stability Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations of stone dust and styrofoam filler combinations shown in Table 4, the stability values varied but all met the requirements of the General Specification of Bina Marga 2018 Revision 2, which specifies a minimum of 800 kg. The AB100 mixture (100% stone dust) produced a stability value of 1007.5 kg, indicating a good ability of the mixture to withstand traffic loads. In the ABS-1 mixture, the stability value slightly decreased to 939.8 kg, but it still remained above the required minimum limit. This decrease indicates that the addition of 25% styrofoam began to affect the stiffness of the mixture; however, it did not significantly reduce the structural performance.

Furthermore, the ABS-2 mixture showed a stability value of 956.0 kg, which increased compared to ABS-1. This indicates a balance between the properties of stone dust filler and styrofoam that is able to improve the interlocking between aggregates. In the ABS-3 mixture, the stability value increased again to 1004.6 kg, approaching the stability value of the AB100 mixture. This result shows that a higher proportion of styrofoam is still able to contribute positively to the stability of the AC-WC mixture.

Overall, the variations of stone dust and styrofoam filler combinations did not reduce the stability values below the required standard. This indicates that the use of styrofoam as an alternative filler, either partially or dominantly, is still feasible to be applied in AC-WC mixtures in terms of the Marshall stability parameter.

4.2 Flow Value

The flow value represents the amount of plastic deformation of the asphalt mixture at the point of maximum load. This parameter reflects the flexibility of the mixture, where a very low flow value indicates a stiff and brittle mixture that is prone to cracking, while a very high flow value indicates an overly plastic mixture that is susceptible to permanent deformation. The flow values of various combinations of stone dust and styrofoam filler are presented in Table 5 below.

Table 5. Flow Values

No	DMF Type	Test Results (mm)	Specification 2018 Revisi 2 (mm)
1	AB100	3,17	Min 2,0- 4,0
2	ABS-1	3,50	
3	ABS-2	3,30	
4	ABS-3	3,10	

Source: Analysis Results

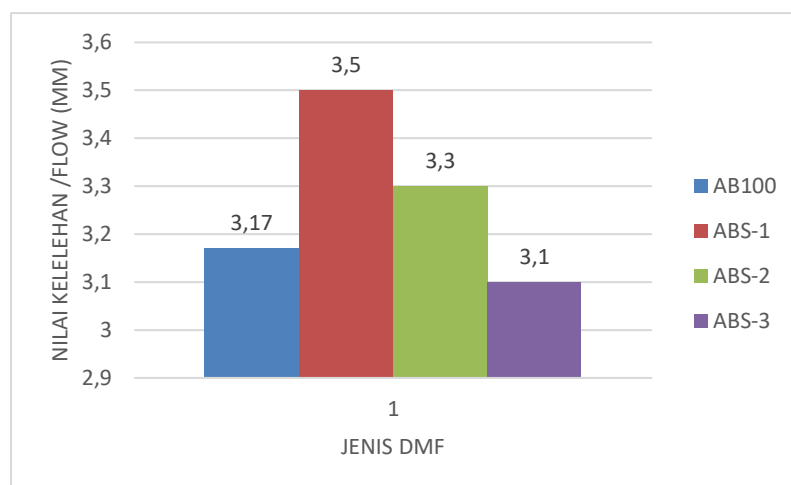


Figure 2. Flow Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 5, the flow values ranged from 3.10 mm to 3.50 mm. All of these flow values met the requirements of the General Specification of Bina Marga 2018 Revision 2, which specifies a range of 2.0–4.0 mm. The AB100 mixture produced a flow value of 3.17 mm, indicating a mixture condition with good flexibility and a balanced combination of elastic and plastic behavior. In the ABS-1 mixture, the flow value increased to 3.50 mm, indicating that the addition of 25% styrofoam made the mixture more flexible and resulted in greater deformation under loading.

Furthermore, in the ABS-2 mixture, the flow value decreased to 3.30 mm, indicating that a balanced proportion of stone dust and styrofoam was able to increase the stiffness of the mixture, resulting in relatively reduced deformation. In the ABS-3 mixture, the flow value further decreased to 3.10 mm, indicating that increasing the styrofoam content up to 75% tended to make the mixture stiffer and more resistant to plastic deformation.

Overall, the use of a combination of stone dust and styrofoam filler in AC-WC mixtures affects the flow value; however, all mixture variations remain within the allowable specification limits. Therefore, this filler combination is considered suitable for use in AC-WC mixtures in terms of the Marshall flow parameter.

4.3 Void in Mix (VIM) Value

VIM is the percentage of air voids in the asphalt mixture relative to the total mixture volume. These voids are used to evaluate the density of the mixture and influence its resistance to wear and permanent deformation. The Void in Mix (VIM) values are presented in Table 6 below.

Table 6. Void in Mix (VIM) Values

No	DMF Type	Test Results (%)	Specification 2018 Revisi 2 (%)
1	AB100	4,76	3,0 – 5,0
2	ABS-1	5,88	
3	ABS-2	5,24	
4	ABS-3	4,40	

Source: Analysis Results

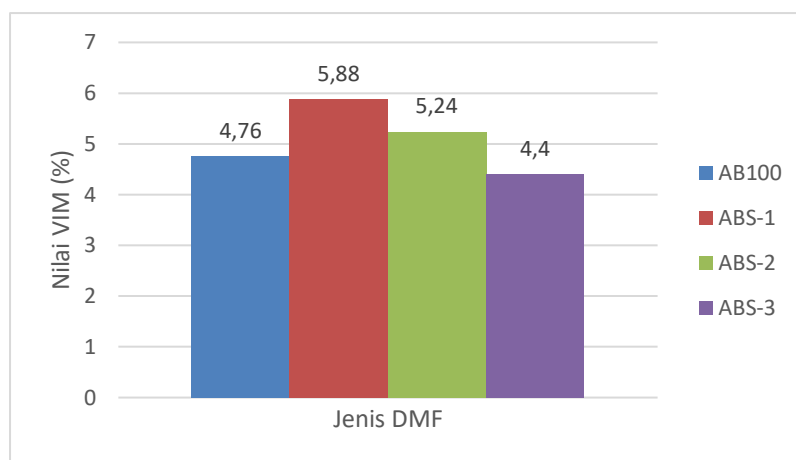


Figure 3. VIM Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 6, the Void in Mix (VIM) values ranged from 4.40% to 5.88%. According to the General Specification of Bina Marga 2018 Revision 2, the required VIM value for AC-WC mixtures is in the range of 3.0–5.0%. The AB100 mixture produced a VIM value of 4.76%, which is still within the specified range. This value indicates that the air voids in the mixture are in a relatively ideal condition, providing a balance between durability and stability.

In the ABS-1 mixture, the VIM value increased to 5.88%, thus exceeding the maximum specification limit. This increase indicates that the addition of 25% styrofoam caused larger air voids within the mixture, which may potentially reduce durability due to a higher likelihood of air and water ingress into the pavement layer. Furthermore, in the ABS-2 mixture, the VIM value decreased to 5.24%, but it was still slightly above the specified maximum limit. This suggests that although the proportion of stone dust and styrofoam was balanced, the mixture still contained relatively high air voids and had not yet fully met the desired density criteria.

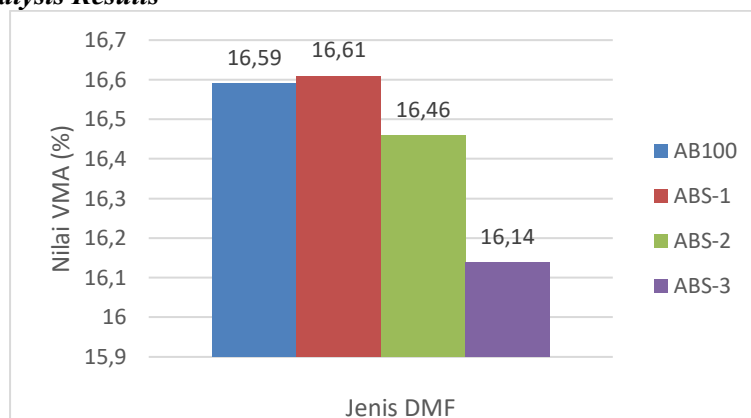
In the ABS-3 mixture, the VIM value decreased again to 4.40%, which complies with the specification requirements. This reduction in VIM indicates that a higher proportion of styrofoam was able to increase the mixture density and reduce air voids, thereby potentially improving the durability of the AC-WC mixture. Overall, the variation in stone dust and styrofoam filler combinations had a significant effect on the VIM values of the AC-WC mixtures. The AB100 and ABS-3 mixtures met the specification requirements, while the ABS-1 and ABS-2 mixtures did not meet the maximum VIM limit. Therefore, the filler proportions must be properly controlled to obtain an AC-WC mixture with appropriate air voids and optimal pavement performance.

4.4 Void in Mineral Aggregate (VMA) Value

VMA is the percentage of the volume of void spaces between aggregate particles that are filled with asphalt and air relative to the total volume of aggregate. The VMA value is used to evaluate the mixture's ability to resist deformation and structural stability. The VMA values are presented in Table 7.

Table 7. Void in Mineral Aggregate (VMA) Values

No	DMF Type	Test Results (%)	Specification 2018 Revisi 2 (%)
1	AB100	16,59	Min 15
2	ABS-1	16,61	
3	ABS-2	16,46	
4	ABS-3	16,14	

Source: Analysis Results**Figure 4. VMA Values of Stone Dust and Styrofoam Filler**

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 7, the Void in Mineral Aggregate (VMA) values ranged from 16.14% to 16.61%. All VMA values met the requirements of the General Specification of Bina Marga 2018 Revision 2, which sets a minimum of 15% for AC-WC mixtures. The AB100 mixture produced a VMA value of 16.59%, indicating that the volume of voids between aggregate particles is sufficient to accommodate effective asphalt and air voids, thereby supporting the durability and stability performance of the mixture. In the ABS-1 mixture, the VMA value slightly increased to 16.61%, indicating that the addition of 25% styrofoam tended to increase the voids between aggregates, although the increase was still within the allowable limits.

Furthermore, in the ABS-2 mixture, the VMA value decreased to 16.46%. This reduction indicates that a balanced proportion of stone dust and styrofoam can produce a denser aggregate structure. In the ABS-3 mixture, the VMA value decreased further to 16.14%, indicating that increasing the styrofoam content up to 75% resulted in smaller voids between aggregates, although the value still met the minimum specification requirement. Overall, the variation in stone dust and styrofoam filler combinations had an influence on the VMA values of the AC-WC mixtures. However, all mixtures remained above the required minimum limit. This shows that the use of styrofoam in combination with stone dust does not significantly reduce VMA values and is still feasible for use in AC-WC mixtures in terms of the VMA parameter.

4.5 Void Filled with Asphalt (VFA) Value

Void Filled with Asphalt (VFA) is the percentage of voids within the mineral aggregate (VMA) that are filled with asphalt. The VFA value indicates the extent to which asphalt is able to fill the voids between aggregate particles in the asphalt mixture. This parameter is very important because it affects the impermeability of the mixture, resistance to water damage, and the durability of the pavement. The VFA values are presented in Table 8 below.

Table 8. Void Filled with Asphalt (VFA) Values

No	DMF Type	Test Results (%)	Specification 2018 Revisi 2 (%)
1	AB100	71,30	Min 65
2	ABS-1	64,59	
3	ABS-2	68,18	
4	ABS-3	72,75	

Source: Analysis Results

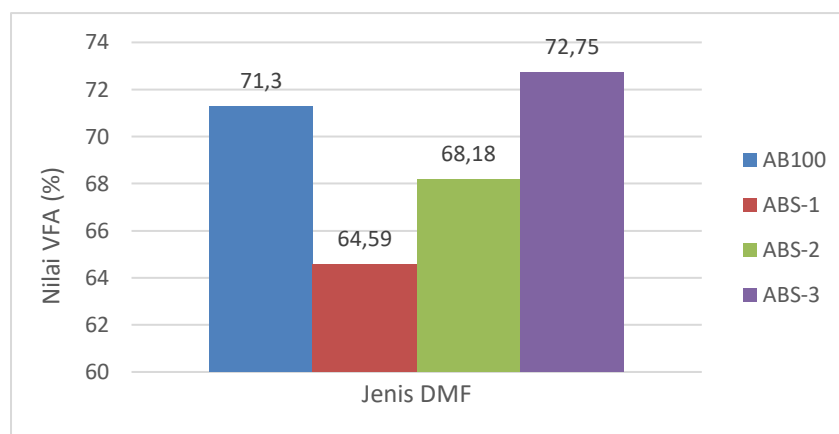


Figure 5. VFA Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 8, the Void Filled with Asphalt (VFA) values ranged from 64.59% to 72.75%. According to the General Specification of Bina Marga 2018 Revision 2, the required VFA value for AC-WC mixtures is a minimum of 65%. The AB100 mixture produced a VFA value of 71.30%, which meets the specification requirements. This value indicates that most of the voids within the aggregate are filled with asphalt, resulting in good mixture durability and resistance to water effects.

In the ABS-1 mixture, the VFA value decreased to 64.59%, thus not meeting the minimum specification requirement. This reduction indicates that the addition of 25% styrofoam caused the aggregate voids not to be optimally filled with asphalt, which may increase the mixture's susceptibility to water damage and oxidation. Furthermore, in the ABS-2 mixture, the VFA value increased again to 68.18%, and it met the specification requirements. This indicates that a balanced proportion of stone dust and styrofoam was able to improve the asphalt filling within the voids. In the ABS-3 mixture, the VFA value increased further to 72.75%, which is the highest among all mixture variations. This result shows that a higher proportion of styrofoam can enhance the filling of aggregate voids by asphalt, thereby potentially improving the durability of the AC-WC mixture.

Overall, the variation in stone dust and styrofoam filler combinations had a significant effect on the VFA values. The AB100, ABS-2, and ABS-3 mixtures met the specification requirements, while the ABS-1 mixture did not meet the minimum VFA limit. Therefore, proper control of filler proportions is necessary to obtain AC-WC mixtures with an optimal level of void filling and good pavement performance.

4.6 Marshall Quotient (MQ) Value

Marshall Quotient (MQ) is the ratio between stability and flow values that describes the stiffness or structural strength of an asphalt mixture. A high MQ value indicates a stiffer mixture with better resistance to deformation, while a low MQ value indicates a more flexible mixture that may be prone to permanent deformation. The Marshall Quotient (MQ) values are presented in Table 9 below.

Tabel 9. Nilai Marshall Quotient (MQ)

No	DMF Type	Test Results (kg/mm)	Specification 2018 Revisi 2 (kg/mm)
1	AB100	318,15	Min 250
2	ABS-1	268,50	
3	ABS-2	289,68	
4	ABS-3	324,05	

Source: Analysis Results

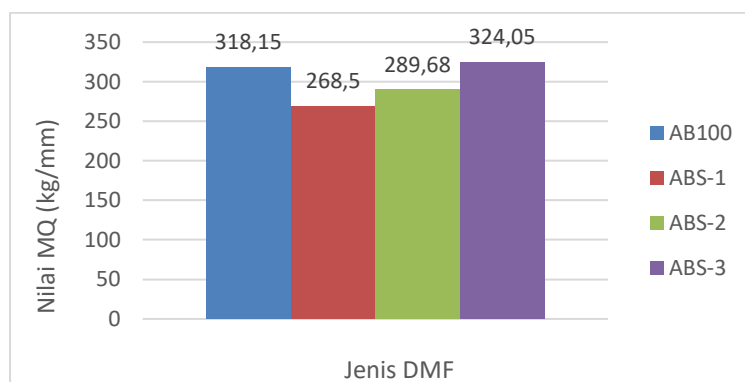


Figure 6. Marshall Quotient (MQ) Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 9, the Marshall Quotient (MQ) values ranged from 268.50 kg/mm to 324.05 kg/mm. All MQ values met the requirements of the General Specification of Bina Marga 2018 Revision 2, which sets a minimum value of 250 kg/mm. The AB100 mixture produced an MQ value of 318.15 kg/mm, indicating that the mixture has good stiffness and is capable of resisting permanent deformation caused by traffic loads. In the ABS-1 mixture, the MQ value decreased to 268.50 kg/mm. This decrease indicates that the addition of 25% styrofoam made the mixture more flexible, thereby reducing its stiffness, although it still remained within the specified limits.

Furthermore, in the ABS-2 mixture, the MQ value increased to 289.68 kg/mm. This increase indicates that a balanced proportion of stone dust and styrofoam was able to improve the stiffness of the mixture and enhance its resistance to deformation. In the ABS-3 mixture, the MQ value further increased to 324.05 kg/mm, which is the highest among all mixture variations. This result indicates that a higher proportion of styrofoam combined with stone dust was able to produce a stiffer mixture with higher structural stability.

Overall, the variation in stone dust and styrofoam filler combinations had an effect on the Marshall Quotient (MQ) values of the AC-WC mixtures; however, all variations still met the specification requirements. The ABS-3 mixture showed the best performance in terms of MQ value, indicating a greater potential to provide better resistance to permanent deformation in the pavement layer.

4.7 Standard Bulk Density (Unit Weight)

Bulk density or unit weight of the asphalt mixture is a parameter that indicates the density level of the asphalt mixture after the compaction process. The bulk density value is influenced by aggregate gradation, asphalt content, type of additives, and the degree of compaction. The higher the bulk density value, the denser the asphalt mixture produced. The Standard Bulk Density values are presented in Table 10 below.

Tabel 10. Nilai Buld Density Standar (Berat Jenis)

No	DMF Type	Test Results (gr/cc)	Specification 2018 Revisi 2 (gr/cc)
1	AB100	2,234	Tidak disyaratkan
2	ABS-1	2,236	
3	ABS-2	2,242	
4	ABS-3	2,252	

Source: Analysis Results

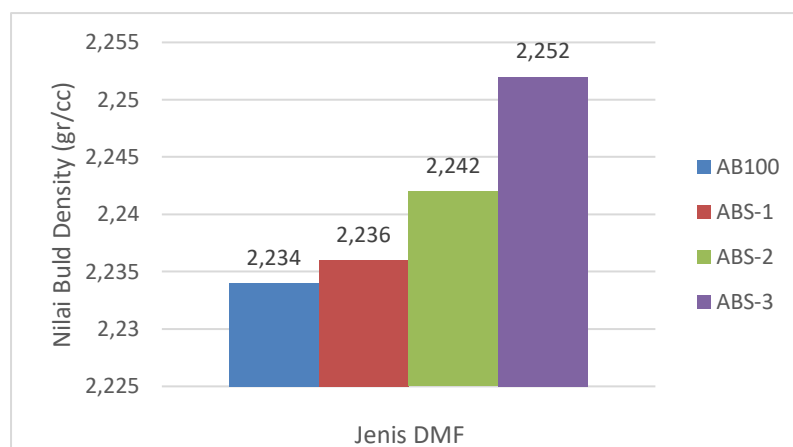


Figure 7. Bulk Density Values of Stone Dust and Styrofoam Filler

Based on the Marshall test results of AC-WC mixtures with variations in stone dust and styrofoam filler combinations shown in Table 10, the Standard Bulk Density (unit weight) values ranged from 2.234 gr/cc to 2.252 gr/cc. According to the General Specification of Bina Marga 2018 Revision 2, the bulk density parameter is not specifically required, but it is still used as an indicator of mixture density and compaction quality. The AB100 mixture produced a bulk density value of 2.234 gr/cc, indicating the density level of the mixture using 100% stone dust filler. In the ABS-1 mixture, the bulk density slightly increased to 2.236 gr/cc, indicating that the addition of 25% styrofoam began to contribute to an increase in mixture density.

Furthermore, in the ABS-2 mixture, the bulk density increased to 2.242 gr/cc. This increase indicates that a balanced proportion of stone dust and styrofoam was able to produce a more compact arrangement of aggregates and filler. In the ABS-3 mixture, the bulk density reached 2.252 gr/cc, which is the highest value among all mixture variations. This result indicates that a higher proportion of styrofoam was able to further increase the density of the AC-WC mixture. Overall, the variation in stone dust and styrofoam filler combinations shows a tendency to increase bulk density as the styrofoam content increases. Although this parameter is not specifically limited by specifications, the increase in mixture unit weight indicates a denser mixture, which has the potential to improve the stability and durability of the AC-WC pavement.

5. Conclusions and Recommendations

5.1 Conclusions

Based on the test results obtained, the following conclusions can be drawn:

1. Based on the Marshall characteristics of the Asphalt Concrete Wearing Course (AC-WC) mixture using a combination of stone dust filler and styrofoam, it was found that all mixture variations had the same Optimum Asphalt Content (OAC) of 5.90%. The addition of styrofoam in the mixture tended to increase mixture density, reduce air voids (VIM), and increase VFA values, resulting in a denser and stiffer mixture.
2. The test results showed that the ABS-3 mixture provided the best performance, with the highest Bulk Density, VFA, and Marshall Quotient (MQ) values, as well as stability values that were nearly equal to the standard mixture. In addition, the lower flow value indicates that the mixture has good stiffness. Therefore, the combination of 25% stone dust filler and 75% styrofoam (ABS-3) is considered the most optimal mixture variation and has the potential to be used as an alternative AC-WC mixture that is more effective and environmentally friendly.

5.2 Recommendations

Based on the results of this study, the following recommendations can be proposed for future research:

1. The ABS-3 mixture variation can be considered as an alternative AC-WC mixture because it provides optimal Marshall characteristics.
2. Further research is needed on the durability of the mixture under field conditions and long-term traffic loading.
3. The utilization of styrofoam waste in asphalt mixtures should be further developed to reduce environmental pollution.

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