Research Inventy: International Journal of Engineering and Science
Vol.16, Issue 7 (July 2026), PP 08-21
Issn (e): 2278-4721, Issn (p):2319-6483, www.researchinventy.com

Marshall Performance Analysis Of AC-WC Asphalt Mixture with Polypropylene Plastic Waste as A Substitution Material for Fine Aggregate

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Abstract: *This study is motivated by two major issues, namely the increasing volume of plastic waste every year and the limitations of natural aggregates for road infrastructure. The main objective is to analyze the effect of Polypropylene plastic waste substitution on the Marshall performance characteristics of AC-WC mixtures. The methodology of this study is an experimental approach carried out in the laboratory, focusing on various percentages of PP plastic substitution as a substitute for fine aggregate. Marshall test is used to evaluate the main performance parameters, namely Stability, Flow, VIM (Void in Total Mix), VMA (Void in Mineral Aggregate), VFA (Void Filled in Asphalt), and MQ (Marshall Quotient). The main findings of this study indicate that increasing PP substitution generally leads to an increase in stability, Flow, and VIM while VMA, VFA, and MQ tend to decrease. The Optimum Asphalt Content (OAC) value obtained decreased along with increasing PP content, namely 6.25% (PP 0%), 6.10% (PP 10%), 6.0% (PP 20%), 5.97 (PP 30%) and 5.95% (PP 40%). The increase in PP content caused the stability value to increase from 1,046 kg to 1,412 kg. Flow increased from 3.02 mm to 3.88 mm, and VIM increased from 3.82% to 4.95. Conversely, the VMA value decreased from 16.77% to 15.14%, VFA decreased from 77.24% to 67.38% and MQ increased from 347 kg/mm to 364 kg/mm. Based on the 2025 Bina Marga Specifications, a mixture with 10% - 40% PP substitution meets all Marshall parameters, while 50% PP does not meet KAO requirements, so it is not recommended for use in Modified AC-WC mixtures.*
Keywords: *AC-WC, Polypropylene, Subtitusi Agregat Halus, Karakteristik Marshall, Kadar Aspal Optimum.*

Date of Submission: 02-07-2026 Date of Acceptance: 11-07-2026

I. INTRODUCTION

Road improvement and maintenance require pavements that provide safety and comfort for road users. In Indonesia, one of the most widely used types of pavement is the flexible asphalt concrete wearing course (AC-WC). The performance of the AC-WC mixture is greatly influenced by the characteristics of its constituent materials, particularly the aggregate and asphalt (Kementrian Pekerjaan Umum, 2025). However, the availability of quality natural aggregates is increasingly limited, while over-exploitation has the potential to cause environmental damage.

Aggregates are a natural resource as the main construction material which has a very high per capita consumption rate in the world (Franesqui et al., 2023). The increasing demand for natural resources, amidst the increasingly limited availability of these materials, is one of the main challenges facing the asphalt pavement industry in the construction and maintenance of road infrastructure throughout the world (You et al., 2022). In the coastal area of Palu – Donggala along approximately 19 km, there are 97 mining companies operating in an area of approximately 1,700 hectares. A total of 33 C mining business permits covering an area of approximately 540 hectares are conducting mining in the mountains only 100 – 200 meters from the national road and residential areas. According to the Central Sulawesi BPJN, C mining materials are transported daily through national roads, thus accelerating road damage and causing sedimentation in drainage channels. This causes the community to live side by side with dust, bear the impact of flooding, road damage, and the cliffs of former C mining areas that are getting closer are putting pressure on the availability of community living space (Beritapalu, n.d.).

On the other hand, the increasing production of plastic waste has become one of the significant environmental problems worldwide (Lee et al., 2024). The increasing amount of plastic waste has become a global environmental problem that has not been optimally addressed. As population growth continues, the amount of plastic waste produced each year continues to increase (Pallavi et al., 2024). According to data from the Ministry of Environment's National Waste Management System, plastic waste is the second largest type of waste after food waste, accounting for 20.07% of the total waste volume. In Palu City, the waste volume in 2025 reached 79,726.96 tons, with 10.43% of the total plastic content. This high volume of plastic is a concern because plastic is difficult to decompose naturally (Kementrian Lingkungan Hidup Deputi Bidang Pengelolaan Sampah, 2024).

The increase in plastic waste production is a global environmental challenge because most plastics are not biodegradable and can persist in the environment for hundreds to thousands of years (Cardoso et al., 2023). One of the most widely used types of plastic is polypropylene (PP), which is derived from household and industrial waste. PP is lightweight, dense, non-porous, and does not absorb water. It has a specific gravity of around 0.90-0.91g/cm³ and a melting point of around 160°C (Wu et al., 2025). The relatively high melting point and good mechanical properties make PP potentially useful as a substitute aggregate material in asphalt mixtures (Ma et al., 2021).

Research on the use of plastic waste in asphalt mixtures is generally still dominated by its use as an asphalt modification material (binder modifier) using the wet process and dry process methods (Xu et al., 2022), While its use as an aggregate substitute is still relatively limited, several studies have evaluated High Density Polyethylene (HDPE) plastic waste as a fine aggregate substitute and have shown quite good results (Ika Kumalaning Tias et al., 2020). Besides that (Latif & Setiawan, 2023) studied the use of HDPE and Low Density Polyethylene (LDPE) plastic waste as modification materials in AC-WC asphalt mixtures using the dry method.

However, research on Polypropylene plastic waste as a substitute for fine aggregate in AC-WC mixtures is still limited, therefore this study aims to analyze the effect of PP plastic waste as a partial substitute for fine aggregate so that it is expected to improve the performance of asphalt mixtures while reducing the impact of environmental pollution due to plastic waste.

II. RESEARCH METHODS

This research is included in the experimental research conducted in the laboratory with the aim of determining the effect of substitution of Polypropylene (PP) type plastic waste on the performance characteristics of the AC-WC (Asphalt Concrete - Wearing Course) type asphalt mixture based on the Marshall test. This research was conducted at the Laboratory UPT of the Department of Highways and Spatial Planning of Central Sulawesi Province, Jl. Towua No. 85 Palu City. All data obtained from this research will be processed using Microsoft Excel software, then presented in the form of tables and graphs. In addition, the analysis of the distribution and area of PP distribution in the mixture will be carried out using ImageJ software, while the microstructural characteristics will be observed using SEM (Scanning Electron Microscope) testing to support the interpretation of the performance of the AC-WC mixture..

2.1 Aggregate

Aggregate is a mineral material that makes up most of the volume of hot asphalt mix, ranging from 90% to 95% of the total material, so its physical and mechanical quality greatly determines the overall performance of the road pavement (Sakthivel et al., 2022)

The aggregates used in this study consisted of coarse aggregates of crushed stone 3/4, crushed stone 3/8, and fine aggregates of stone ash originating from the Watusampu quarry, Palu City. Aggregate sampling was carried out using a simple random sampling method at 3 different points using a shovel and placed in a sack-shaped container according to their respective fractions. The collected aggregates were then taken to the laboratory for testing in accordance with the applicable SNI or ASTM to ensure the suitability of the aggregates for use as AC-WC mixtures.

2.2 Asphalt

60/70 penetration asphalt was chosen as the binder in the hot asphalt mix because it meets the requirements of the General Bina Marga Specifications and is recommended as a binder for Asphalt Concrete (AC) mixes (Fadilah et al., 2024).

The asphalt used in this study was 60/70 penetration asphalt produced by PT Pertamina and obtained from the Central Sulawesi Provincial Highways and Spatial Planning Agency Laboratory. Sampling was carried out by taking material from the center of the storage container, either a tank or drum, after the asphalt was mixed until homogeneous. Samples were taken using clean, dry, heat-resistant metal tools to avoid contamination. The collected asphalt was then placed in a clean, tightly closed metal container, labeled with the sample's identity, and prepared for laboratory testing. Laboratory testing was conducted in accordance with the applicable Indonesian National Standard (SNI) to assess whether the asphalt met the technical specifications required for use in asphalt mixtures.

2.3 Polypropylene (PP)

Polypropylene (PP) is a widely used type of plastic due to its low weight, good chemical resistance, and relatively strong mechanical properties. Furthermore, PP is easily processed at high temperatures without significant damage, making it suitable for a variety of engineering applications (Maddah, 2016).

The polypropylene plastic used in this study was recycled in the form of pellets measuring 2.38 mm or passing through sieve No. 4 and retained by sieve No. 8. Then, melting point and specific gravity tests were carried out to determine the properties of the plastic before being mixed into the asphalt mixture.

Figure 1. Polypropylene plastic pellets

III. RESULTS AND DISCUSSIONS

3.1 Material Testing Results

1. Aggregate

Table 1. Aggregate Test Results

Testing	Test Method	Results			Unit	Condition	Information
Abrasion with *Los Angeles machine*	SNI 2417: 2008	0.1 mm			20.44	Max. 30	**Met the requirements**
Specific gravity and absorbency of coarse and fine aggregates	SNI 1969 : 2026 SNI 1979 : 2016	Fraction 3/4	Fraction 3/8	Stone Ash			**Met the requirements**
		2,79	2,75	2,63			
Percentage of material passing sieve No. 200 (0.075 mm)	SNI C117:2012	0.72	0.51	6.02	%	Gross Agg. Max. 1 Fine Ag Max 10	**Met the requirements**
Aggregate adhesion to asphalt	SNI 2439:2011	> 95			%	Min. 95	**Met the requirements**
Flatness and ovality	SNI 8287: 2016	2.65			%	Max. 10	**Met the requirements**
Rough angularity	SNI 7619:2012	100/96			%	95/90	**Met the requirements**
Smooth angularity	SNI 03-6877-2002	46.2			%	Min. 45	**Met the requirements**
Sand Equivalent	SNI 03-4428-1997	89.0				<60	**Met the requirements**
Soundness	SNI 3407: 2008	1.74			%	<10	**Met the requirements**

2. Asphalt

Table 2. Asphalt Test Results

Testing	Test Method	Unit	Results	Condition	Information
Penetration	SNI 2456:2011	0.1 mm	64.0	60-70	**Met the requirements**
Softening Point	SNI2434:2011	°C	48.63	>48	**Met the requirements**
Ductility	SNI 2432:2011	cm	>100	>100	**Met the requirements**
Asphalt Specific Gravity	SNI 2441:2011	gr/cm ^{3}	1,025	>1	**Met the requirements**
Flash point and fire point	SNI 2433:2011	°C	282.5/313.0	>232	**Met the requirements**
Solubility in *Trichloroethylene*	SNI 06-2438-1991	%	99.38	>99	**Met the requirements**

3. Polypropylene (PP) plastic

Table 2. Polypropylene Test Results

Testing	Results
Melting point of *Polypropylene plastic*	160 °C
Specific Gravity of *Polypropylene Plastic*	0.909

3.3 Preparation of test objects

In this study, conventional AC-WC test specimens without PP mixture were prepared with asphalt content variations of 4.5%, 5%, 5.5%, 6%, and 6.5%, each consisting of three specimens. Next, modified AC-WC test specimens were prepared using polypropylene plastic as a substitute for fine aggregate that passed sieve No. 4 and retained sieve No. 8, with substitution variations of 10%, 20%, 30%, 40%, and 50% of the aggregate weight retained on sieve No. 8. Three specimens were prepared for each substitution level of polypropylene (PP) plastic and asphalt content. Because the use of this plastic causes differences in specific gravity with fine aggregate, a specific gravity correction is required before determining the asphalt mixture proportions.

The asphalt mixing process is carried out using the dry method. The dry method (dry process) is the simplest technique and can be applied using technology available in the laboratory (Miranda et al., 2023). The aggregate is heated to the specified mixing temperature, then the asphalt is added and mixed until homogeneous, before the heated asphalt is added to the mixture and the mixture reaches the mixing temperature. Then all test objects were compacted using a Marshall Automatic Compactor according to standard provisions with a total of 75 impacts on each side (2x75 impacts). (SNI 2489 : 2018)

3.4 Marshall Test Results

Table 1. Marshall Test Results

Marshall performance		AC-WC Specifications	Asphalt Content	*Polypropylene* (PP) Plastic					
			%	0%	10%	20%	30%	40%	50%
Density	gr/cm ^{3}	Min. 2	4.5	2,317	2,272	2,212	2,155	2,098	2,045
			5.0	2,328	2,277	2,215	2,160	2,103	2,051
			5.5	2,311	2,284	2,222	2,168	2,110	2,057
			6.0	2,335	2,290	2,228	2,170	2,115	2,060
			6.5	2,337	2,294	2,234	2,178	2,119	2,070
VMA	%	Min.15	4.5	16.0	15.1	14.9	14.7	14.6	14.5
			5.0	16.1	15.4	15.2	14.9	14.8	14.7
			5.5	16.4	15.5	15.4	15.0	15.0	14.9
			6.0	16.7	15.8	15.6	15.4	15.2	15.2
			6.5	17.1	16.1	15.8	15.5	15.5	15.2
VIM	%	3-5	4.5	7.0	7.1	7.2	7.4	7.4	7.9
			5.0	5.9	6.2	6.5	6.5	6.6	7.1
			5.5	5.1	5.2	5.5	5.6	5.7	6.2
			6.0	4.2	4.3	4.6	4.9	4.9	5.5
			6.5	3.4	3.5	3.7	3.9	4.1	4.5

Marshall performance		AC-WC Specifications	Asphalt Content	*Polypropylene* (PP) Plastic					
			%	0%	10%	20%	30%	40%	50%
VFA	%	Min. 65	4.5	56.0	53.9	52.4	49.9	48.9	46.0
			5.0	63.1	60.4	59.7	56.2	55.2	52.2
			5.5	68.9	66.3	65.5	63.1	61.7	58.6
			6.0	74.7	72.5	70.4	68.4	67.6	64.5
			6.5	79.8	78.6	76.9	75.0	73.4	70.6
Stability	Kg	Min. 800	4.5	1092	1,191	1,250	1,267	1,272	1,286
			5.0	1,176	1,266	1,316	1,340	1,390	1,438
			5.5	1,211	1,329	1,495	1,546	1,569	1,594
			6.0	1,075	1,226	1,343	1,380	1,424	1,441
			6.5	1,022	1,138	1,288	1,328	1,379	1,404
Flow	Mm	2-4	4.5	2.00	2.40	2.63	2.92	3.09	3.37
			5.0	2.17	2.73	3.07	3.19	3.42	3.74
			5.5	2.72	3.07	3.57	3.76	3.84	4.13
			6.0	2.87	3.31	3.67	3.81	3.99	4.51
			6.5	3.17	3.68	4.30	4.58	4.87	5.03
MQ	Kg/mm	>250	4.5	546.89	503.75	476.71	434.01	412.51	391.12
			5.0	542.75	480.09	429.18	420.78	406.71	393.75
			5.5	445.58	432.54	419.24	411.41	408.33	385.67
			6.0	375.04	370.24	366.49	362.09	356.70	319.55
			6.5	322.87	309.75	299.75	289.94	283.54	279.01

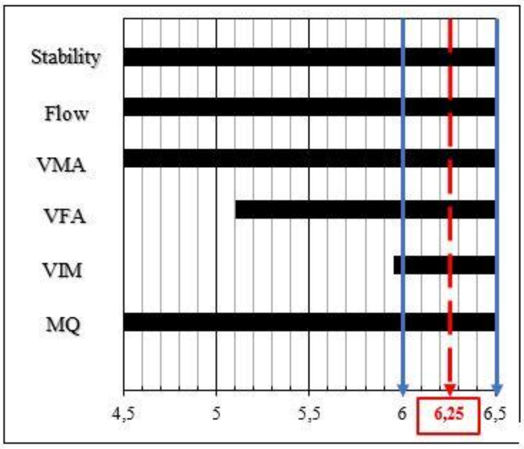


Figure 2. Graph for determining KAO PP 0%

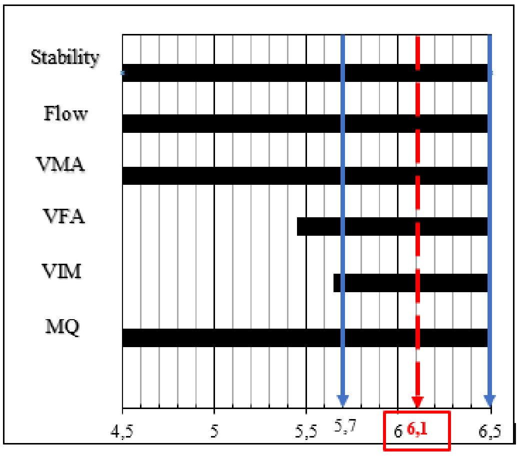


Figure 3. Graph for determining KAO PP 10%

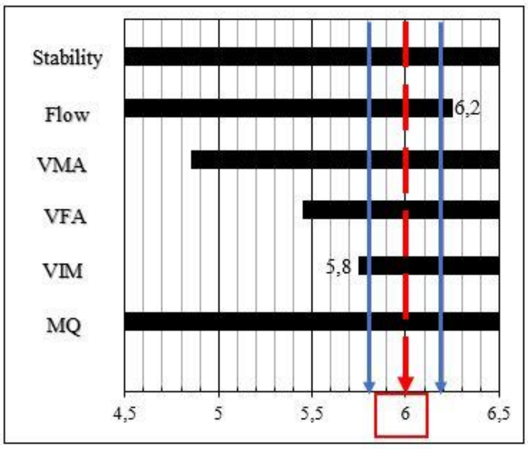


Figure 4. Graph for determining KAO PP 20%

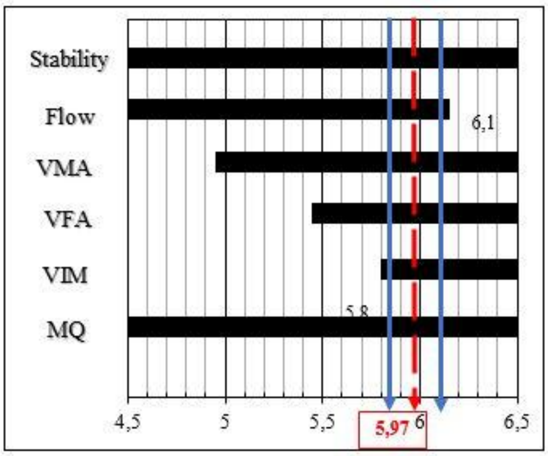


Figure 5. Graph for determining KAO PP 30%

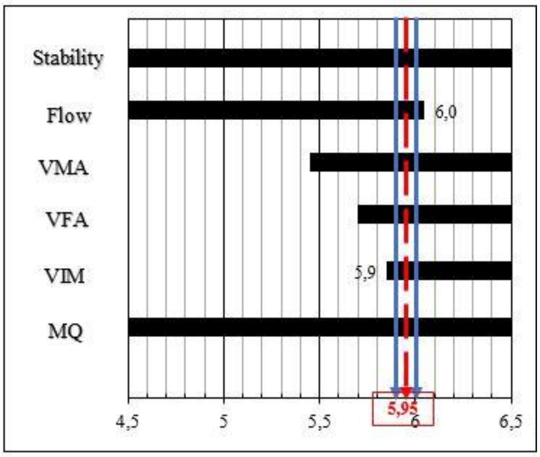


Figure 6. Graph for determining KAO PP 40%

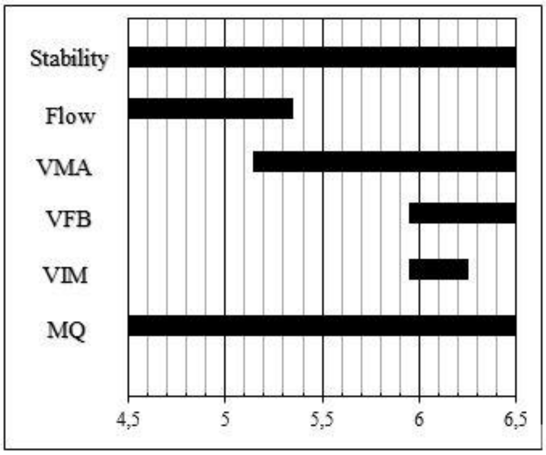


Figure 7. Graph for determining KAO PP 50%

The Optimum Asphalt Content (OAC) value was obtained for each variation of *Polypropylene substitution content* of PP 0% = 6.25, PP 10% = 6.10%, PP20% = 6.0%, PP 30% = 5.97%, and PP 40% = 5.95. Meanwhile, for PP 50% there was no Optimum Asphalt Content (OAC) value because there was no intersection area that met all *Marshall parameter specifications.* This could be caused by the high plastic content that affected the aggregate composition and asphalt distribution in the mixture. Thus, the use of PP plastic at 50% was considered less than optimal because several *Marshall parameters* did not meet the applicable requirements.

After the Optimum Asphalt Content (OAC) value is obtained, the test specimen is remade using that asphalt content using the same procedure as in the previous *Marshall test stage* . The results of the *Marshall test* on OAC are presented in the following table :

Table 2. Marshall Test Results on Optimum Asphalt Content (OAC)

***Marshall's* Traits**	**Unit**	**Plastic Substitution**					**Specification AC Mod**
		PP 0%	**PP 10%**	**PP 20%**	**PP 30%**	**PP 40%**	
OAC	%	6.25	6.10	6.00	5.97	5.95	
VMA	%	16.77	15.86	15.61	15.41	15.14	Min. 15
VIM	%	3.82	4.18	4.62	4.97	4.94	3 – 5
VFA	%	77.24	73.64	70.39	67.76	67.38	Min. 65
Stability	Kg	1046	1179	1345	1376	1412	Min 1000
Flow	mm	3.02	3.41	3.65	3.74	3.88	2 - 4
MQ	Kg/mm	347	346	366	367	364	>250

3.5 Marshall Characteristics

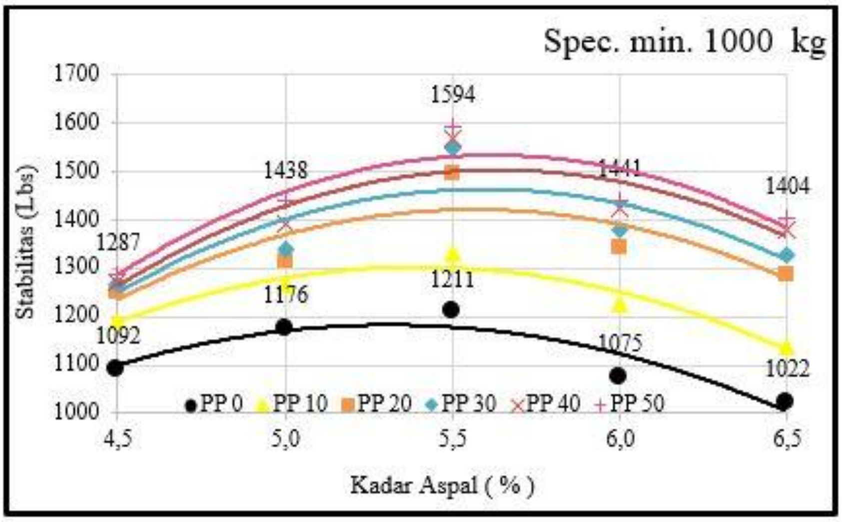


Figure 8. Marshall Stability Value Trend Graph

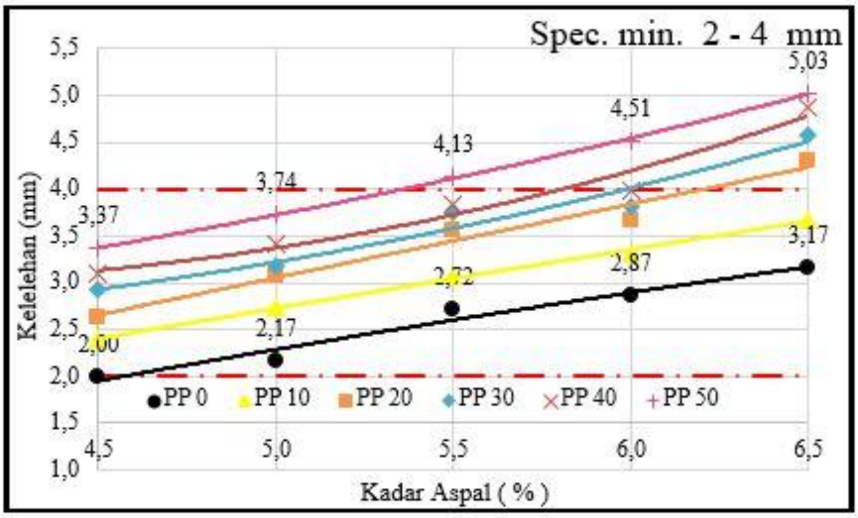


Figure 9. Flow Value Trend Graph

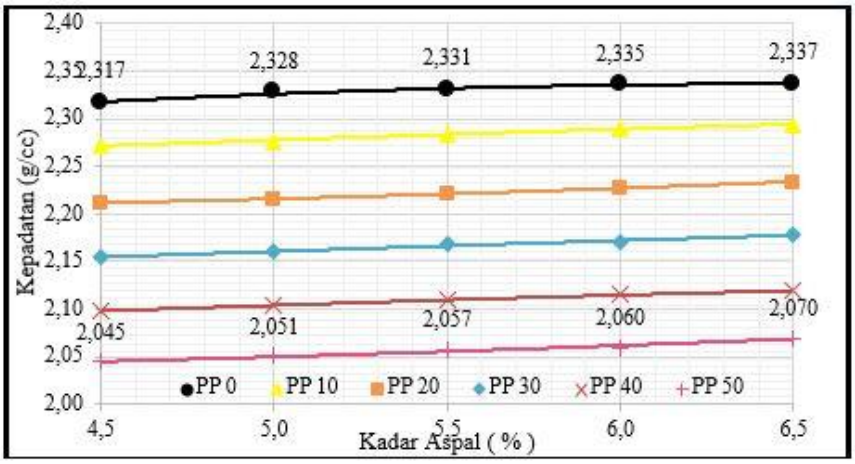


Figure 10. Density value trend graph

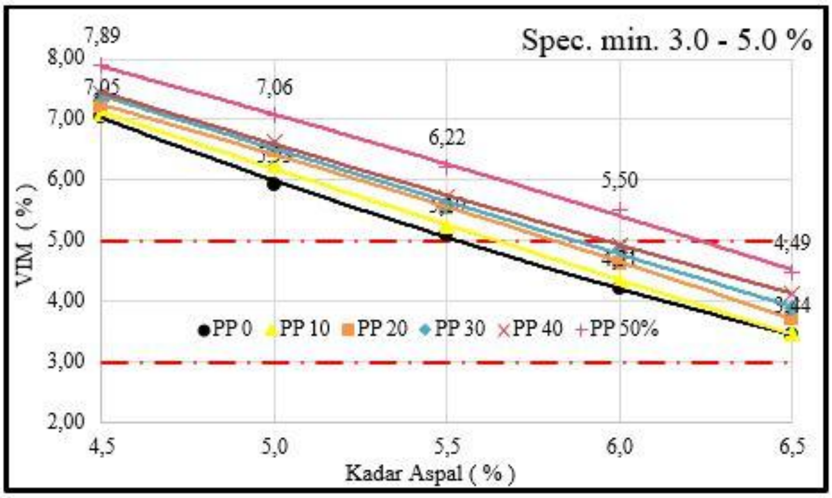


Figure 11. VIM Value Trend Graph

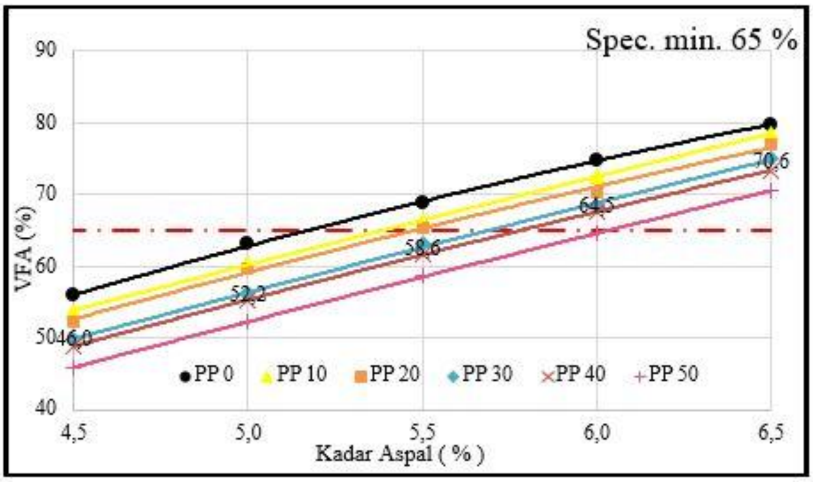


Figure 12. VFA Value Trend Graph

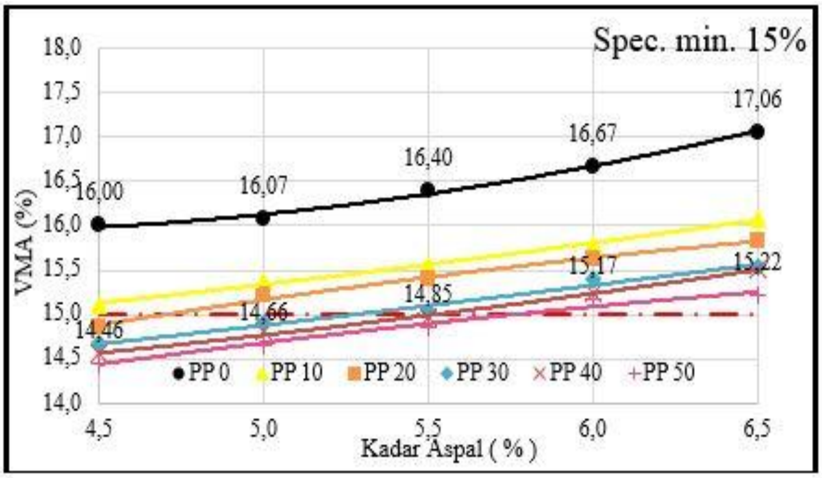


Figure 13. VMA Value Trend Graph

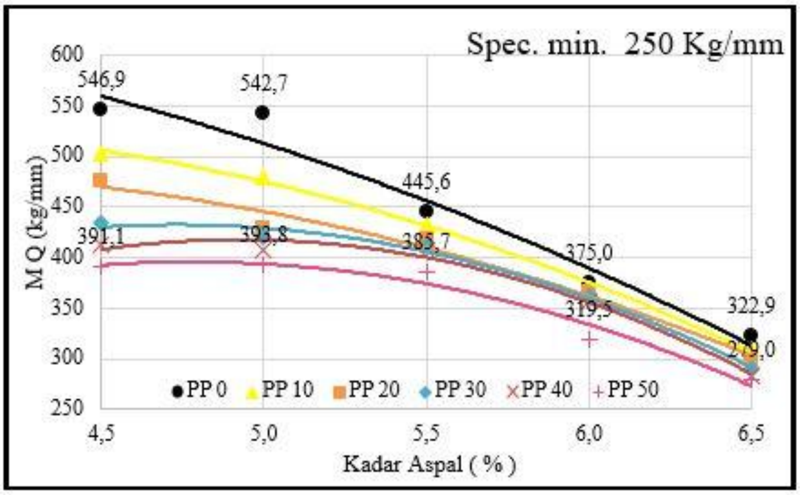


Figure 13. MQ Value Trend Graph

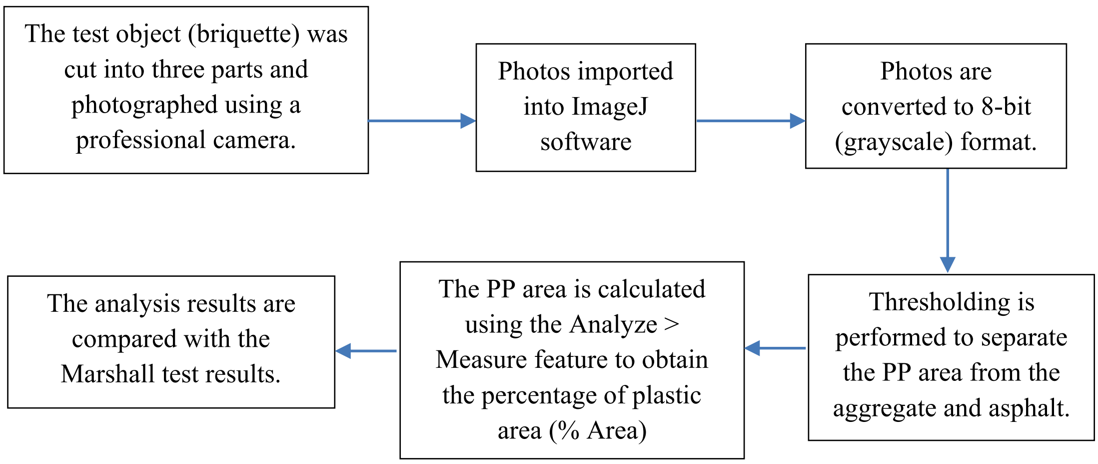
Based on the Marshall characteristic value trend graph, it shows that increasing the PP substitution level affects mechanical performance and volumetric parameters. In mechanical performance parameters, the stability and flow values tend to increase, indicating that the mixture has better load-bearing capacity, flexibility, and stiffness. Meanwhile, in volumetric parameters, increasing the PP content causes density, VMA, and VFA to decrease, while the VIM value increases due to the lower weight of PP compared to natural aggregates. This is in line with research conducted by (Tambunan, 2021) who reported that increasing the percentage of PP can increase the stability and melting values.

3.6 Visual Analysis of Polypropylene (PP) Distribution using ImageJ

ImageJ is open-source software widely used for digital image visualization, processing, and analysis. It offers various features for measuring, segmenting, and quantifying objects in images, making it widely used in various research fields (Schroeder et al., 2021).

To support the Marshall test results, image analysis was performed using ImageJ software to identify and calculate the plastic area within the cross-section of the AC-WC test specimen.

The image analysis steps using ImageJ are as follows:



The identification results for each variation in PP content are shown in the following image:

Figure 14 Results of image analysis of AC-WC cross-section with 10% PP substitution

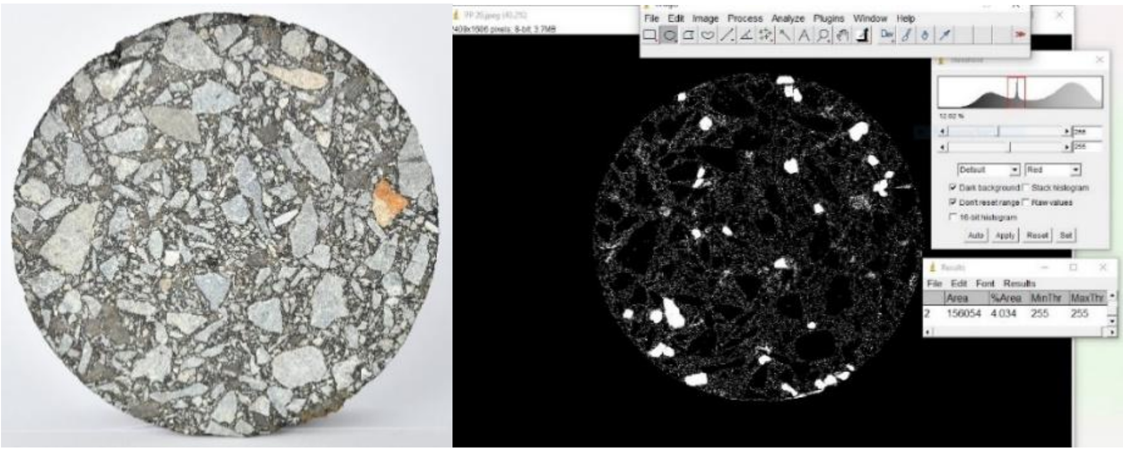


Figure 15 Results of image analysis of AC-WC cross-section with 20% PP substitution

Figure 16 Results of image analysis of AC-WC cross-section with 30% PP substitution

Figure 17 Results of image analysis of AC-WC cross-section with 40% PP substitution

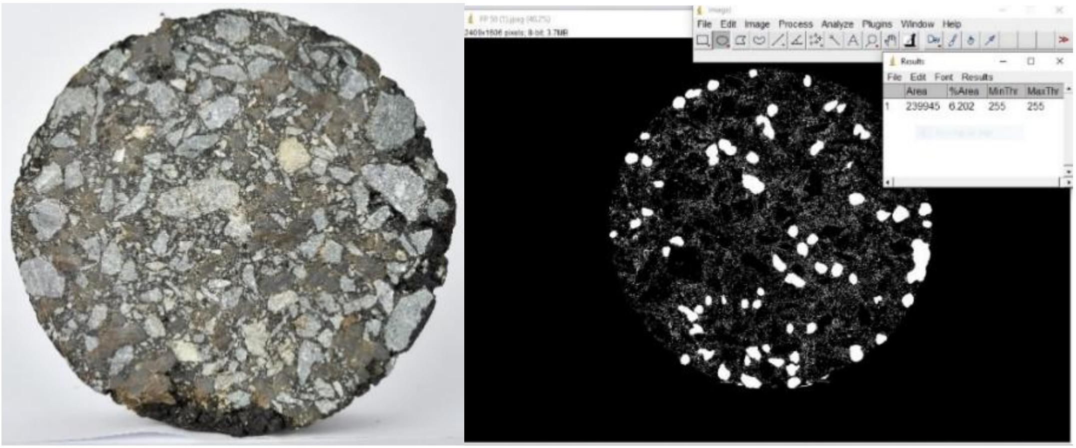


Figure 18 Results of image analysis of AC-WC cross-section with 50% PP substitution

Based on the results of image analysis using ImageJ, the percentage of PP area in the cross-section of the test specimens increased with increasing polypropylene substitution levels in the AC-WC mixture, from 2.717% (PP 10%) to 4.034% (PP 20%), 5.962% (PP 30%), 6.813% (PP 40%), and 8.550% (PP 50%). These results indicate that the higher the PP content used as a fine aggregate substitute, the greater the PP area distributed within the mixture structure.

At PP levels of 10–20%, the small PP area indicates its insignificant effect on the Marshall characteristics. At PP levels of 30–40%, the PP distribution becomes more even, thus positively contributing to the internal structure of the mixture. However, at PP levels of 50%, the excessively large PP area causes the mixture structure to become unbalanced, resulting in several Marshall parameters not meeting specifications, indicating that the level exceeds the optimum limit for PP use.

3.7 Microstructural Analysis using Scanning Electron Microscope (SEM)

SEM testing was conducted at the Tadulako University Integrated Laboratory. The test specimens used were Marshall's residual briquettes at 0%, 10%, and 40% PP, shaped into 1x1x1 mm cubes.

Figure 19 Test specimen for SEM test

The following presents the results of observations of the microstructure of the mixture using SEM :

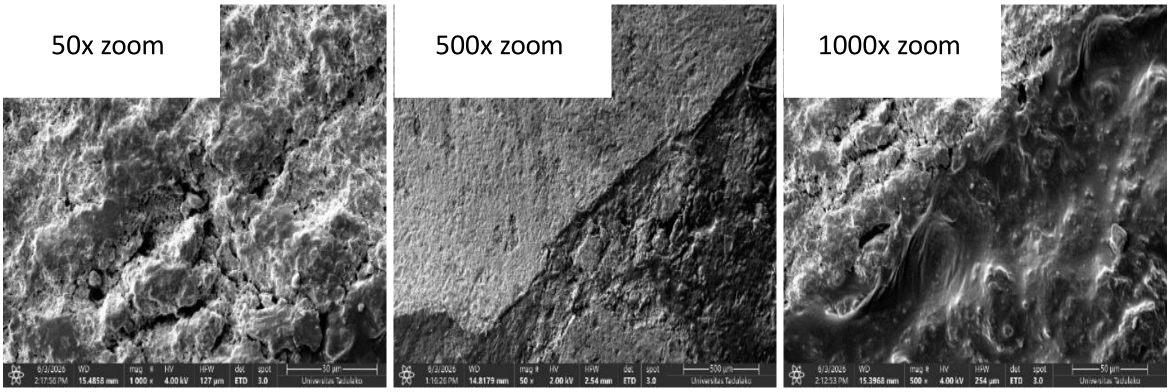


Figure 20 SEM Photo Results of AC-WC PP substitute 0%

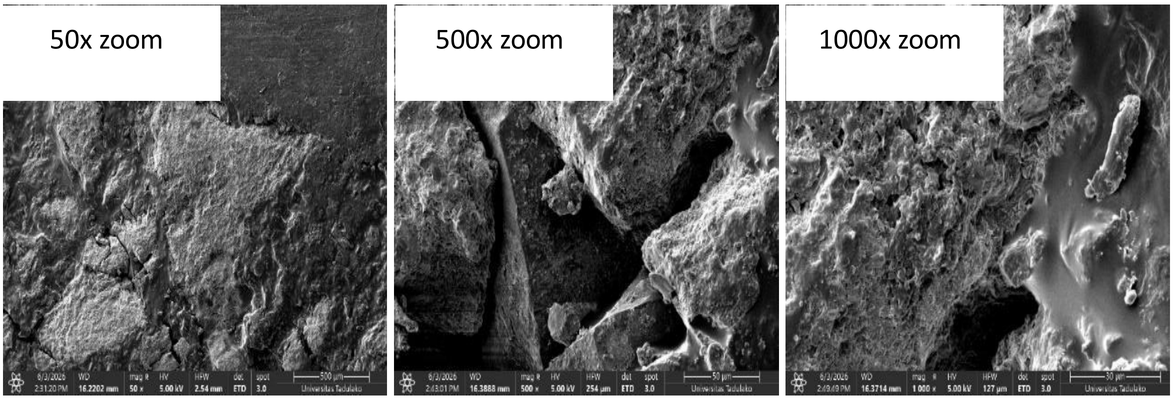


Figure 21 SEM Photo Results of AC-WC PP substitute 10%

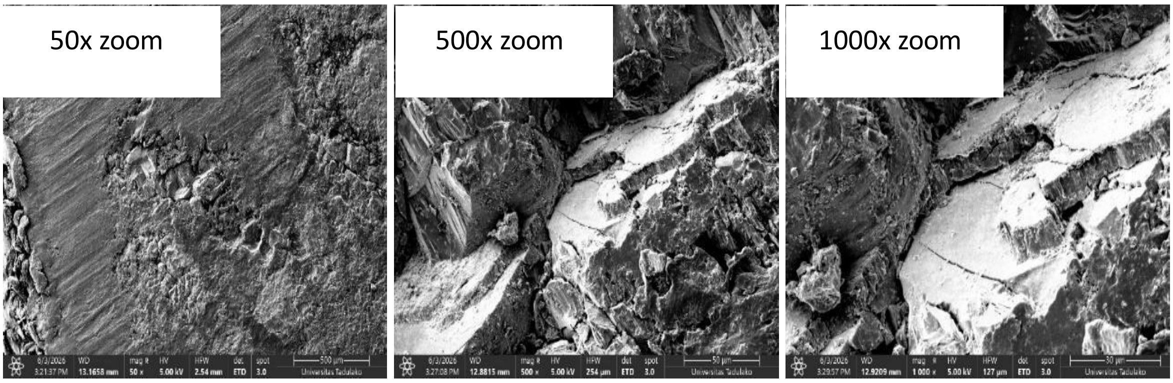


Figure 22 SEM Photo Results of AC-WC PP substitute 40%

Overall, increasing PP content from 0% to 40% shows gradual morphological changes, starting from a homogeneous and porous asphalt-aggregate matrix at 0% content, developing into a matrix with PP particles functioning as void fillers at 10% content, and finally forming a structure dominated by PP particles as reinforcing elements at 40%. These morphological changes show a consistent relationship with the increasing trend in Marshall stability values. These findings indicate that the use of PP plastic waste as a substitute material in the fine aggregate fraction provides a positive contribution to increasing the Marshall stability of AC-WC mixtures, especially up to a substitution content of 40%.

IV. CONCLUSION

This study shows that the use of polypropylene (PP) plastic waste as a partial substitute for fine aggregate in AC-WC mixtures significantly impacts Marshall characteristics. Increasing the PP content decreases the Optimum Asphalt Content (OAC) from 6.25% in mixtures without PP to 5.95% with 40% PP substitution. PP substitution of up to 40% improves the mechanical performance of the mixture, as indicated by an increase in the stability value from 1,046 kg to 1,412, the yield strength from 3.02 mm to 3.88 mm, and the Marshall Quotient (MQ) from 347 kg/mm to 364 kg/mm. Conversely, increasing the PP content decreases the VMA and VFA values, and the VIM increases due to the lower specific gravity of PP compared to natural aggregate.

All Marshall parameters at PP substitution levels of 10% to 40% still meet the requirements of the 2025 General Highways Specifications.

Image analysis using ImageJ shows that the higher the PP content, the greater the PP distribution area within the mixture. A more even distribution at levels of 30-40% correlates with improved Marshall characteristics, while excessive PP distribution at levels of 50% leads to an imbalance in the mixture's internal structure. These findings are supported by SEM observations, which indicate that PP particles act as both void fillers and reinforcing elements in the asphalt-aggregate matrix, resulting in a denser structure and increased mixture stability up to a substitution level of 40%.

Overall, polypropylene plastic waste has the potential to be used as a fine aggregate substitute in AC-WC mixtures, with an optimum substitution level of 40%. This is because it can improve Marshall performance while supporting efforts to reduce the use of natural aggregates and the sustainable use of plastic waste.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to all fellow researchers for their cooperation, assistance, and valuable contributions throughout this research. They also express their deepest appreciation to their academic supervisors for their guidance, constructive suggestions, and continued support throughout the research process. Furthermore, special thanks are extended to the laboratory and laboratory staff who supported this research by providing the necessary facilities, equipment, and technical assistance.

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