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Integrated Mechanical and Volumetric Evaluation of Plastic Modified RAP Mixtures Using Marshall Parameters

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ABSTRACT: This study investigates the combined influence of plastic waste modification and centrifugal extraction on the mechanical and volumetric performance of reclaimed asphalt pavement (RAP) mixtures. Five plastic types (LDPE, HDPE, PET, PP, and PVC) were incorporated at 0–8% by asphalt weight, and performance was evaluated through standardized centrifugal extraction and Marshall testing in accordance with Bina Marga 2018. Extracted asphalt contents ranged from 4.22% to 5.87%, demonstrating reliable binder recovery within the RAP system. Plastic incorporation significantly improved mechanical performance, with maximum Marshall stability reaching approximately 1300 kg and Marshall Quotient exceeding 350 kg/mm, indicating enhanced stiffness and deformation resistance. Despite increased rigidity, flow values remained within the specified 2–4 mm range, and density values (2.28–2.33 g/cm³) showed minimal variation, confirming stable compaction behavior. Volumetric parameters generally complied with specification limits, although higher plastic contents slightly affected air void balance. Moderate plastic contents (4–6%) provided the most balanced performance. The findings establish a comprehensive framework for evaluating plastic–RAP interaction and demonstrate the technical feasibility of integrating plastic waste into RAP mixtures for sustainable pavement applications.

KEYWORDS: RAP, Plastic Modification, Marshall Properties, Volumetric Performance, Pavement Engineering.

I. INTRODUCTION

Flexible pavement systems continue to be widely implemented in road infrastructure because of their ease of construction, adaptability to various site conditions, and cost effectiveness. Nevertheless, their long-term performance is increasingly affected by rising traffic volumes and axle loads, as well as climate-induced aging that accelerates material deterioration over time [1], [2]. Elevated service temperatures accelerate rutting and binder softening, while oxidative aging contributes to stiffness increase and cracking susceptibility over time [3]. These combined mechanical and environmental stresses demand more durable and sustainable asphalt mixtures capable of maintaining structural stability throughout their service life. Reclaimed Asphalt Pavement (RAP) has become a widely adopted strategy to reduce the consumption of virgin aggregates and asphalt binder while minimizing environmental impacts and construction costs [4], [5]. The incorporation of RAP aligns with circular economy principles and sustainable pavement engineering practices. Nevertheless, RAP contains aged asphalt binder that has undergone oxidation, resulting in increased stiffness and reduced ductility [6]. Without proper evaluation and adjustment, the presence of aged binder may compromise cracking resistance and mixture durability [7].

Accurate determination of asphalt content and binder distribution in RAP mixtures is therefore critical for quality control and performance prediction. Asphalt extraction testing remains a fundamental procedure in assessing RAP materials, with centrifugal extraction methods commonly used due to their operational efficiency and limited thermal impact compared to ignition methods [8], [9]. However, binder recovery accuracy can be influenced by solvent selection, binder modification, and material heterogeneity. The interaction between aged RAP binder and modified binder during extraction has not been sufficiently clarified in the literature, particularly when polymer or plastic modifiers are incorporated [10].

In parallel, plastic waste modification of asphalt mixtures has received considerable research attention as a dual-benefit approach to enhance mechanical performance while mitigating plastic pollution [11]. Previous studies have demonstrated that plastics such as LDPE, HDPE, PET, PP, and PVC can improve stability, stiffness, and resistance to permanent deformation by altering binder rheology [12]. Despite these findings, most investigations focus on conventional hot mix asphalt without RAP or examine a single plastic type, limiting comparative evaluation under consistent experimental conditions [13].

Furthermore, limited research has systematically examined the combined influence of plastic type and dosage on both asphalt extraction characteristics and Marshall performance within RAP systems. The influence of plastic modified binders on asphalt recovery behavior, mixture homogeneity, and stability, flow balance during centrifugal extraction remains inadequately documented [14]. This methodological gap restricts the development of reliable technical guidance for integrating plastic waste into RAP mixtures under standardized testing procedures. Therefore, this study aims to systematically evaluate plastic-modified RAP mixtures using a standardized centrifugal extraction approach combined with Marshall mechanical and volumetric analysis [15]. The effects of LDPE, HDPE, PET, PP, and PVC at varying contents are investigated in terms of asphalt content recovery, stability, Marshall Quotient, flow, density, and volumetric properties. By integrating extraction evaluation with mechanical performance assessment, this research contributes to a clearer understanding of plastic–RAP interaction and provides technical insight for sustainable pavement applications.

II. MATERIALS AND METHODS

This study employed a controlled laboratory experimental program to evaluate asphalt content recovery using centrifugal extraction and the mechanical–volumetric performance of plastic-modified reclaimed asphalt pavement (RAP) mixtures.

A. Research Design

This study employed an experimental laboratory approach to evaluate the effects of plastic waste modification on reclaimed asphalt pavement (RAP) mixtures and to assess asphalt content recovery using a centrifugal extraction method. The experimental framework was designed to ensure repeatability and comparability by applying consistent procedures, controlled variables, and standardized testing protocols in accordance with Bina Marga 2018 specifications.

B. Material

Reclaimed Asphalt Pavement (RAP) materials used in this study were obtained from patching works on the Medan–Banda Aceh National Road, located in Gampong Baroe, Peusangan District, Bireuen Regency. The RAP was collected in chunk form (approximately 20 × 15 cm) and subsequently crushed into smaller sizes to facilitate processing and testing. Asphalt separation from the aggregate was performed using a centrifugal extraction method, with pertalite employed as a solvent to assist in effective binder separation [16].

Virgin aggregates (coarse and fine) were supplied by PT. Takabeya to improve mixture gradation, while penetration grade 60/70 asphalt binder produced by PT. Shell Bitumen was used as the base binder for modification. Portland cement (Padang brand) was incorporated as filler to enhance mixture stability and density. Five types of plastic waste LDPE, HDPE, PET, PP, and PVC were used as asphalt modifiers and incorporated at contents of 0%, 2%, 4%, 6%, and 8% by weight of asphalt [13]. Prior to mixing, all plastic materials were cleaned, dried, and prepared to ensure uniform dispersion during the modification process. All experimental procedures were conducted in the Road Pavement Laboratory, Faculty of Engineering, Universitas Almuslim.

C. Aggregate and Asphalt Characterization

Aggregate properties were evaluated through sieve analysis, specific gravity, water absorption, and abrasion tests to ensure compliance with specification limits. Asphalt binder tests included penetration, softening point, ductility, specific gravity, and viscosity measurements. These preliminary tests were conducted to verify material suitability before mixture preparation [17].

D. Mixture Design and Plastic Modification

The asphalt concrete wearing course (AC-WC) mixture was designed using the Marshall method. Plastic waste was incorporated into the asphalt binder at proportions of 0%, 2%, 4%, 6%, and 8% by weight of asphalt. The modified binder was prepared using a wet mixing process to ensure uniform dispersion of plastic particles within the asphalt matrix. RAP, virgin aggregates, and modified binder were then combined following the target gradation [18].

Table 1. Overall design of test specimens

No	Type Plastic	Percentage of Pastic Waste					Total
		0%	2%	4%	6%	8%	
1	LDPE	3	3	3	3	3	15
2	PET	3	3	3	3	3	15
3	PP	3	3	3	3	3	15
4	HDPE	3	3	3	3	3	15
5	PVC	3	3	3	3	3	15
Total							**75**

E. Centrifugal Extraction Test

The recovery of aged asphalt binder from RAP was performed using a centrifugal extraction method to minimize thermal degradation and preserve the chemical integrity of the binder. Prior to extraction, RAP samples were crushed to pass through a 25 mm sieve to ensure uniform particle size and efficient solvent penetration. The prepared samples were then placed into the extraction chamber of the centrifugal extractor [19].

A controlled volume of pertalite was used as the extraction solvent due to its effective dissolving capability and relatively lower volatility compared to conventional solvents such as trichloroethylene [20]. The centrifugal extractor was operated at a rotational speed of approximately 3000–3500 rpm for 30 minutes to ensure adequate separation of the asphalt binder from the aggregate matrix. During the extraction process, temperature was continuously monitored and maintained below 60 °C to prevent oxidative hardening and excessive volatilization of the binder.

Following extraction, the solvent–binder solution was collected and allowed to settle before the binder was recovered through controlled evaporation under laboratory conditions [21]. The recovered binder was subsequently filtered to remove residual fine particles and conditioned prior to further modification with plastic additives. The use of centrifugal extraction in this study was intended to enhance binder recovery efficiency, reduce chemical residue, and maintain compatibility between the aged RAP binder and plastic modifiers during subsequent blending stages.

F. Marshall Testing

Marshall tests were conducted to evaluate the mechanical performance of the mixtures. The parameters analyzed included stability, flow, density, Marshall Quotient (MQ), voids in mix (VIM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). Each test condition was replicated to ensure data reliability. The results were used to assess the influence of plastic type and content on mixture performance [22].

G. Data Analysis

Experimental data were analyzed by comparing asphalt extraction results and Marshall characteristics across different plastic types and contents. Trends in asphalt content recovery, mixture homogeneity, and mechanical performance were examined to identify optimal plastic modifiers and content ranges. All results were evaluated against Bina Marga 2018 specifications and discussed in relation to previous studies.

III. RESULTS AND DISCUSSION

This section presents the results obtained from laboratory testing and provides a comprehensive discussion of the findings. The analysis focuses on evaluating the material characteristics and their influence on mixture performance in accordance with the specified standards.

A. Test Results of Aggregate and Modified Asphalt Characteristics

The examination results showed that both coarse and fine aggregates had specific gravity values that met the required standards. Coarse aggregates exhibited relatively uniform values, while fine aggregates had higher absorption, indicating a more porous nature that could potentially increase asphalt demand in the mixture *[23]*. Overall, these conditions suggest that the aggregates used are suitable for application in asphalt mixtures as they still comply with the technical specification limits (see Table 2).

Pure asphalt and plastic modified asphalt demonstrated significant differences in their physical properties. The addition of plastic tended to increase the stiffness of the asphalt, as reflected by the decrease in penetration values [24]. In addition, the softening point increased, making the asphalt more resistant to high temperatures and plastic deformation. However, ductility decreased with higher plastic content, indicating that the asphalt became less elastic (see Table 3).

Table 2. Test results of coarse and fine aggregate physical properties

No	Physical Properties	19.1 mm (3/4")	9.5 mm (3/8")	Fine Aggregate	Req
1	Bulk specific gravity	2.633	2.626	2.565	>2.5
2	Saturated surface dry	2.661	2.656	2.609	>2.5
3	Apparent specific gravity	2.709	2.707	2.683	>2.5
4	Absorption	1.041	1.132	1.719	<3.0

Table 3. Test results of physical properties of asphalt and modified asphalt

Asphalt Physical Properties	Asphalt specific gravity (g/cm³)	Penetration (mm)	Softening point (°C)	Ductility (cm)
Aspal Pen 60/70	1,031	62	51,25	138
LDPE 2%	1,032	53,6	51,15	125
HDPE 2%	1,037	56,7	52,5	113
PP 2%	1,034	55,2	52	122
PET 2%	1,036	54	52,8	119
PVC 2%	1,038	53	53,5	116
LDPE 4%	1,035	52,4	52	122
HDPE 4%	1,038	55,1	52,8	111
PP 4%	1,039	53,1	52,9	115
PET 4%	1,041	52	53,8	113
PVC 4%	1,043	51	54,8	110
LDPE 6%	1,041	52,1	51,55	121
HDPE 6%	1,039	53,6	53,7	108
PP 6%	1,044	52	53,7	111
PET 6%	1,046	50,8	55	108
PVC 6%	1,048	49,5	56,5	105
LDPE 8%	1,048	51,8	51,85	118
HDPE 8%	1,039	52,3	54,2	103
PP 8%	1,047	50,5	54,5	106
PET 8%	1,050	49	56,2	102
PVC 8%	1,051	47,8	58	101

B. Centrifugal Extraction Results

The centrifugal extraction results in Table 4 indicate extracted asphalt contents ranging from 4.22% to 5.87%, demonstrating effective binder recovery for both conventional and plastic-modified RAP mixtures. LDPE and PET showed more consistent extraction values, while HDPE and PP exhibited greater variability at intermediate plastic contents, reflecting the influence of binder stiffness on asphalt dispersion and recovery behavior elastic (see Table 4).

Table 4. Results of Centrifugal Asphalt Content Extraction of the Mixture

Type of Plastic	Test Results				
	BU 1 (0%)	BU 2 (2%)	BU 3 (4%)	BU 4 (6%)	BU 5 (8%)
LDPE	4,74	4,37	4,69	5,87	4,83
HDPE	5,42	4,67	4,22	4,70	5,45
PP	4,64	5,78	5,74	5,59	4,88
PET	5,03	5,45	5,53	5,27	5,34
PVC	5,22	5,21	5,38	5,25	4,99

C. Marshall Characteristics

The Marshall characteristics of the plastic-modified RAP mixtures in Table 5 generally complied with Bina Marga 2018 specifications, indicating acceptable mechanical and volumetric performance.

Table 5. Marshall Characteristics of Mixtures with Centrifugal Extraction

Marshall Characteristics	0%	2%	4%	6%	8%	Type of Plastic	Spec
Stability (kg)	1156,67	1193,68	1221,44	1235,32	1281,59	LDPE	> 1000
	1133,53	1216,81	1230,69	1281,59	1300,09	PET	
	1175,17	1207,56	1221,44	1295,47	1258,45	PP	
	1128,91	1179,80	1230,69	1272,33	1244,57	HDPE	
	1138,16	1184,43	1212,19	1276,96	1235,32	PVC	
MQ (kg/mm)	356,01	482,40	485,71	461,43	458,59	LDPE	> 250
	287,14	324,10	365,76	374,87	409,26	PET	
	329,40	413,63	489,51	499,29	455,94	PP	
	301,97	318,55	361,11	359,07	347,12	HDPE	
	281,75	314,11	363,56	378,54	359,47	PVC	
Flow (mm)	3,16	2,84	2,73	2,68	2,49	LDPE	2 - 4
	3,29	2,63	2,59	2,42	2,37	PET	
	3,12	2,96	2,79	2,67	2,58	PP	
	3,69	3,64	3,53	3,15	3,42	HDPE	
	3,21	3,58	3,46	2,89	3,45	PVC	
Density (g/cm3)	2,29	2,28	2,28	2,29	2,29	LDPE	-
	2,33	2,32	2,31	2,30	2,29	PET	
	2,31	2,29	2,28	2,28	2,29	PP	
	2,33	2,31	2,31	2,30	2,29	HDPE	
	2,31	2,32	2,32	2,29	2,29	PVC	
VIM (%)	4,65	4,80	4,76	4,66	4,51	LDPE	3 - 5
	3,45	3,91	4,09	4,51	4,88	PET	
	3,31	3,95	4,43	4,56	4,12	PP	
	3,78	4,40	4,66	5,06	5,36	HDPE	
	4,19	3,90	4,06	5,10	5,24	PVC	
VMA (%)	17,05	17,19	17,15	17,07	16,93	LDPE	> 15
	15,87	16,27	16,43	16,79	17,12	PET	
	16,38	16,93	17,35	17,46	17,08	PP	
	15,53	16,07	16,31	16,65	16,91	HDPE	
	16,31	16,06	16,19	17,10	17,23	PVC	
VFA (%)	72,75	72,06	72,25	72,68	73,38	LDPE	> 65
	78,26	75,99	75,09	73,15	71,49	PET	
	79,79	76,67	74,45	73,87	75,86	PP	
	75,65	72,64	71,40	69,63	68,34	HDPE	
	74,31	75,70	74,94	70,19	69,57	PVC	

Plastic modification increased mixture stiffness and load-bearing capacity, while density remained relatively stable, confirming that performance improvements were mainly governed by binder modification rather than compaction effects.

D. Analysis of Marshall Characteristics Data

1. Effect of Plastic Content on Marshall Stability of RAP Mixtures

As illustrated in Figure 1, the Marshall stability of the plastic-modified RAP mixtures generally increases with increasing plastic content for all plastic types. All stability values exceed the minimum requirement specified by Bina Marga 2018, which requires a stability value greater than 1000 kg for AC-WC mixtures, confirming that the incorporation of plastic waste maintains adequate structural capacity. The most significant improvements are observed at 6–8% plastic content, particularly for PET and PP, indicating enhanced interaction between the modified binder and the aged binder present in RAP.

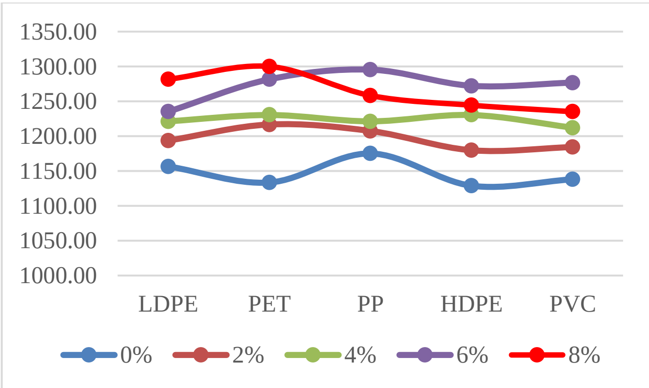

Figure 1. Marshall Stability of Plastic Modified RAP Mixtures

This improvement suggests that plastic incorporation enhances the stiffness and cohesion of the RAP mixture by strengthening the binder aggregate interaction. However, beyond the optimal range, excessive plastic content may increase mixture brittleness, which should be carefully controlled to maintain balanced mechanical performance and long term durability

2. Effect of Plastic Content on Marshall Quotient (MQ) of Plastic-Modified RAP Mixtures

As illustrated in Figure 2, the Marshall Quotient (MQ) of the plastic-modified RAP mixtures generally increases with increasing plastic content, indicating improved stiffness and resistance to permanent deformation. All MQ values exceed the minimum requirement specified by Bina Marga 2018, which requires MQ values greater than 250 kg/mm, confirming that the mixtures possess adequate structural rigidity.

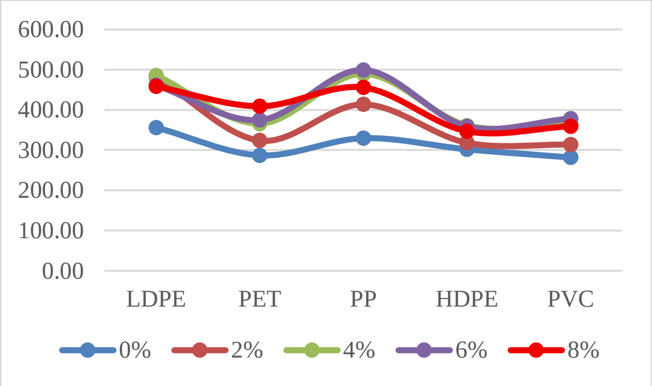

Figure 2. Marshall Quotient of Plastic Modified RAP Mixtures

The most pronounced MQ enhancement is observed in PP and LDPE at intermediate plastic contents (4–6%), where the stability-to-flow ratio reaches its peak. This behavior suggests that plastic addition strengthens the binder matrix within the RAP system, improving internal resistance against deformation under loading. Although slight reductions are observed at higher plastic contents for certain plastics, the overall trend demonstrates that controlled plastic incorporation enhances the structural performance of RAP mixtures without compromising specification compliance.

3. Effect of Plastic Content on Flow of RAP Mixtures

As illustrated in Figure 3, the flow values of the plastic-modified RAP mixtures generally decrease with increasing plastic content for LDPE, PET, and PP, indicating increased mixture stiffness due to binder modification. All flow values remain within the specification limits of 2–4 mm as required by Bina Marga 2018, confirming that adequate flexibility is maintained despite the increase in stability and Marshall Quotient.

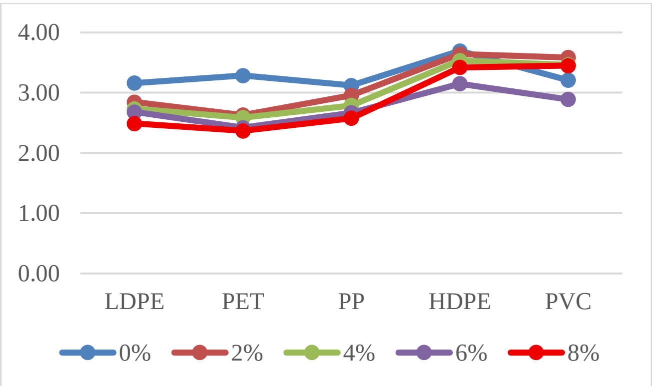

Figure 3. Flow Values of Plastic Modified RAP Mixtures

HDPE and PVC mixtures exhibit relatively higher flow values compared to other plastics, particularly at lower plastic contents, suggesting a different stiffness response within the RAP system. Although minor fluctuations are observed at higher plastic contents, the overall trend demonstrates that plastic incorporation enhances structural rigidity while maintaining deformation tolerance within acceptable limits.

4. Effect of Plastic Content on Density of RAP Mixtures

As shown in Figure 4, the density of the plastic-modified RAP mixtures exhibits only minor variation across different plastic types and contents. The density values range approximately between 2.28 and 2.33 g/cm³, indicating that plastic incorporation does not significantly affect mixture compactability. The relatively stable density trend suggests that improvements in Marshall stability and MQ are primarily attributed to binder modification rather than changes in compaction characteristics.

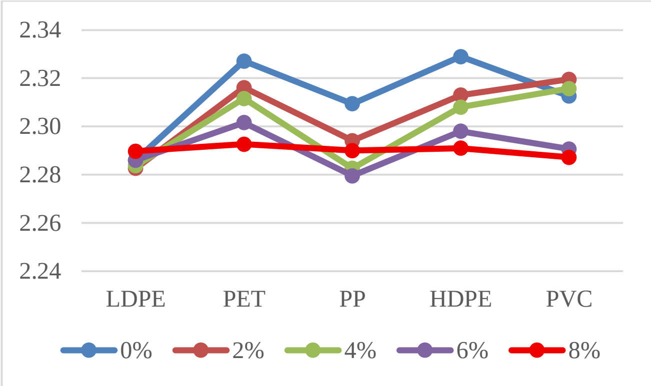

Figure 4. Density of Plastic Modified RAP Mixtures

Although slight fluctuations are observed at intermediate plastic contents, particularly for PET and HDPE, the overall pattern remains consistent across all mixtures. This behavior confirms that plastic modification within the evaluated range does not adversely influence the internal structure or volumetric integrity of RAP mixtures.

6. Effect of Plastic Content on VIM of RAP Mixtures

As illustrated in Figure 5, the VIM values of the plastic-modified RAP mixtures generally fall within or close to the specification range of 3–5% as required by Bina Marga 2018. For LDPE, PET, and PP mixtures, VIM values remain relatively stable across increasing plastic contents, indicating adequate air void distribution and proper compaction within the RAP system.

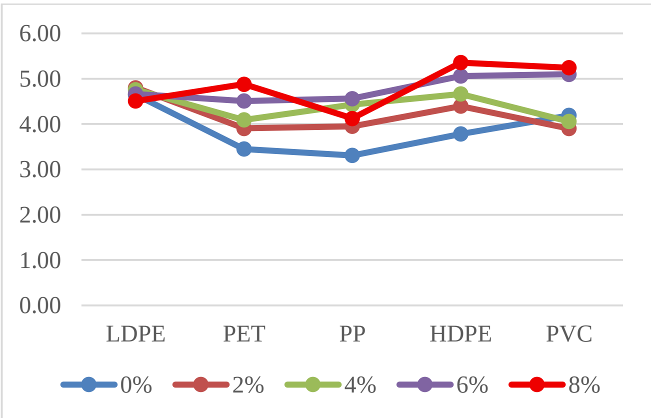

Figure 5. VIM of Plastic Modified RAP Mixtures

However, HDPE and PVC exhibit a noticeable increase in VIM at higher plastic contents (6–8%), with values slightly exceeding the upper specification limit. This trend suggests that excessive plastic addition may increase mixture stiffness, reducing workability and limiting effective void filling during compaction. Overall, the results indicate that controlled plastic dosage is essential to maintain balanced volumetric performance while enhancing mechanical properties of RAP mixtures.

7. Effect of Plastic Content on VMA of RAP Mixtures

As shown in Figure 6, the VMA values of the plastic-modified RAP mixtures remain consistently above the minimum requirement of 15% specified by Bina Marga 2018, indicating adequate void space within the aggregate structure to accommodate asphalt binder. The VMA values generally range between approximately 15.5% and 17.5%, demonstrating stable volumetric characteristics across different plastic types and contents.

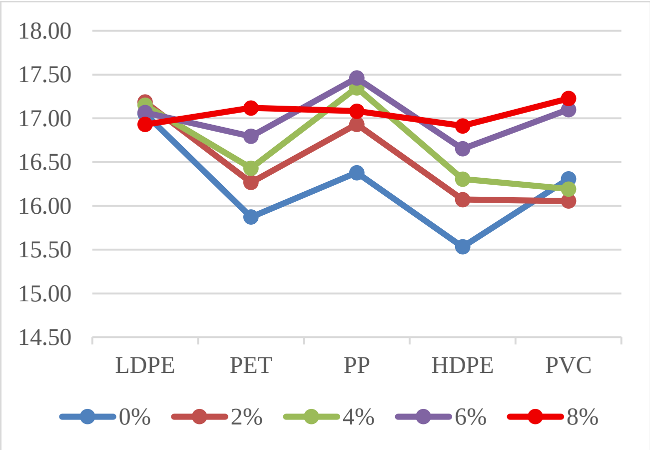

Figure 6. VMA of Plastic Modified RAP Mixtures

Slight fluctuations are observed at intermediate plastic contents, particularly for PET and PP mixtures, which exhibit relatively higher VMA values. This trend suggests improved internal aggregate structure and sufficient binder film thickness within the RAP system. Overall, plastic incorporation within the evaluated range does not adversely affect the mineral aggregate void structure, confirming that volumetric stability is maintained.

8. Effect of Plastic Content on VFA of RAP Mixtures

As illustrated in Figure 7, the VFA values of the plastic-modified RAP mixtures generally remain above the minimum requirement of 65% specified by Bina Marga 2018, indicating adequate asphalt filling within the aggregate void structure. The VFA values range approximately between 68% and 80%, demonstrating that the mixtures maintain sufficient binder coverage across varying plastic contents.

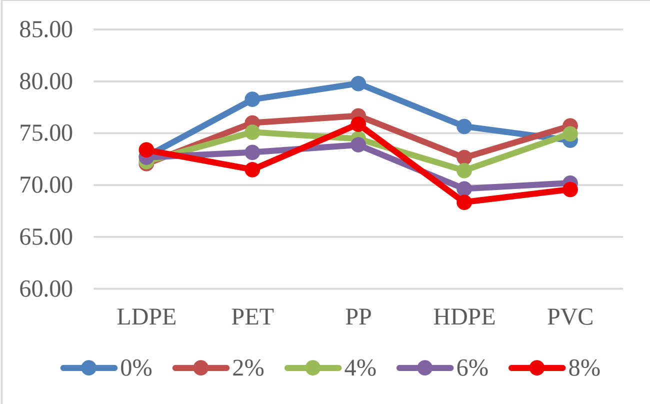

Figure 7. VFA of Plastic Modified RAP Mixtures

A gradual decrease in VFA is observed at higher plastic contents, particularly for HDPE and PVC, which corresponds with the increasing VIM values at similar dosage levels. This behavior suggests that excessive plastic addition may reduce effective void filling due to increased mixture stiffness and reduced workability. Nevertheless, all mixtures remain within acceptable specification limits, confirming that plastic incorporation within the evaluated range maintains volumetric balance in RAP mixtures.

E. Integrated Mechanical and Volumetric Analysis of Plastic-Modified RAP Mixtures

The integrated evaluation of Marshall mechanical properties and volumetric characteristics provides a comprehensive understanding of the performance of plastic-modified RAP mixtures. The combined interpretation of stability, Marshall Quotient (MQ), flow, and density confirms that plastic incorporation enhances mechanical performance without compromising compliance with specification limits. The observed increase in stability and MQ indicates improved structural rigidity and greater resistance to permanent deformation, while controlled flow values demonstrate that adequate deformation capacity is maintained. Meanwhile, relatively constant density values suggest that the improvement in performance is primarily attributed to binder modification and enhanced interaction between the modified binder and aged RAP binder rather than changes in mixture compactability.

From a volumetric perspective, the mixtures exhibit stable internal structural behavior across all plastic types and contents. VIM values remain within or close to the specified 3–5% range in accordance with Bina Marga 2018, indicating proper air void distribution and satisfactory compaction. Slight increases in VIM at higher plastic contents, particularly for HDPE and PVC, reflect increased binder stiffness that may reduce workability and limit effective void filling. Nevertheless, VMA values consistently exceed the minimum requirement of 15%, confirming adequate void space within the aggregate structure to accommodate asphalt binder. Similarly, VFA values remain above 65%, demonstrating sufficient binder filling within internal voids, although gradual reductions at higher plastic dosages correspond with the inverse relationship between VIM and VFA.

The synergistic relationship between increased stiffness (represented by higher stability and MQ) and acceptable deformation capacity (indicated by flow) highlights the effectiveness of controlled plastic incorporation in strengthening the internal structure of RAP mixtures. Moderate plastic contents in the range of 4–6% provide the most balanced mechanical and volumetric performance across all evaluated plastic types, achieving stiffness enhancement without inducing excessive brittleness or volumetric instability. Overall, these findings confirm that controlled plastic dosage plays a critical role in optimizing both mechanical behavior and internal structural stability of RAP mixtures, supporting their potential application in sustainable pavement systems.

V. CONCLUSIONS

This study investigated the performance of plastic-modified reclaimed asphalt pavement (RAP) mixtures through centrifugal extraction and Marshall mechanical–volumetric evaluation. The results confirm that centrifugal extraction is effective in recovering asphalt binder from RAP mixtures and is sufficiently sensitive to detect variations caused by different plastic types and contents. Plastic incorporation enhances the mechanical performance of RAP mixtures, as indicated by increased Marshall stability and Marshall Quotient values, while flow and density remain within acceptable specification limits. These findings demonstrate that stiffness improvement does not compromise flexibility or compaction characteristics. Volumetric parameters generally comply with Bina Marga 2018 requirements, although higher plastic contents may slightly affect air void balance, emphasizing the need for dosage control. Moderate plastic contents (4–6%) provide the most balanced performance across the evaluated plastics, indicating an optimal modification range for RAP applications. Overall, the integration of centrifugal extraction analysis with mechanical and volumetric assessment offers a comprehensive approach for evaluating plastic–RAP interaction and supports the practical implementation of plastic waste modification in sustainable pavement engineering.

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