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Durability of Asphalt Concrete-Wearing Course (AC-WC) Mixtures Incorporating Polypropylene (PP) Plastic Waste as a Fine Aggregate Substitute

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Abstract: *Flexible pavements are susceptible to water-induced damage, which weakens the bond between asphalt binder and aggregates, thereby reducing mixture durability. This study evaluated the effect of polypropylene (PP) plastic waste as a fine aggregate substitute on the durability of Asphalt Concrete-Wearing Course (AC-WC) mixtures, determined the optimum substitution level, and investigated the mixture microstructure using Scanning Electron Microscopy (SEM). PP substitution levels of 0%, 10%, 20%, 30%, and 40% were investigated. Marshall tests were conducted to determine the Optimum Asphalt Content (OAC), followed by Residual Marshall Stability testing after immersion periods of 30 minutes, 24, 48, 72, and 96 hours. Durability was evaluated using the Residual Strength Index (RSI), First Durability Index (FDI), Second Durability Index (SDI), and Retained Marshall Stability (RMS). The results showed that PP significantly influenced the durability of AC-WC mixtures. The optimum performance was achieved at 20% PP, producing a residual Marshall stability of 1179 kg, an RSI of 87.84%, an FDI of 0.51 %/h, an SDI of 7.89%, and an RMS of 92.11% after 96 hours of immersion. SEM observations supported the durability results by revealing microstructural differences among the selected mixtures, indicating that appropriate PP substitution improves the internal structure and water resistance of AC-WC mixtures.*

Keywords: *Asphalt Concrete-Wearing Course (AC-WC); durability; polypropylene; residual Marshall stability; scanning electron microscopy (SEM).*

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I. INTRODUCTION

Flexible pavements are the most widely used pavement type due to their ability to accommodate traffic loads, ease of construction, and relatively simple maintenance (Direktorat Jenderal Bina Marga, 2024). However, their long-term performance is strongly influenced by the durability of asphalt mixtures, which reflects their ability to maintain mechanical properties under the combined effects of water, temperature fluctuations, and repeated traffic loading. Water infiltration is one of the primary causes of durability deterioration, as it weakens the adhesion between asphalt binder and aggregates, leading to stripping, raveling, cracking, and premature pavement failure (Asphalt Institute, 2014).

The growing accumulation of plastic waste has become a significant environmental concern, encouraging the development of sustainable construction materials through waste recycling. Among various plastic types, polypropylene (PP) has attracted considerable attention because of its low density, excellent moisture resistance, thermal stability, and favorable mechanical properties. These characteristics make PP a promising alternative material for partial replacement of fine aggregate in Asphalt Concrete-Wearing Course (AC-WC) mixtures. In addition to reducing plastic waste, the incorporation of PP is expected to enhance the moisture resistance and durability of asphalt mixtures (Yang et al., 2025).

Previous studies have reported that incorporating PP waste into asphalt mixtures can improve Marshall stability, rutting resistance, and moisture resistance. Nevertheless, the effectiveness of PP largely depends on the substitution level, particle size, and mixing method. Moreover, most existing studies have focused primarily on conventional Marshall characteristics, while comprehensive evaluations of mixture durability using the Residual Strength Index (RSI), First Durability Index (FDI), Second Durability Index (SDI), and Retained Marshall Stability remain limited. Furthermore, studies correlating these durability indicators with microstructural observations obtained through Scanning Electron Microscopy (SEM) are still scarce (Oyelere, 2024).

Therefore, this study aims to evaluate the durability of AC-WC mixtures incorporating polypropylene (PP) plastic waste as a fine aggregate substitute through the Residual Marshall Stability test, determine the optimum PP substitution level, and investigate the relationship between mixture durability and microstructural characteristics using Scanning Electron Microscopy (SEM). The findings are expected to provide a sustainable alternative for utilizing plastic waste in asphalt pavement construction while contributing to a better understanding of the relationship between microstructure and durability performance.

II. RESEARCH METHODOLOGY

2.1 Materials

The materials used in this study consisted of coarse and fine aggregates obtained from the Watusampu Quarry, Palu City, Central Sulawesi, Indonesia. A 60/70 penetration grade asphalt binder was used as the binder material, while polypropylene (PP) plastic waste in pellet form was utilized as a substitute for the fine aggregate retained on the No. 8 sieve. Prior to mixture preparation, all materials were tested to ensure compliance with the 2025 General Specifications for Road and Bridge Construction issued by the Directorate General of Highways.

2.2 Experimental Program

Five AC-WC mixtures were prepared with PP substitution levels of 0%, 10%, 20%, 30%, and 40% by weight of the fine aggregate retained on the No. 8 sieve. The Optimum Asphalt Content (OAC) for each mixture was determined using the Marshall mix design method. Subsequently, specimens were fabricated at their respective OAC values and subjected to durability evaluation.

The Residual Marshall Stability test was conducted by immersing the specimens in a water bath maintained at 60°C for 30 minutes, 24, 48, 72, and 96 hours. The Marshall stability values obtained after each immersion period were used to determine the Residual Strength Index (RSI), First Durability Index (FDI), Second Durability Index (SDI), and Retained Marshall Stability (RMS) as indicators of mixture durability.

2.3 Microstructural Analysis

Microstructural observations were performed using Scanning Electron Microscopy (SEM) at a magnification of 1000×. Representative AC-WC mixtures were selected to examine surface morphology, particle distribution, void characteristics, and the quality of bonding between the asphalt binder and aggregates. The SEM observations were used to support the interpretation of the durability performance of the mixtures.

2.4 Data Analysis

The durability performance of the AC-WC mixtures was evaluated based on changes in Marshall stability during the immersion period. The Residual Strength Index (RSI), First Durability Index (FDI), Second Durability Index (SDI), and Retained Marshall Stability (RMS) were subsequently calculated to assess the ability of each mixture to retain its stability under prolonged water exposure. The quantitative results were then correlated with the SEM observations to provide a comprehensive understanding of the influence of polypropylene plastic waste on the durability of AC-WC mixtures.

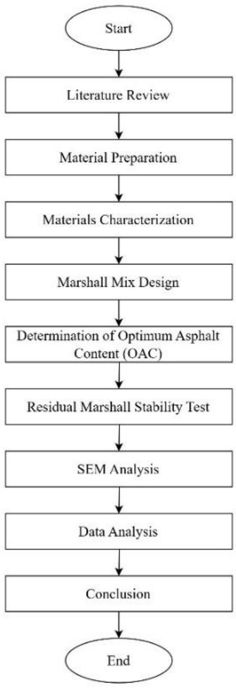


Figure 1 Research workflow

III. RESULTS AND DISCUSSION

3.1 Material Characteristics

The material characterization results indicated that the coarse aggregate, fine aggregate, and 60/70 penetration grade asphalt binder satisfied the requirements of the 2025 General Specifications for Road and Bridge Construction. Therefore, all materials were considered suitable for producing Asphalt Concrete-Wearing Course (AC-WC) mixtures. The compliance of the constituent materials ensured that the variations observed in the mechanical and durability properties of the mixtures were primarily attributed to the substitution of polypropylene (PP) plastic waste rather than to differences in material quality.

3.2 Optimum Asphalt Content (OAC)

The Marshall mix design method was employed to determine the Optimum Asphalt Content (OAC) for each PP substitution level. As presented in Table 1, the OAC gradually decreased from 6.25% for the control mixture to 5.95% for the mixture containing 40% PP. This trend indicates that replacing part of the fine aggregate with PP reduced the asphalt binder demand of the mixture.

Table 1. Optimum Asphalt Content (OAC) for Different PP Substitution Levels

PP Substitution (%)	OAC (%)
0	6.25
10	6.10
20	6.00
30	5.97
40	5.95

The reduction in OAC suggests that the incorporation of PP pellets influenced the volumetric characteristics of the asphalt mixture, thereby decreasing the amount of asphalt binder required to achieve the optimum mixture composition. Nevertheless, all mixtures satisfied the Marshall design requirements and were subsequently used for durability evaluation.

3.3 Durability Evaluation Based on the Residual Marshall Stability Test

The durability of the AC-WC mixtures was evaluated using the Residual Marshall Stability test after immersion in a water bath at 60°C for 30 minutes, 24, 48, 72, and 96 hours. The measured stability values for each PP substitution level are presented in Table 2, while their relationship with immersion time is illustrated in Figure 2.

Table 2. Residual Marshall Stability of AC-WC Mixtures at Different PP Substitution Levels

OAC	PP Substitution (%)	0,5 h (kg)	24 h (kg)	48 h (kg)	72 h (kg)	96 h (kg)	Specification
6.25	0	1056	973	933	874	841	800 kg
6.1	10	1185	1097	1077	1044	1017	
6	20	1342	1250	1232	1210	1179	
5.97	30	1384	1266	1238	1208	1167	
5.95	40	1426	1276	1236	1168	1092	

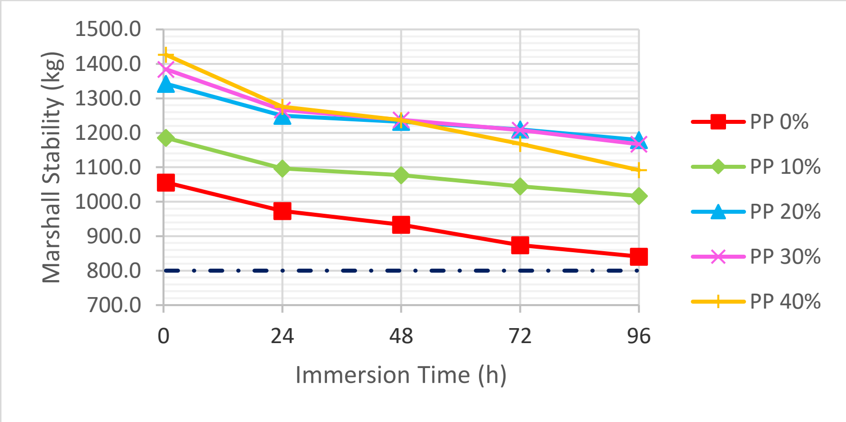


Figure 2. Marshall stability versus immersion time

As shown in Table 2 and Figure 2, the Marshall stability of all mixtures gradually decreased with increasing immersion time, indicating the detrimental effect of prolonged water exposure on mixture durability. However, the rate of stability reduction differed among the mixtures depending on the PP substitution level.

The mixture containing 20% PP exhibited the highest residual Marshall stability throughout the immersion period, maintaining a stability value of 1179 kg after 96 hours of immersion. This result indicates that the incorporation of PP at an appropriate substitution level enhanced the resistance of the asphalt mixture to moisture-induced damage. The improved durability is attributed to the more effective interaction between the asphalt binder and aggregate skeleton, which reduced the susceptibility of the mixture to strength loss during prolonged water immersion.

In contrast, mixtures with PP contents exceeding the optimum level exhibited lower residual stability after long-term immersion. This finding suggests that excessive PP substitution may adversely affect the internal structure of the mixture, thereby reducing its ability to retain mechanical strength under moisture exposure. Overall, the results demonstrate that 20% PP provides the most favorable balance between moisture resistance and structural stability among the mixtures investigated.

3.4 Residual Strength Index (RSI)

The Residual Strength Index (RSI) was used to evaluate the ability of AC-WC mixtures to retain their stability after water immersion. The RSI values for each PP substitution level are presented in Table 3, while the variation in RSI with immersion time is illustrated in Figure 3.

Table 3. Residual Strength Index (RSI) of AC-WC Mixtures

OAC	PP Substitution (%)	0,5 h (%)	24 h (%)	48 h (%)	72 h (%)	96 h (%)	Specification
6.25	0	100	92.16	88.39	82.78	79.64	min. 90%
6.1	10	100	92.51	90.83	88.11	85.77	
6	20	100	93.10	91.79	90.14	87.84	
5.97	30	100	91.46	89.40	87.24	84.30	
5.95	40	100	89.44	86.67	81.89	76.54	

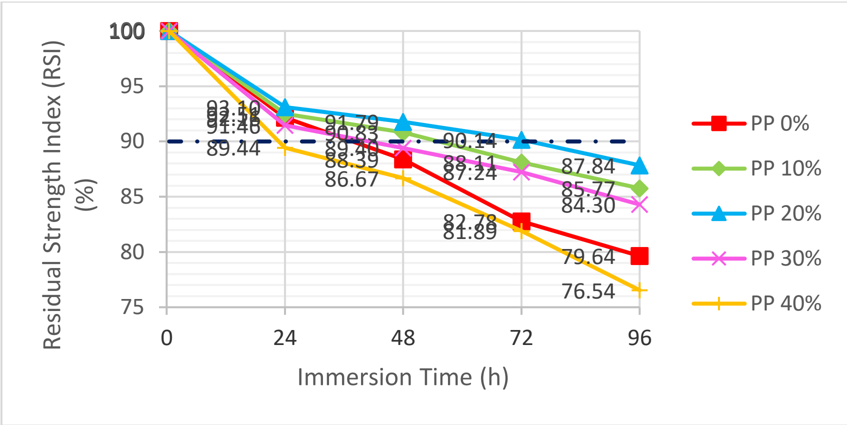


Figure 3. Residual Strength Index (RSI) versus immersion time

As presented in Table 3 and Figure 3, the RSI values initially increased with increasing PP substitution and then decreased at higher substitution levels. The mixture containing 20% PP exhibited the highest RSI value, reaching 87.84% after 96 hours of immersion. This indicates that the mixture retained its mechanical strength more effectively than the other mixtures during prolonged water exposure.

Conversely, the control mixture and the mixture containing 40% PP showed lower RSI values, indicating a greater reduction in strength due to moisture damage. These results suggest that an appropriate amount of PP enhances the resistance of asphalt mixtures to water-induced deterioration, whereas excessive PP substitution may adversely affect the internal structure of the mixture and reduce its durability.

3.5 First Durability Index (FDI)

The First Durability Index (FDI) was used to evaluate the rate of stability loss during the immersion period. Lower FDI values indicate a slower rate of deterioration and, consequently, better durability. The calculated FDI values for all mixtures are presented in Table 4, while their distribution is shown in Figure 4.

Table 4. First Durability Index (FDI) of AC-WC Mixtures

PP Substitution (%)	Immersion Time (h)	RSI (%)	*Si-Si*+1 A	*ti*+1-*ti* B	r = A/B (%/h)
0	0.5	100			
	24	92.16	7.84	23.5	0.33
	48	88.39	3.77	24	0.16
	72	82.78	5.61	24	0.23
	96	79.64	3.14	24	0.13
		$\sum r =$			0.86
10	0.5	100			
	24	92.51	7.49	23.5	0.32
	48	90.83	1.68	24	0.07
	72	88.11	2.71	24	0.11
	96	85.77	2.35	24	0.10
		$\sum r =$			0.60
20	0.5	100			
	24	93.10	6.90	23.5	0.29
	48	91.79	1.31	24	0.05
	72	90.14	1.64	24	0.07
	96	87.84	2.30	24	0.10
		$\sum r =$			0.51
30	0.5	100			
	24	91.46	8.54	23.5	0.36
	48	89.40	2.06	24	0.09
	72	87.24	2.16	24	0.09
	96	84.30	2.95	24	0.12

PP Substitution (%)	Immersion Time (h)	RSI (%)	*Si*-*Si*+1 A	*ti*+1-*ti* B	r = A/B (%/h)
		∑*r* =			0.66
40	0.5	100			
	24	89.44	10.56	23.5	0.45
	48	86.67	2.77	24	0.12
	72	81.89	4.78	24	0.20
	96	76.54	5.35	24	0.22
		∑*r* =			0.99

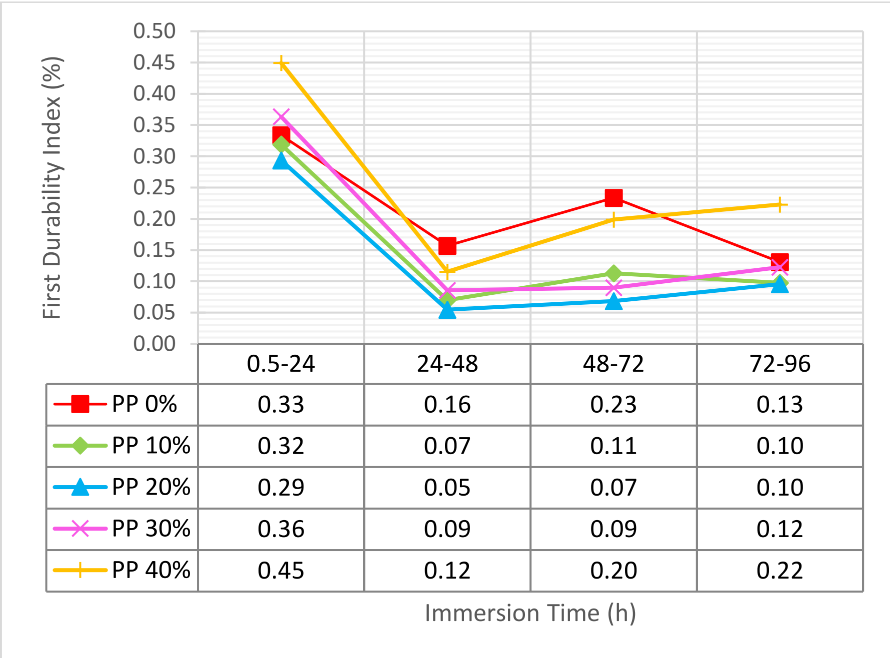


Figure 4. First Durability Index (FDI) at different immersion intervals

As shown in Figure 4, the FDI values decreased with increasing PP substitution up to 20%, after which they increased as the PP content continued to rise. The lowest FDI value (0.51 %/h) was obtained for the mixture containing 20% PP, indicating the slowest reduction in Marshall stability during immersion. In contrast, the highest FDI value (0.99 %/h) was recorded for the 40% PP mixture, demonstrating a faster deterioration rate under prolonged water exposure.

These findings indicate that the incorporation of PP at the optimum substitution level effectively delays the degradation of mixture stability, thereby improving the moisture resistance and long-term durability of AC-WC mixtures.

3.6 Second Durability Index (SDI) and Retained Marshall Stability (RMS)

The Second Durability Index (SDI) and Retained Marshall Stability (RMS) were employed to assess the cumulative durability loss and the ability of asphalt mixtures to retain stability throughout the immersion period. The calculated SDI and RMS values are presented in Table 5, while Figures 5 and 6 illustrate their variation with PP substitution and immersion time.

Table 5. Second Durability Index (SDI) and Retained Marshall Stability (RMS)

PP Substitution (%)	Immersion Time (h)	RSI (%)	*Si*-*Si*+1 A	*ti*+1-*ti* B	C	*a* = (AxC) *2tn*	RMS (%)
0	0.5	100.00					100.00
	24	92.16	7.84	23.5	24.5	4.00	96.00
	48	88.39	3.77	24	72.0	2.83	93.17

PP Substitution (%)	Immersion Time (h)	RSI (%)	*Si-Si*+1 A	*ti*+1-*ti* B	C	*a* = (AxC) *2tn*	RMS (%)
	72	82.78	5.61	24	120	4.67	88.50
	96	79.64	3.14	24	168	2.75	85.75
		∑ *a* =				14.25	
10	0.5	100.00					100.00
	24	92.51	7.49	23.5	24.5	3.82	96.18
	48	90.83	1.68	24	72.0	1.26	94.92
	72	88.11	2.71	24	120	2.26	92.65
	96	85.77	2.35	24	168	2.05	90.60
		∑ *a* =				9.40	
20	0.5	100.00					100.00
	24	93.10	6.90	23.5	24.5	3.52	96.48
	48	91.79	1.31	24	72.0	0.99	95.49
	72	90.14	1.64	24	120	1.37	94.12
	96	87.84	2.30	24	168	2.01	92.11
		∑ *a* =				7.89	
30	0.5	100.00					100.00
	24	91.46	8.54	23.5	24.5	4.36	95.64
	48	89.40	2.06	24	72.0	1.54	94.10
	72	87.24	2.16	24	120	1.80	92.30
	96	84.30	2.95	24	168	2.58	89.72
		∑ *a* =				10.28	
40	0.5	100.00					100.00
	24	89.44	10.56	23.5	24.5	5.39	94.61
	48	86.67	2.77	24	72.0	2.08	92.53
	72	81.89	4.78	24	120	3.98	88.55
	96	76.54	5.35	24	168	4.68	83.87
		∑ *a* =				16.13	

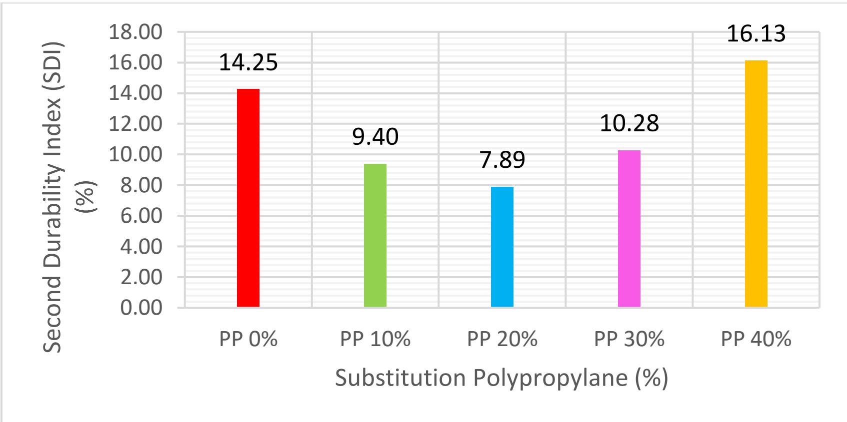


Figure 5. Second Durability Index (SDI) at different PP substitution levels

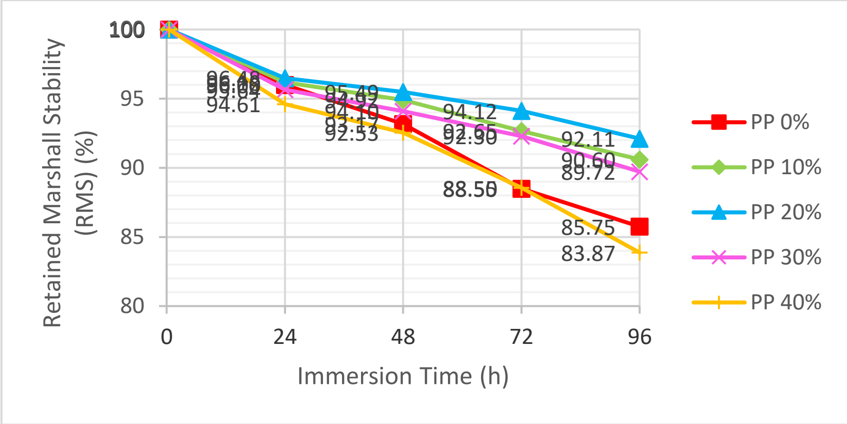


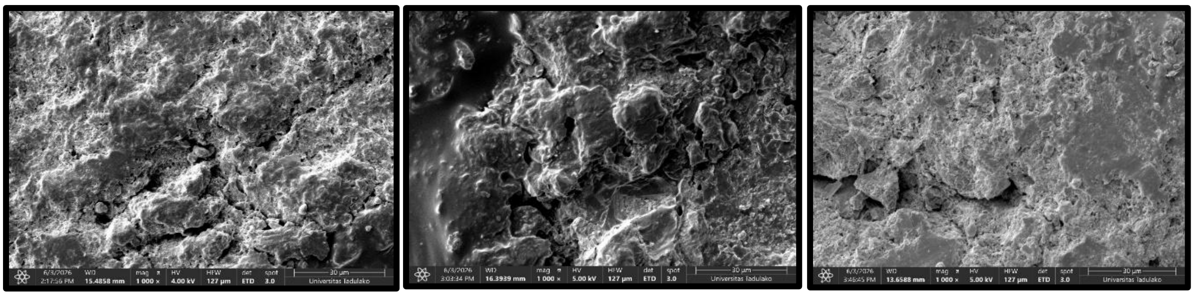
Figure 6. Retained Marshall Stability (RMS) versus immersion time

As presented in Table 5, Figure 5, and Figure 6, the SDI values decreased as the PP substitution increased up to 20%, followed by an increase at higher substitution levels. In contrast, the RMS values increased until the PP content reached 20% and then gradually decreased with further PP addition.

The mixture containing 20% PP exhibited the lowest SDI (7.89%) and the highest RMS (92.11%) after 96 hours of immersion, demonstrating the highest resistance to moisture-induced deterioration. On the other hand, mixtures containing 30% and 40% PP showed a reduction in RMS, indicating that excessive PP substitution negatively affected the durability performance of the asphalt mixture. These results confirm that 20% PP represents the optimum substitution level for improving the durability of AC-WC mixtures under prolonged water exposure.

3.7 Microstructural Analysis Using Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was employed to investigate the influence of polypropylene (PP) substitution on the microstructural characteristics of AC-WC mixtures. Representative mixtures containing 0%, 10%, and 40% PP were examined at a magnification of 1000× to observe surface morphology, particle distribution, void characteristics, and the quality of bonding between the asphalt binder and aggregates. The SEM images are presented in Figure 7.



(b) PP 0% (c) PP 10% (a) PP 40%

Figure 7. SEM micrographs of AC-WC mixtures with different PP substitution levels (1000× magnification).

Based on Figure 7, the control mixture (0% PP) exhibited a relatively non-uniform surface with visible voids and interparticle gaps, indicating less effective bonding between the asphalt binder and aggregates. The mixture containing 10% PP displayed a denser and more homogeneous microstructure with fewer visible voids, suggesting an improvement in the internal bonding of the mixture.

In contrast, the mixture containing 40% PP exhibited noticeable changes in surface morphology due to the higher PP content. The microstructure appeared less uniform than that of the 10% PP mixture, indicating that excessive PP substitution did not provide a proportional improvement in the internal structure of the asphalt mixture. These observations support the durability results, demonstrating that PP improves the moisture resistance of AC-WC mixtures only up to an optimum substitution level, whereas excessive PP content tends to reduce durability performance.

IV. CONCLUSION

The incorporation of polypropylene (PP) plastic waste as a fine aggregate substitute significantly influenced the durability of Asphalt Concrete-Wearing Course (AC-WC) mixtures. The durability evaluation based on the Residual Marshall Stability test, Residual Strength Index (RSI), First Durability Index (FDI), Second Durability Index (SDI), and Retained Marshall Stability (RMS) demonstrated that the addition of PP improved the resistance of asphalt mixtures to moisture-induced deterioration up to an optimum substitution level.

The optimum performance was achieved at a PP substitution level of 20%, which produced a residual Marshall stability of 1179 kg, an RSI of 87.84%, an FDI of 0.51 %/h, an SDI of 7.89%, and an RMS value of 92.11% after 96 hours of water immersion. These results indicate that the 20% PP mixture exhibited the highest ability to retain its mechanical stability under prolonged moisture exposure.

SEM observations further revealed that PP substitution altered the microstructural characteristics of the AC-WC mixtures. Mixtures containing lower PP contents exhibited a denser and more homogeneous internal structure than the control mixture, whereas excessive PP substitution resulted in less favorable microstructural characteristics. These observations are consistent with the durability evaluation, confirming that polypropylene plastic waste has considerable potential as a sustainable fine aggregate substitute for enhancing the durability of AC-WC mixtures.

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