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Performance and Durability of Asphalt Concrete Modified with Plastic Waste

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Abstract: Damage to asphalt roads is frequently caused by waterlogging and overloading. While asphalt pavement remains an economical choice, Indonesia imports 75% of its supply, coinciding with a growing crisis of low-value plastic waste e.g., Low-Density Polyethylene (LDPE), Polystyrene (PS), and Polypropylene (PP) that is economically challenging to sort and recycle. This study proposes a novel solution by utilizing a blended mixture of these plastics (40% LDPE, 30% PP, 30% PS) to simulate unsorted waste streams for modifying Asphalt Concrete-Wearing Course (AC-WC) pavement. The dry mixing process was employed to substitute asphalt at dosages of 0%, 8%, 10%, 12%, and 14% by weight. The research methodology encompassed material characterization, aggregate gradation design, and Marshall testing to determine the Optimum Asphalt Content (OAC) and Optimum Plastic Content (OPC). The durability of the optimal mix was subsequently rigorously assessed through prolonged water immersion at 60 °C for durations of 30 minutes, 24, 48, 72, and 96 hours. Results indicated that a 10% plastic substitution at an OAC of 6.3% yielded the highest Marshall stability, with all volumetric parameters within specified tolerance limits. The mixture exhibited exceptional resistance to moisture damage, evidenced by an Index of Retained Stability (IRS) of 94.64% after 24 hours, surpassing the 90% requirement. Furthermore, the Retained Marshall Stability was 87.40% after 96 hours. Additional durability metrics, including the First Durability Index (FDI) and Second Durability Index (SDI), were analyzed to comprehensively evaluate the performance degradation over time. The findings conclusively demonstrate that modifying asphalt with this blended, unsorted plastic composition is not only feasible but also enhances mechanical properties and durability, offering a viable and sustainable strategy for large-scale plastic waste management in infrastructure development.

Keywords: Asphalt Concrete-Wearing Course; Plastic waste; Durability; Marshall stability; Durability index

1 Introduction

The quality of materials and technical standards in implementation will affect the quality of asphalt mixtures. The government, through the Ministry of Public Works and Public Housing, has established requirements for the quality of materials and the technical standards of asphalt mixtures [1]. Low material quality and substandard implementation are factors causing road damage [2]. Other factors include road overloading and climatic conditions such as high rainfall, which often causes puddles on the road surface [3]. When the bond between asphalt and aggregate loosens due to submersion in water and the passage of heavy vehicles, it will damage the road surface bond [4]. Flexible pavement remains the more economical choice to date, while 75% of the asphalt needed to meet domestic demand is still imported [5].

On the other hand, plastic waste problems in Indonesia have become a public concern. Based on population density within 50 km of the coastline, waste management systems, and economic status, Indonesia ranks second in the world after China in terms of plastic waste pollution in the sea, at around 0.48–1.29 million tons/year [6]. A study notes that 20% of plastic debris in the sea comes from sea-based sources, such as fishing vessels, and 80% from land-based sources, of which 75% comes from uncollected waste and 25% from formal urban waste management systems. Recycling efforts alone are insufficient to reduce plastic waste leakage into the oceans [7, 8]; only 18% of plastics are valuable enough to be recycled, such as PET and HDPE types, while 82% are of medium and low value, such as Low-Density Polyethylene (LDPE), Polystyrene (PS), and Polypropylene (PP) types. Plastics with medium and low values are more likely to end up in the ocean. The problem of accumulating low-value plastic waste continues to increase every year, and this plastic waste is difficult to decompose in nature, taking hundreds of years. Plastic waste pollution in the sea is a global challenge, and the solution requires action at the local level.

LDPE, PP, and PS plastics have thermal properties; when heated, they soften at an average temperature between 100–160 °C without producing gas; at temperatures between 270–350 °C, they decompose, releasing methane and ethane gases, and at temperatures above 700 °C, they combust and produce CO and CO_2 gases. Methods of adding plastic waste to asphalt mixtures include the wet process, which involves mixing plastic waste with hot asphalt and stirring homogeneously, and the dry process, which involves mixing plastic waste with preheated aggregate and then adding hot asphalt [9, 10]. In the dry process, adding plastic to heated aggregate at 140–160 °C produces a thin layer on the aggregate surface, after which hot asphalt at 160 °C is added. When asphalt is mixed with aggregate coated with plastic, some of the asphalt diffuses through the plastic layer and binds to the aggregate [11].

Various modifications to meet the desired criteria for road pavement layer mixtures by utilising plastic waste continue to be carried out by researchers. LDPE plastic types include plastic bags and ice cube plastics [7, 11], PP plastic types include instant noodle wrappers, instant coffee powder packaging, and instant snack packaging, and PS plastic types include Styrofoam food containers and disposable Styrofoam drink containers [12]. In practice, separating these plastic wastes during processing is difficult when only one type is used, such as LDPE, PP, or PS, in large-scale pavement mixtures.

Given the problems mentioned above and the potential of plastic waste, it is technically feasible to conduct research to modify Laston mixtures by substituting low-value plastic waste. This research investigates the performance of AC-WC Laston Mixtures substituted with a combination of LDPE, PP, and PS Plastic Waste using the dry method of mixing plastic waste into the Laston mixture. This study addresses a research gap: most prior work has tested single polymer types (LDPE, PP, or PS), whereas this study investigates unsorted mixed plastics to reflect real-world waste streams. This novelty supports practical scalability and complements recent literature [6–8].

The difference from previous research is that this research combines three plastic wastes into a single mixture with a composition of 40% LDPE, 30% PP, and 30% PS to replace the Laston mixture.

Moreover, this investigation aims to determine the effect of water immersion on plastic waste-modified Laston mixtures (AC-WC) at the selected optimum plastic content (OPC), with immersion times of 30 minutes, 24 hours, 48 hours, 72 hours, and 96 hours.

2 Material and Method

2.1 Material

This research was conducted at the transportation laboratory of Universitas Andalas, using the Asphalt Concrete-Wearing Course (AC-WC) hot-mix design, in accordance with the general specifications of Bina Marga 2018, division 6 [13].

The testing of asphalt and aggregate materials follows the Indonesian National Standard (SNI), and the Marshall sample and test procedures follow the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM) [14, 15]. The research flow stages are presented in Figure 1.

The testing was carried out in stages, namely testing of coarse and fine aggregate materials, asphalt, and for LDPE, PP, and PS plastic materials, an examination of plastic materials passing a 19 mm sieve and retained on a 4.74 mm sieve, gradation design, Marshall testing, and durability testing using the immersion method.

Laboratory tests were carried out on coarse and fine aggregates. Abrasion testing with the Los Angeles machine with standard testing method SNI-2417-2008, aggregate adhesion with bitumen testing as per SNI-2439-2011, water absorption testing of coarse aggregate and specific gravity of coarse aggregate as per SNI-1969-2008, water absorption testing of fine aggregate and specific gravity of fine aggregate with standard testing method SNI-1970-2008.

The asphalt used in this research is a Shell product with a penetration of 60/70. Examination of asphalt characteristics was carried out using various tests, including Penetration, Softening Point, Ductility, Flash Point, and Specific Gravity, as per SNI-2456-2011, SNI-2434-2011, SNI-2432-2011, SNI-2433-2011, and SNI-2441-2011, respectively [14–16].

The gradation used in this research is a continuous gradation based on the middle value of the technical specifications of Bina Marga 2018 division 6, as shown in Table 1 [13].

2.2 Sample Production

The chosen composition ratio of 40% LDPE, 30% PP, and 30% PS reflects the typical proportions of unsorted low-value plastic waste in Indonesia. While the dry process was selected for its practicality in asphalt plants, it is acknowledged that it may result in lower homogeneity than the wet process. The use of three specimens per test is consistent with Marshall standards, but future research should increase the sample size ($n \geq 5$) to allow for statistical validation.

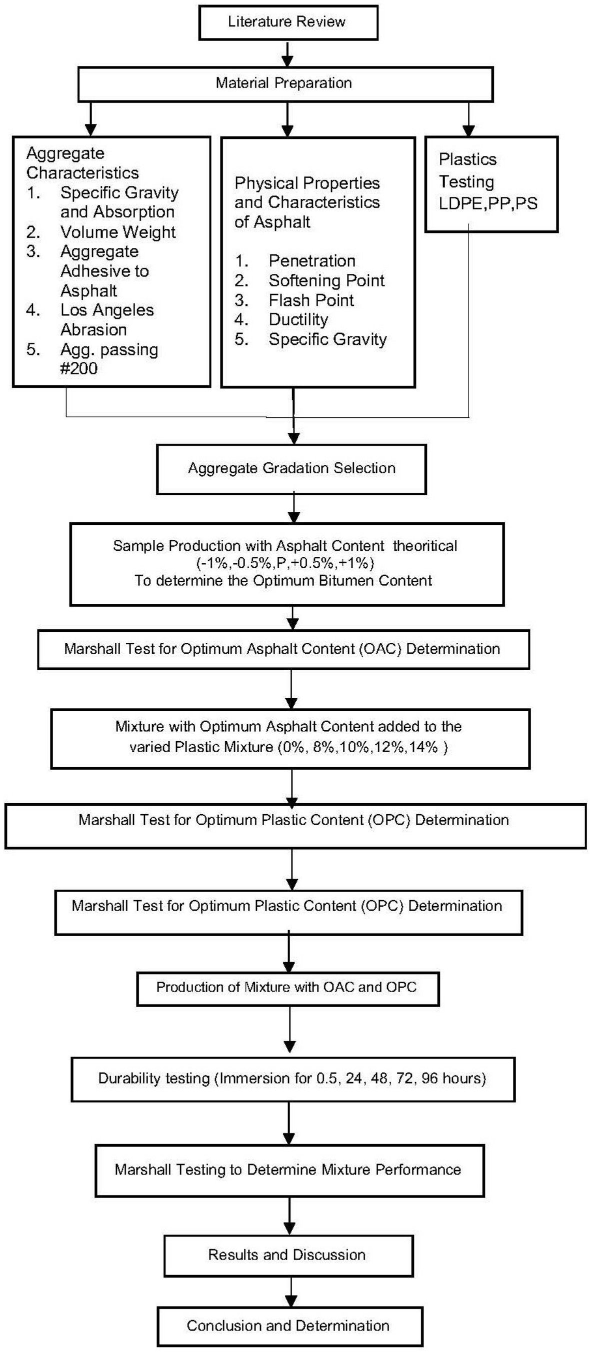

Figure 1. The flow chart of the investigation

The dry mixing method was selected for this investigation due to its practical advantages for potential large-scale applications and its effectiveness in coating aggregates with plastic [9]. This method is simpler to implement in conventional asphalt plants as it does not require significant modification to the machinery; the plastic waste can be added directly to the mixer alongside the heated aggregates. The technical rationale is that the preheated aggregate (155–160 °C) provides the thermal energy to melt and coat the plastic onto the stone surface, creating a thin polymeric film that can potentially enhance the bond between the aggregate and the bitumen [11]. It is acknowledged that a limitation of the dry process is the potential for incomplete plastic homogenization within the mixture compared to the wet process. Furthermore, a sample size of three specimens per test condition was used, which is consistent with standard Marshall mix design procedures (e.g., ASTM D6927) but limits the ability to perform robust statistical analysis. Future studies should use a larger sample size (e.g., $n \geq 5$) to enable detailed statistical validation of results and a more comprehensive assessment of variability.

Table 1. Asphalt Concrete-Wearing Course (AC-WC) mixture gradation design

Sieve Size		Passing (%)	Specification
American Society for Testing and Materials (ASTM)	(mm)	AC-WC Mixture Gradation Design	AC-WC
3/4”	19.00	100.0	100
1/2”	12.50	93.2	90–100
3/8”	9.50	85.2	77–90
#4	4.75	63.0	53–69
#8	2.36	44.6	33–53
#16	1.18	31.5	21–40
#30	0.60	23.7	14–30
#50	0.30	15.8	9–22
#100	0.15	8.9	6–15
#200	0.075	5.8	4–9

Stage 1: Determination of Optimum Asphalt Content (OAC). A total of 15 test specimens were prepared, with three specimens per variation in asphalt content. The objective of this stage is to determine the OAC. The mixing process is carried out at 155 $\pm$ 1 °C, while compaction is conducted at 145 $\pm$ 1 °C. Each test specimen is compacted using 2 $\times$ 75 blows.

Marshall testing is performed to measure stability, flow, and the Marshall Quotient. Additionally, volumetric parameters such as voids in the mixture (VIM), volume of voids in the mineral aggregate (VMA), and voids filled with bitumen (VFB) are calculated using volumetric equations.

Stage 2: Determination of OPC. After obtaining the OAC, 15 new samples are produced, subsequently, with three test specimens for each variation of plastic content. The plastic used as a substitute in the asphalt is varied at 0%, 8%, 10%, 12%, and 14% of the asphalt weight, using the dry mixing method.

At this stage, the aggregate is preheated to 155–160 °C, after which it is mixed with plastic. Then, the aggregate-plastic mixture is combined with preheated hot asphalt at 155 $\pm$ 1 °C. The compaction process is performed at 145 $\pm$ 1 °C with 2 $\times$ 75 blows. From the relationship between plastic content and Marshall parameters, the OPC can be determined.

Stage 3: Durability testing of asphalt-plastic mixture. After obtaining the OPC at the OAC, an additional 15 test specimens are prepared, with three specimens per immersion duration. The specimens are immersed in a water bath at 60 °C for 0.5, 24, 48, 72, and 96 hours. After each immersion, a Marshall test is conducted.

Subsequently, the residual stability index is calculated using the equation from Bina Marga, while the first and second durability indices are calculated using the equation from Craus et al. [17].

3 Result and Discussion

3.1 Results of Aggregate Characteristics Testing

Before being utilised as road construction materials, the characteristics of aggregates must be thoroughly assessed to ensure compliance with established standards. This evaluation is crucial for determining their suitability for durability, strength, and overall performance in pavement structures. Table 2 presents a summary of characteristics that align with the specified standards to ensure that the selected aggregates meet the required criteria for effective application in road engineering; thus, it can be used in this investigation.

As seen in Table 2, most of the results of aggregate characteristics testing have met the specified requirements, except for the absorption of fine aggregate, which does not meet the requirements, with results obtained of 4.384%, which is slightly greater than the specification standard of 3%, it affected the amount of asphalt content.

3.2 Results of Asphalt Characteristics Testing

Based on the asphalt testing results, the asphalt to be used meets all the specified requirements, as shown in Table 3.

The testing of bitumen characteristics, including penetration, softening point, ductility, flash point, and specific gravity, has been successfully conducted, and the results meet the required specifications.

The penetration test confirms the 60/70 penetration value. The asphalt has the appropriate hardness and consistency, making it suitable for the intended application. Its penetration value ensures proper resistance to deformation under varying temperatures and traffic conditions. The softening point test shows a value of 58 °C, which means that the bitumen can withstand high temperatures without excessive softening, ensuring pavement stability in hot climates. Moreover, the ductility test indicates flexibility, with a value exceeding 100 cm, indicating that the asphalt can stretch without breaking. This property is crucial for preventing road cracks due to temperature fluctuations and traffic stress. The flash point of 237 °C indicates that the bitumen has a high ignition temperature, ensuring safe handling and application during construction. A high flash point reduces the risk of fire hazards.

Finally, the specific gravity test confirms that the bitumen's density is within the required range of 1.035, ensuring proper mix design in asphalt pavements.

Table 2. Aggregate characteristics used

No.	Type of Experiment	Value	Specification
	Coarse Aggregate		
1	Absorption	0.560	<3%
	Bulk Density	2.564	
2	Saturated Surface Dry Density	2.578	
	Apparent Density	2.601	
3	Abrasion	24.93%	<30%
4	Aggregate adhesion to asphalt	95%	>95%
	Fine Aggregate		
1	Absorption	4.384%	<3%
	Bulk Density	2.643	
2	Saturated Surface Dry Density	2.759	
	Apparent Density	2.990	

Table 3. Bitumen characteristics used

No.	Type of Experiment	Value	Specification
1	Penetration 25 °C (0.01)	66	60–70
2	Softening Point (°C)	58	≥48
3	Ductility	100	≥100
4	Flash Point	237 °C	>232 °C
5	Specific Gravity	1.035	≥1.0

3.3 Results of Plastic Waste Preparation

The specific gravity of the combined LDPE, PP, and PS plastic is calculated from the specific gravity data for each plastic, as reported in the literature.

The diverse use of plastic is expected to simulate real-world conditions, with the types commonly encountered in the field being LDPE, PP, and PS. To align with these conditions, this study utilises a composition of 40% LDPE, 30% PP, and 30% PS, as presented in Table 4, ensuring that the materials used in the research are representative of those found in practical applications.

Table 4. Plastic combination density

No.	Types of Plastics	Density	Percentage in Mixture	Density Combination
1	LDPE	0.91–0.93	40%	
2	PP	0.85–0.83	30%	0.935
3	PS	1.05	30%	

3.4 Marshall Testing Results for Determining Optimum Asphalt Content

The process of preparing samples for evaluating the suitability of the AC-WC mixture with the incorporation of plastic begins with determining the OAC. This step is essential to ensure that the modified mixture achieves the required performance standards for durability, stability, and workability.

The determination of the Optimum Asphalt Content (OAC) is based on a comprehensive analysis of key performance indicators, primarily the maximum stability value obtained from testing, as well as other Marshall parameters that must comply with established specifications, the overall strength, flexibility, and resistance of the pavement mixture under various loading conditions.

Table 5 presents the results of the Marshall test conducted in the laboratory, which serves as the basis for determining the OAC required to achieve the desired balance between mechanical performance and long-term durability in AC-WC pavement applications.

Table 5. Plastic combination density

Mixture Characteristics	Result of Test					Specification
Stability (kg)	1453	1529	1604	1608	1484	Min 800
Flow (mm)	5.77	6.59	7.47	5.37	5.33	2–4
Marshall Quotient (MQ, kg/mm)	271	254	226	299	295	200–400
Voids in the mixture (VIM, %)	10,0	8,98	4,94	6,00	3,70	3–5
Voids in the mineral aggregate (VMA, %)	19.6	19.7	17.1	19.1	18.1	Min 15
Voids filled with bitumen (VFB, %)	48.9	54.3	79.3	68.5	79.7	Min 65

Based on Marshall testing with variations in planned asphalt content, an OAC of 6.3% was obtained, which meets the requirement of having the highest stability and Marshall parameters for AC-WC asphalt concrete mixtures.

This OAC value is used for further testing, namely, the test object mixture with plastic waste substitution.

3.5 Marshall Testing Results for Asphalt Concrete-Wearing Course Mixture with Plastics Substitution

The test results are illustrated as a value showing the relationship between plastic content and the desired parameters. The OPC is determined using the bar-chart method, which is defined as the midpoint of the range between the maximum and minimum plastic content that meets the mixture criteria.

Using plastic in the AC-WC pavement mixture with an OAC of 6.3% as presented in Table 6, shows that the Marshall values meet the standards for modified asphalt mixtures.

Table 6. Marshall testing results for the Asphalt Concrete-Wearing Course (AC-WC) mixture with plastics substitution

Mixture Characteristics	Result of Test					Specification
Stability (kg)	1630	1835	1596	1804	2037	Min 900
Flow (mm)	4.37	4,87	5,28	5.03	7.77	2–4
Marshall Quotient (MQ, kg/mm)	375	412	429	388	263	250–500
Voids in the mixture (VIM, %)	3.66	4.73	4.93	4.65	5.43	3–5
Voids in the mineral aggregate (VMA, %)	17.6	18.2	183	18	18.6	Min 15
Voids filled with bitumen (VFB, %)	79.4	69.8	67.7	67.5	63.4	Min 65

The results demonstrate that a blend of mixed plastics (LDPE, PP, PS) can effectively enhance Marshall stability, achieving optimal performance at a 10% substitution rate. This is a significant finding as it proves that meticulous sorting into pure polymer types is not a prerequisite for performance gains, validating the practical approach of using commingled plastic waste. The highest stability value is achieved at a plastic content of 10%, although the flow value tends to increase when the plastic content exceeds 10%. The combination of polymers appears to create a synergistic effect that improves the structural properties of the mix, validating the practical approach of using commingled plastic waste. Using plastic in the AC-WC pavement mixture with an OAC of 6.3% shows that the Marshall values meet the standards for modified asphalt mixtures. The highest stability value is achieved at a plastic content of 10%, although the flow value tends to increase when the plastic content exceeds 10%. While the parameters mostly fall within standards, instances in which VMA values slightly exceed the limits highlight potential sensitivity to plastic dosage. Statistical testing (e.g., ANOVA) was not performed and represents a limitation of this study. Nonetheless, the overall performance trend supports the practical applicability of mixed plastic waste. The highest stability value is achieved at a plastic content of 10%, although the flow value tends to increase when the plastic content exceeds 10%.

The combination of polymers appears to create a synergistic effect that improves the structural properties of the mix, validating the practical approach of using commingled plastic waste. Using plastic in the AC-WC pavement mixture with an OAC of 6.3% demonstrates that the Marshall values conform to the standards for modified asphalt mixtures. The highest stability value is achieved at a plastic content of 10%, although the flow value tends to increase when the plastic content exceeds 10%.

Regarding VMA, although the values exceed 15%, a plastic content of 10% remains within acceptable limits. The VMA parameter is crucial for determining the air voids available for asphalt absorption, which directly influences the durability and performance of the pavement.

Based on the obtained parameters, it can be concluded that the OPC for AC-WC pavement is 10%, with a plastic composition of 40% LDPE, 30% PP, and 30% PS.

3.6 Durability Testing Results

The test results for the AC-WC mixture with plastic waste showed an OPC of 10%. This OPC value is used as the reference for creating test specimens for further testing. In practical terms, the First Durability Index (FDI) reflects the rate of strength loss under immersion, while the Second Durability Index (SDI) indicates the total loss of strength. These indices suggest that the plastic-modified mix resists water damage better than conventional asphalt, supporting its potential for field application.

Durability testing is essential to assess asphalt's resistance to ageing, weather conditions, and traffic loads. It ensures long-term performance by evaluating oxidation, moisture damage, and temperature fluctuations.

The test results indicate that the Index of Retained Stability (IRS), which measures the ability of an asphalt mixture to maintain stability after being immersed in water, gradually decreases as the immersion duration increases. This decline is expected, as prolonged exposure to water typically weakens asphalt mixtures. However, despite the reduced IRS values, they remain above the minimum threshold of 90% specified by the Bina Marga 2018 General Specifications, Division 6, which serves as Indonesia's road construction standard.

As shown in Table 7 and confirmed in Figure 2, at 24 hours of immersion, the IRS value is 94.64 per cent, indicating that the mixture retains most of its original stability.

Table 7. Durability value

Immersion Time (hours)	Average Stability (kg)	Index of Retained Stability (%)
0.5	1731	100.00
24	1638	94.64
48	1491	91.04
72	1270	85.18
96	1049	82.57

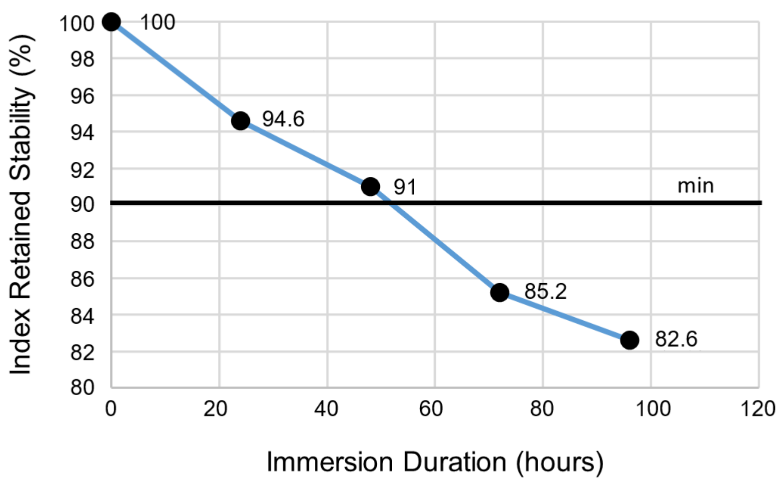

Figure 2. Index of Retained Stability (IRS) (%)

This value is above the required 90 per cent, indicating good durability. After 48 hours of immersion, the IRS value decreases slightly to 91.04 per cent, which is still above the minimum requirement. Beyond this point, the IRS decreases gradually, as shown in Figure 2, reflecting the natural impact of water exposure over time.

Furthermore, the FDI measures the rate of strength loss over time during immersion. It is derived from the slope of the strength loss curve over time. The FDI value focuses on how quickly the asphalt loses strength in water. A higher FDI means a faster rate of deterioration.

Moreover, the test results showed a positive "r" value that identified a loss of strength. The slope value of the stability decline (r) at 24-hour immersion time was steeper when compared to the 48-hour immersion time curve, meaning that the one-day immersion criteria did not always reflect the durability properties of the mixture.

Table 8. First Durability Index (FDI, %)

Duration (hours)	Index of Retained Stability (IRS) (%)	$S_i - S_{i+1}$ (A)	$t_i - t_{i+1}$ (B)	$r = \frac{A}{B}(\%)$
0.5	100.00			
24	94.64	5.357	23.5	0.228
48	91.04	3.604	24	0.150
72	85.18	5.857	24	0.244
96	82.57	2.609	24	0.109
				$\sum$ = 0.731

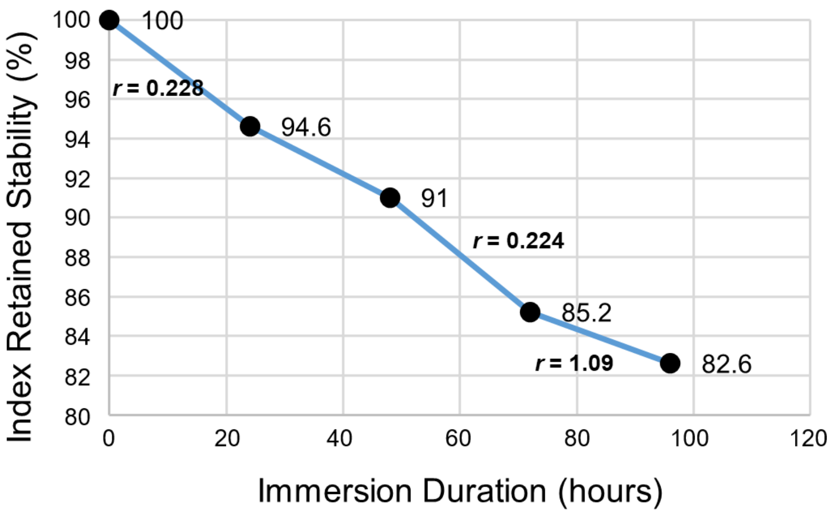

Figure 3. First Durability Index (FDI, %)

The first day of immersion, lost more strength than on the second. So, on the third and fourth days, different r-values were observed. The lowest r value was at a 96-hour immersion variation of 0.109%, and the largest was at a 24-hour immersion variation. The FDI or total slope value was 0.731%, meaning that, on average, the strength of the asphalt mix reduced by 0.731% per hour (or per day) over the immersion period, as clearly seen in Table 8 and in Figure 3.

Meanwhile, the SDI were calculated and presented in Table 9 and Figure 4.

Table 9. Second Durability Index (SDI, %)

Duration (hours)	Index of Retained Stability (IRS) (%)	$S_i - S_{i+1}$ (A)	$t_i - t_{i+1}$ (B)	$2t_n - B$ (C)	$a = \left(\frac{1}{2 \cdot t_n}\right) \cdot$ A.C	Retained Marshall Stability (RMS, %)
0.5	100.00	0	0	0	0.000	100.000
24	94.64	5.357	23.5	24.5	2.734	97.266
48	91.04	3.604	24	72	2.703	94.563
72	85.18	5.857	24	120	4.881	89.683
96	82.57	2.609	24	168	2.283	87.400
						$\sum$ = 12.6

The SDI measures the total percentage of strength lost after a specific immersion period. Calculated as the percentage decrease in Marshall Stability after immersion. Focuses on the total strength lost after full immersion. A higher SDI means a weaker mix after immersion.

The test results show a positive "a" value that identifies the loss of strength. The highest value of the average loss of strength in one day (a) in the variation of 72-hour immersion is 4.881%, and the lowest is 2.703% in the variation of 48-hour immersion. The value of the SDI is 12.6%, representing a total loss of strength of 12.6%.

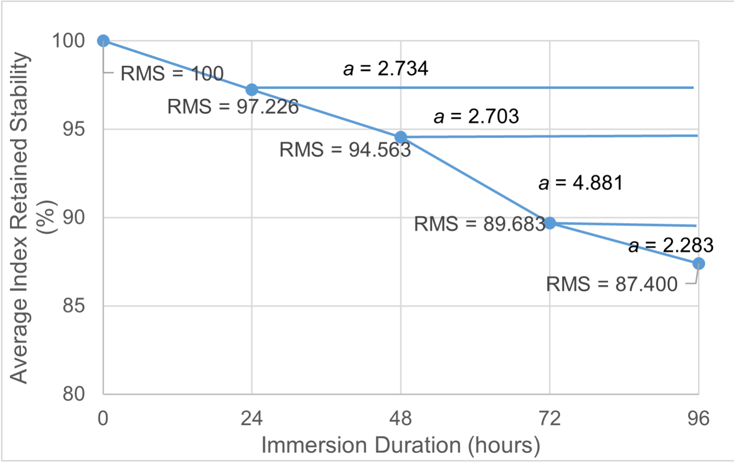

Figure 4. Second Durability Index (SDI, %)

Note: RMS refers to Retained Marshall Stability

The SDI value indicates a 12.6% loss in strength after 96 hours of immersion. This means that the asphalt mixture retained 87.4% of its original strength after prolonged exposure to water.

The AC-WC plastics mixture loses some strength due to water exposure. However, it still retains a significant portion of its stability, indicating a relatively good level of water resistance and durability. However, if the SDI value were much higher (e.g., 30% or more), it would indicate poor moisture resistance, leading to concerns about long-term pavement performance [17].

The FDI is 0.731%, indicating that the asphalt mix loses 0.731% of its strength per hour (or per day) on average during the immersion period. Meanwhile, the SDI is 12.6%, indicating that the mixture lost 12.6% of its total strength after 96 hours of immersion [18].

The durability of the mixture can be attributed to the substitution of asphalt with plastic waste, specifically LDPE, PP, and PS, which alters the mixture's characteristics. Plastic-modified asphalt exhibits greater sensitivity to temperature changes, which affects its interaction with water. Despite this sensitivity, the plastic modification plays a crucial role in maintaining the overall strength of the asphalt mixture, making it more resistant to water-induced damage than conventional asphalt mixtures.

The strong durability indices (IRS, FDI, SDI) observed, even with a mixed plastic composition, further support the viability of this approach. The mixture's resistance to water damage indicates that the composite plastic coating remains effective despite the use of different polymers, addressing a potential concern regarding the compatibility of LDPE, PP, and PS in a single matrix. This enhances the potential for real-world applications where plastic waste is inherently mixed.

4 Environmental and Practical Implications

Modifying asphalt pavements with mixed plastic waste offers significant environmental and potential economic advantages. From an environmental perspective, this research provides a direct pathway to diverting low-value, commingled LDPE, PP, and PS waste from landfills and oceans, aligning with global efforts to promote a circular economy. Utilising this waste stream in asphalt, a high-volume infrastructure material, offers a scalable recycling solution [19].

From a practical and economic standpoint, the dry process method was intentionally selected for its scalability. The feasibility of integrating this mixed plastic blend into existing asphalt plant operations without major capital investment is high, as it primarily involves adding a feeder for the plastic shreds into the aggregate mixer. A preliminary qualitative cost analysis indicates that reduced costs can be achieved through waste disposal avoidance, such as savings on landfill fees, as well as potential long-term benefits from the extended service life of pavements due to improved durability. In addition, substituting 10% of the asphalt, a relatively expensive binder, with cheaper plastic waste could yield direct material cost savings, depending on local asphalt prices and the costs of collecting and processing the plastic waste [19, 20].

However, these advantages need to be weighed against processing costs, which include collection, sorting to eliminate non-plastic contaminants and undesirable plastics like PVC, shredding, and storage of the plastic waste. While a detailed life-cycle cost analysis is beyond the scope of this study, the initial technical results are promising. The main practical challenge for real-world application would be establishing a reliable supply chain for collecting and pre-processing the plastic waste to a consistent size and quality. Future work must therefore focus on addressing these logistical challenges and conducting full-scale field trials to validate both the long-term performance and the economic viability of pavements constructed with mixed plastic waste.

5 Conclusions

Based on the findings of this study, several conclusions can be drawn. The results indicate that increasing the percentage of plastic waste substitution, incorporating a collaborative blend of LDPE, PP, and PS into the AC-WC asphalt mixture, improves Marshall stability values. However, this study is limited to laboratory-scale tests with relatively small sample sizes. Future work should include full-scale field trials, life-cycle cost and environmental impact analyses, and statistical validation using larger datasets. The results hold important implications for sustainable road construction policy and large-scale plastic waste management.

At an OAC of 6.3%, the addition of 10% LDPE, PP, and PS yielded the highest stability value while ensuring that key Marshall parameters, including Marshall Quotient, VIM, VFB, and VMA, remained within acceptable tolerance limits.

The optimal plastic content was determined to be 10% of the total asphalt weight. This composition resulted in an IRS of 94.64% after 24 hours of immersion, surpassing the 90% threshold required by Bina Marga standards. Furthermore, the absolute RMS was 87.40% after 96 hours of immersion, demonstrating enhanced durability and resistance of the modified asphalt mixture.

This study demonstrates that a collaborative blend of unsorted, low-value plastics (40% LDPE, 30% PP, 30% PS) can effectively enhance the performance and durability of AC-WC asphalt mixtures. This approach directly addresses a key knowledge gap between laboratory studies of single-polymer modifications and the practical realities of mixed plastic waste streams.

This study has demonstrated that a mixed blend of LDPE, PP, and PS plastic waste can be successfully incorporated into AC-WC asphalt mixtures using the practical dry process method, enhancing Marshall stability and durability. Beyond its technical performance, this approach offers a promising, scalable waste management solution with positive environmental implications. Even after prolonged exposure to water, the mixture continues to meet the Bina Marga standard, providing strong evidence that using plastic waste in asphalt mixtures can enhance road pavement performance.

Author Contributions

Conceptualization, E.E.P. and P.; methodology, E.E.P. and P.; investigation, E.E.P.; formal analysis, E.E.P. and N.E.P.; data curation, E.E.P.; writing—original draft preparation, E.E.P.; writing—review and editing, P. and N.E.P.; visualization, E.E.P.; validation, E.E.P., P., and N.E.P.; resources, P. and N.E.P.; supervision, P. and N.E.P.; project administration, E.E.P.; funding acquisition, E.E.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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