

Recycled Waste Polypropylene in Asphalt Pavement: An Experimental Research of Adopting Two Modification Processes



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ABSTRACT: Incorporating waste materials in road construction will not only improve pavement performance but also significantly reduce road material cost and address the environmental challenges posed by hazardous waste disposal. This study explores the potential of using Recycled Waste Polypropylene (RWPP) as an asphalt modifier and an artificial aggregate to enhance the characteristics of the asphalt mixture. New recycling techniques are adopted in this work to produce RWPP with controlled dimensions. In addition, two modification processes were applied to prepare RWPP-modified mixtures: Wet Process (WP) and Semi-Wet Process (S-WP). The RWPP with a particle size of 0.075 mm was blended with base asphalt in WP at different ratios of 0.15%, 0.25%, and 0.35% by total mixture weight. Whereas, in S-WP, RWPP was used as a partial replacement of fine aggregate at three sizes of 2.36, 0.3, and 0.075 mm and dosages of 1%, 3% and 5% by the weight of the asphalt mixture. The asphalt tests, which included softening point, ductility, and penetration, were conducted to examine the tensile properties, consistency, and temperature sensitivity of base and RWPP-modified binders. Marshall and tensile strength tests were performed to evaluate the RWPP-modified mixtures' behaviour, and the storage stability test was performed to measure the segregation phase between RWPP and base binder. The outcome showed that the addition of RWPP significantly enhances the mechanical characteristics and resistance against moisture damage for the asphalt mixture. It is recommended to use 0.15% and 3% of RWPP for WP and S-WP, respectively, to achieve the optimal performance. Finally, S-WP is more effective than WP in terms of avoiding storage stability issues, incorporating large amounts of plastic in road pavement field, and reducing the carbon emissions and energy consumption during mixing and paving.

Keywords: Recycling, Waste Polypropylene, Wet Process, Semi-Wet Process, Modified Asphalt

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I. INTRODUCTION

Enhancing the performance of asphalt binders plays a crucial role in improving pavement durability and extending its service life. This allows asphalt roads to endure heavy traffic and challenging conditions while remaining cost-effective and environmentally friendly. To achieve these benefits, researchers have incorporated polymers into asphalt binders, enhancing the flexibility and resilience of pavement at a reasonable cost (Basheet & Latief, 2024 (a)). Over the past decades, polymer-modified asphalt has gained excellent popularity in pavement production. However, this modified asphalt is a relatively costly asphalt for paving roads. Therefore, using inexpensive polymers like plastic waste can reduce the cost of pavement construction (Lingyun et al., 2022).

Currently, the increasing production of waste materials in the world is one of the high-impact environmental issues. Based on the statistics from the Ministry of Planning in Iraq, about 11 million tons of waste materials in 2023 was generated from Iraq provinces with a daily average of 1.5 kg of waste/person. As a results, in that year, Iraq ranked sixth on the list of the most polluted countries in the world with pollution level at 43.8 micrograms per cubic meter, exceeding

the acceptable level of 2.5 micrograms per cubic meter that specified by World Health Organization (IQAir's, 2023).

Waste materials included gaseous waste, liquid waste, solid waste, organic waste, and hazardous waste. To recycle these wastes and reduce the pressure on the environment, scientific researchers in Iraq, especially in civil engineering branch, investigated the feasibility of incorporating waste materials in many sectors such as soil stabilization (Rozan & Nadhmiah, 2021), road pavement (Al-Hindawi et al., 2023), building rehabilitation (Abd Kudhaer et al., 2024), and others. Particularly, in road pavement sector, many studies were conducted to utilize waste materials in asphalt mixture production like glass (Latief, 2019), crumb rubber (Abdullah & Al-Hadidy, 2025), plastic, and fiber (Jabbar et al., 2021).

One of the growing and significant waste components is plastic waste. Unfortunately, Iraq struggles with the accumulation of this waste, especially in urban areas, due to a lack of proper disposal processes and recycling infrastructure. For instance, based on the report of the Japan International Cooperation Agency in 2021, approximately 21% of total waste materials generated from Baghdad city-Iraq was plastic and dumped in unregulated landfills (Japan International Cooperation Agency, 2022). These quantities of plastic waste represent a huge resource and must be recycled to produce new

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usable materials that can be used in various fields, such as road construction sector, to protect the environment, encourage sustainable practices, and preserve the raw resources. Therefore, in this research, waste polypropylene (WPP) is utilized as a binder modifier and an artificial aggregate in asphalt pavement production because utilizing this waste in asphalt mixtures offer vital benefits: enhancing pavement performance, reducing reliance on traditional polymer modifiers, saving natural aggregate recourse, and repurposing waste materials.

The production of asphalt mixtures primarily depends on natural materials, such as mineral aggregates and asphalt binder. The binder plays a vital role in ensuring performance by bonding the aggregates and providing strength during service (Mohsin & Latief, 2025 (a)). Currently, enhancing the sustainability of road paving materials is a key strategic priority. As a result, the incorporating of waste plastic, particularly WPP, in pavement construction is being investigated (Hossain et al., 2024). Globally, polypropylene (PP) is the second most produced plastic, and it is a thermoplastic hydrocarbon with a crystalline structure (Yuetan et al., 2021).

As a renewable resource, current investigations have demonstrated that WPP can be transformed into recycled waste aggregate after shredding and screening and then used as partial replacement of mineral aggregate in asphalt mixture using dry process (DP). Using WPP as an aggregate significantly enhances the performance of asphalt pavement especially rutting resistance (Kim & Kim, 2025; Bueno & Teixeira, 2024). For example, Lee et al. (2024) evaluated the potential of replacing natural aggregate, with fine size less than 5 mm, in asphalt mixture with WPP aggregate. Notably, the outcomes showed that incorporating 5% WPP can improve the strength, plastic deformation resistance, and moisture damage resistance.

In addition, in many studies and field practices, using WPP as a modifier into asphalt mixture through applying wet process (WP) is a feasible approach, which can successfully enhance the overall behavior of pavement, particularly water damage resistance by enhancing the adhesion of a binder to aggregates (Vamegh et al., 2019; Duarte & Faxina, 2021; Ma et al., 2021). For example, Hamedi et al. (2018) examined the moisture susceptibility of a PP-modified mixture and revealed that modifying asphalt binder with 2% of PP-modifier can significantly enhance the moisture damage resistance in wet and dry conditions. This occurs because the free energy of adhesion between asphalt and aggregates will increase owing to the anti-stripping effect of PP, resulting in reducing the binder-aggregate stripping. However, when WPP-modified binder stored at high temperatures condition, a segregation between WPP and asphalt binder can be observed, which indicates agglomeration of WPP at the top surface of asphalt (Hu et al., 2024). As a result, longer time and higher temperatures are required to achieve a consistent asphalt binder when reused during asphalt mixture preparing. The previous issue often increases the modification costs as more fuel consumption is required to reheating the modified asphalt to achieve a homogenous binder. Besides, the reheating process can cause premature oxidation for the modified asphalt which

had a negative effect on the performance of asphalt pavement (Basheet & Latief, 2024 (b)).

In general, as reported by previous studies (Movilla-Quesada et al., 2019; Moghaddam et al., 2016; Mouratidis & Manthos, 2024) waste plastic in flake shapes (irregular form) was used in DP and WP modifications. Accordingly, especially at high dosages of waste plastic addition, the flakiness shape had a detrimental effect on the behavior of asphalt mixture, contributing to lower water damage resistance, indirect tensile strength, and stiffness. This is likely because the plastic flakes could not provide the proper dispersion in the asphalt binder and they exhibited a low strength and very loose interconnection of particles which potentially leading to non-uniform properties for asphalt mixture, particularly increasing the air voids content. Thus, it was suggested to use waste plastic in regular shape instead of flakes which can probably lead to better performance of asphalt mixture.

Compared to WP, the DP is the most common and widely method that used in production of WPP-modified asphalt mixtures because WPP has a high melting temperature and at the conventional mixing temperature (150-160 °C), it is difficult to achieve uniform dispersion in asphalt binder through applying WP. Thus, asphalt smoke emission can occur, thus, negatively affect the environment (Saikrishnan et al., 2020; Xu et al., 2022).

Correspondingly, developing the mixing process is essential to ensure the easy handling of WPP-modified bitumen, accomplish the lowering in the costs of modification process, and address the phase separation issue. The Semi-Wet Process (S-WP) is a new mixing approach that utilized specifically to reduce the negative effects that occur in WP, which includes incorporating recycled waste polypropylene (RWPP) into asphalt mixture as a partial replacement of natural aggregate by mixing it with hot asphalt for few minutes before adding to the aggregate mix. The comparison between the mixing processes is presented in Figure 1.

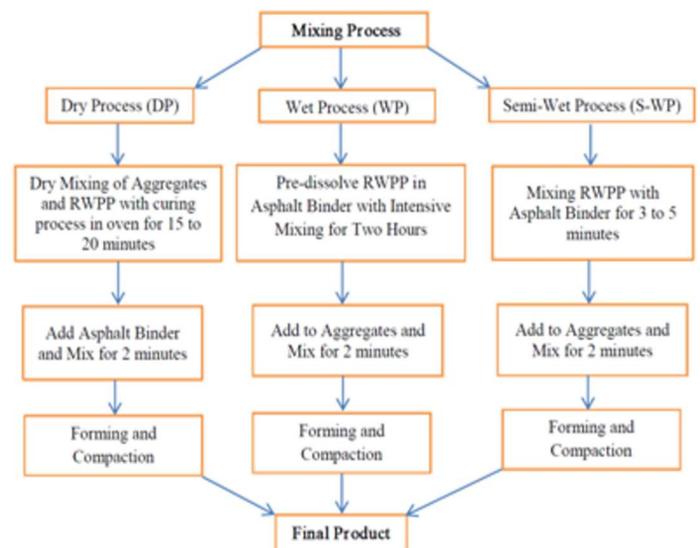


Figure 1 Comparison between mixture processes

In this research, the effect of using S-WP and WP on the performance of RWPP-modified mixtures is assessed in terms of mechanical characteristics, volumetric characteristics,

indirect tensile strength, and the resistance against water damage. In addition, RWPP with controlled dimensions is used to avoid the issues of flaked particles by developing the recycling process.

II. MATERIALS AND METHOD

A. Aggregate Skeleton

The aggregates were made from crushed quartz and supplied from Al-Nibaie quarry, situated northeast of Baghdad. According to the road specifications for the asphalt wearing course (General Specification for Roads and Bridges, 2003), the coarse and fine aggregate size ranges were specified between 19 to 4.75 mm and 4.75 to 0.075 mm, respectively. Also, limestone dust was utilized as the principal mineral filler in this work, accounting for 7% of the total aggregate weight. This filler was obtained from Karbala governorate's lime industry. Table 1 shows the results of typical laboratory experiments to identify the physical characteristics of aggregates. In addition, the target gradation of aggregate for wearing course was outlined in Figure 2.

Table 1. The Physical Characteristics of Aggregates

Material Property	Test Method	Result	Limits [28]
Mineral Filler			
Specific Gravity	-	2.70	-
Passing Sieve No.200 (%)	-	88	70-100
Fine Aggregate			
Apparent Specific Gravity	ASTM C-128	2.72	-
Bulk Specific Gravity	ASTM C-128	2.60	-
Clay Lumps (%)	ASTM C-142	0.98	3 (Max)
Water Absorption (%)	ASTM C-128	1.731	-
Coarse Aggregate			
Apparent Specific Gravity	ASTM C-128	2.61	-
Bulk Specific Gravity	ASTM C-128	2.58	-
Clay Lumps (%)	ASTM C-142	0.509	3 (Max)
Water Absorption (%)	ASTM C-128	1.024	-

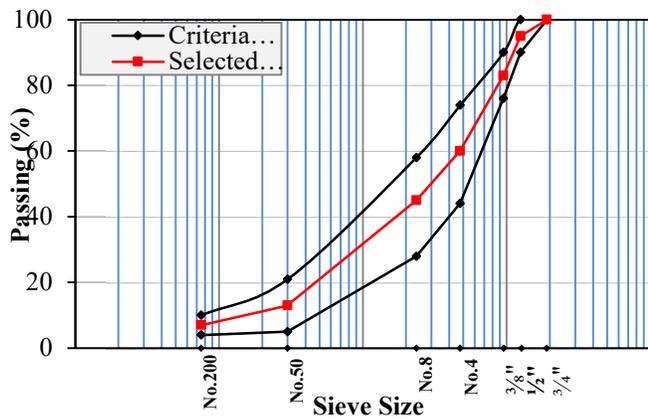


Figure 2 Selected gradation of aggregates for wearing course

The asphalt cement used was denoted as “base asphalt” in this research and it has a penetration grade type of AC (40-50). This type is commonly used for road paving. Base asphalt was supplied from Dora Oil Refinery located in Baghdad city, Iraq.

B. Waste Polypropylene

Waste polypropylene (WPP) was obtained locally and sourced from disposable cups and food packaging. The melting temperature for WPP is between 150 and 165 °C. The physical appearance of WPP is displayed in Figure 3.



Figure 3 Waste Polypropylene

C. Recycling Process of WPP

In this study, the recycled waste polypropylene (RWPP) was produced utilizing a controlled and regulated approach to assure consistency and quality. WPP was collected from domestic trash and underwent thorough cleaning to remove contaminants like dirt, oil, and food residues. After cleaning, WPP were ruptured into smaller bits with a mechanical shredder. The shredded WPP followed a thermal process to produce RWPP in a form and size similar to the aggregate particles. The thermal process involved heating WPP in a convection oven at temperatures ranging from 170-180 °C because WPP has higher melting points. The molten WPP (Figure 4a) was extruded and crushed using custom-designed die, resulting in long strands that were quickly cooled using a water bath to prevent thermal damage. The strands were chopped into aggregate-sized particles with controlled dimensions ranging from 12.5 mm to less than 0.075 mm in diameter using a granulator (Kim & Kim, 2025; Lee et al., 2024). The particle size distribution of RWPP was carefully controlled to meet the grade limits of asphalt mixtures. In this study, three sizes of RWPP were used 2.36, 0.3, and 0.075 mm, as shown in Figure 4b.

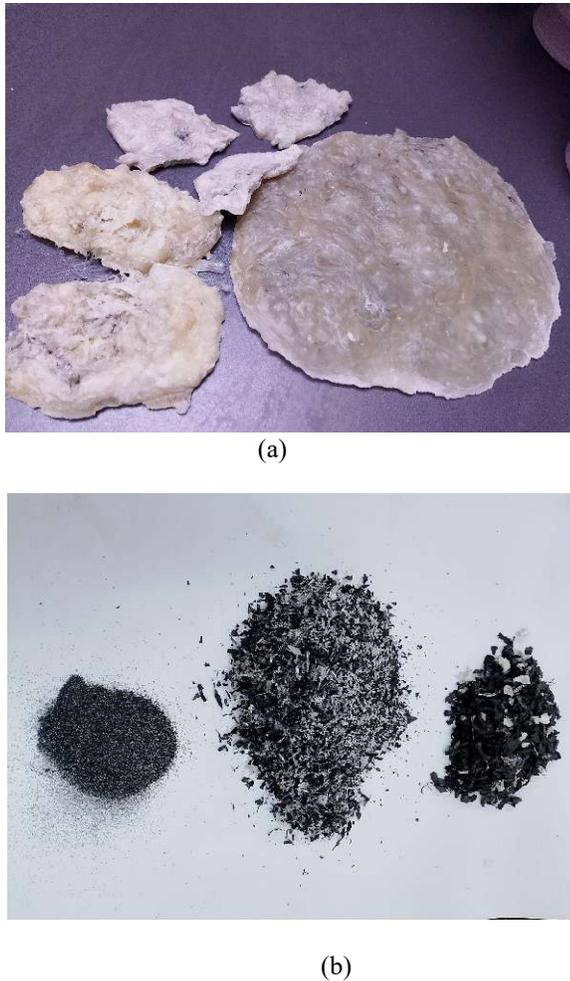


Figure 4 (a) Recycling Process of WPP (b) Surface appearance of RWPP sizes after crushing process.

D. Modification Process

1) Wet process

The particle size of RWPP that was used in binder modification through conducting wet process (WP) was 0.075 mm. The RWPP particles were added and blended with the asphalt in ratios of 0.15%, 0.25%, and 0.35% by total mixture weight. First of all, the asphalt is heated to a temperature of 163°C. The RWPP is then progressively added to the heated asphalt. In order to improve the PP polymer's capacity to melt more readily and suitably mix into the binder, the mixing procedure is carried out at a temperature of 170 ± 5 °C using a high-speed stirrer that runs at 3,000 rpm for two hours, creating a binder that is evenly blended (Al-Hadidy, 2023). The blending temperature is chosen based on the melting point of RWPP which is melted at a temperature of 160 °C. Nevertheless, particular attention is paid to the temperature and mixing time because high temperatures and oxygen might hasten the binder's aging process (Al-Azawee & Latief, 2020; Tauste et al., 2018).

2) Semi-wet process

Regretfully, under cool storage circumstances, PP polymer has a tendency to separate from asphalt binder. This separation will have a detrimental impact on the asphalt mixture's performance. Therefore, the semi-wet process (S-WP) was employed in this study to reduce storage stability concerns. Firstly, the binder is heated to a temperature of 150-160 °C, then mixed it with RWPP replaced with natural aggregate at sizes 2.36, 0.3, and 0.075 mm. The replacement proportions (by the weight of asphalt mixture) were used as follows: 1%, 3%, and 5% for three fine sizes. The blending between the RWPP and the base binder took three to five minutes to achieve the semi-crystalline structure of RWPP granules, improving the overlap between aggregate particles and attaining better adhesion to the aggregate surface (Basheet & Latief, 2025). Finally, this combination of binder and RWPP was immediately mixed with heated natural aggregates for around two minutes at a temperature of 170 °C.

E. Traditional Asphalt Cement Tests

The penetration test according to ASTM D5, the ductility test according to ASTM D113, and the softening point test according to ASTM D36, are the essential tests performed to assess the bitumen performance before and after WP modification. Softening point and penetration are vital tests for measuring the consistency and suitability of asphalt for various applications, specifically in pavement construction. Whereas, the ductility test examined the ability of asphalt binder to resist the deformation and withstand tensile stress in asphalt pavement.

F. Storage Stability Test

In general, polymers have a tendency to separate from modified asphalt binders. Therefore, storage stability test was performed to examine the compatibility and homogeneity between RWPP polymer and asphalt under heated storage conditions. To evaluate the storage stability of RWPP-modified binders, ASTM D7173 method was followed. An aluminum foil tube of 32 mm in diameter and 160 mm in height, containing the modified asphalt sample, was used. The tube was sealed and stored vertically inside a convection oven set to at temperature 163 °C for a period of 48 hours without an airtight seal. After the heating conditioning, the modified asphalt tube was exposed to a freezing cycle at a temperature of typically -10 °C for 4 hours before being divided into three equal parts on the horizontal. After that, the upper and lower parts were placed into separate cans designated T (Top) and B (Bottom), respectively. To determine the degree of separation, the softening point (ASTM D36) of T and B parts are measured and the variation in the softening point (ΔT) between T and B portions was identified. The testing procedure is illustrated in Figure 5.

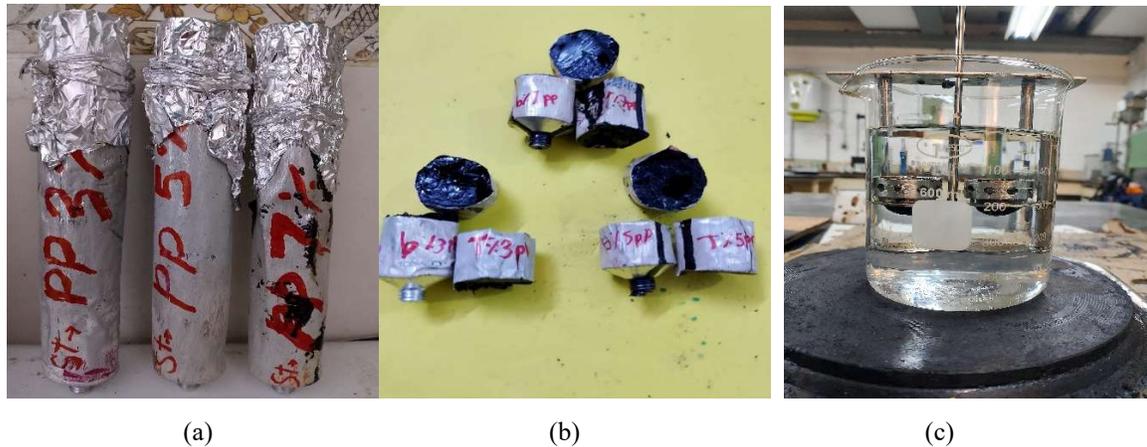


Figure 5 Storage stability test procedure (a) aluminum foil tube filled with RWPP-modified binder (b) three portions of tube, and (c) softening point test set-up

G. Marshall Test

Based on ASTM D6926, Marshall Mix Design Method was conducted to obtain the optimum asphalt content (OAC) and to assess the volumetric and mechanical properties for both mixtures, base and RWPP-modified. Firstly, the aggregates batch, at various percentages of coarse, fine, and filler sizes, were blended to meet aggregate gradation criteria. The aggregate mix was heated in a can for two hours at 150 °C. Meanwhile, the asphalt binder at a content ranging between 4 % and 6 % with a 0.5 % increment was heated at 155°C for two hours to achieve a viscosity of 170 cSt. The components (aggregate and asphalt) were well combined for two minutes at 155 °C. The mixture was transferred into 101.6 mm diameter and 63.5 mm height cylindrical molds and heated at 145°C for 10 minutes to achieve a viscosity of 280 CST. To replicate heavy traffic conditions, samples were compressed with 75 blows on each face using Marshall Hammer. After cooling for 24 hours at room temperature, the specimen was removed from the mold with a mechanical jack. The bulk specific gravity and the volumetric parameters including air voids, voids in mineral aggregate, and voids filled with asphalt, were determined. The specimens were tested using ASTM D6927 after immersion in a water bath at 60 °C for 30-40 minutes. The specimen is subsequently compressed at an average rate of 2 inches per minute (50.8 mm/min) on the lateral surface until the maximum load (stability) and flow values are measured. This technology is largely compactible, simple and one of the most common wireless technologies.

For each mix design, three Marshall replicated were prepared to ensure reliability. In this study, thirty-three specimens were prepared and tested in order to assess the Marshall properties in terms of modification process and RWPP contents: fifteen specimens for base mixture to obtain the OAC, nine specimens for RWPP-modified mixture through applying WP, and nine specimens for RWPP-modified mixture prepared by S-WP. The OAC was 5% for base mixture. To guarantee consistency, the base and RWPP-modified mixtures were prepared with the same optimal asphalt content (5%).

H. Indirect Tensile Strength Test

Following ASTM D4867, the asphalt concrete mixtures' moisture susceptibility was assessed. Each mix's samples were 101.6 mm (4 inches) in diameter and 63.5 mm (2.5 inches) in length. To replicate the field condition, specimens were made using Marshall technique and compressed per side to achieve $(7 \pm 1) \%$ air spaces. These samples were then divided into two groups: conditioned and unconditioned. For condition group, three specimens were put in a vacuum container containing distilled water to reach a saturation level of 55 to 80%, then subjected to freezing cycle at -18 ± 2 °C for 16 hours. Thawing cycle is followed by submerging the specimens in water bath for 24 hours at 60 ± 1 °C. After freezing and thawing cycle, the specimens were submerged in water bath for one hour at temperature of 25 °C. Finally, the specimens were tested. For unconditioned group, three specimens were tested after being submerged in a water bath at 25°C for 20 minutes.

Indirect tensile strength (ITS) calculations were carried out utilizing the method outlined in ASTM D6931. In this test, the compressive load was applied at a speed of 50.8 mm/min along the center of the cylindrical compacted samples. In the cross-section plane, these samples failed by splitting along the vertical diameter. Using the Equation (1), ITS was determined while the tensile strength ratio (TSR) of the asphalt mixture was determined using Equation (2).

$$ITS = \frac{2000 \times P_{max}}{\pi t d} \quad (1)$$

$$TSR = \frac{ITS_c}{ITS_u} \times 100 \quad (2)$$

where The ITS is the indirect tensile strength (kPa); P_{max} is the ultimate load (N); d is the specimens' diameter (mm), and t is the specimens' height (mm). The ITS_c is the conditional indirect tensile strength (kPa), and ITS_u is the unconditional indirect tensile strength (kPa). In this research, to assess the water damage resistance, a total of 42 specimens were produced, including six specimens for base

mixture, eighteen specimens for modified mixture prepared with WP, and eighteen specimens for modified mixture prepared with S-WP.

III. RESULTS AND DISCUSSION

A. Physical Properties of Asphalt Cement

Figure 6 presents the findings of the physical tests for base asphalt (Type 40-50) and RWPP-modified binders including: penetration, softening point, penetration index, and ductility. It is clear in Figure 6a that adding RWPP reduced the asphalt binder's penetration grade, and this is because RWPP increases the hardness of the binder, resulting in improving its internal resistance. This outcome coincides with the results of the previous research (Al-Mousawi et al., 2023).

In terms of softening point, the inclusion of RWPP has raised the softening point of binder (Figure 6b), making the modified binder more resistance to temperature than base binder (unmodified). This is attributed to the fact that RWPP is more resistant to high temperatures than bitumen (Fattah et al., 2021). The temperature susceptibility of asphalt is an

essential property and can be measured by computing the penetration index (PI), which is a quantitative measurement that depending on the softening point and penetration tests. Based on the data presented in Figure 6c, The PI values of asphalt binder increased from -1.283 to 0.882 with the addition of RWPP, indicating lower sensitivity to temperature changes compared to unmodified bitumen (base asphalt). This means that RWPP-modified binder can be applied in a wider range of temperature.

Additionally, as shown in Figure 6d, the ductility values of asphalt reduced with the addition of RWPP. Base asphalt had a ductility of about 133 cm, but with 0.35% of RWPP, it dropped to 80 cm, which is below specification limits. Nevertheless, ductility values within specification limits (above 100 cm) (General Specification for Roads and Bridges, 2003) have been obtained with 0.15% and 0.25% of RWPP addition. The hardness effect of RWPP on asphalt binder causes a drop in ductility values, meaning that RWPP-modified binders are more likely to exhibit brittle behavior at low temperatures than base binder. However, 0.15% RWPP produced a ductility value that was close to base binder.

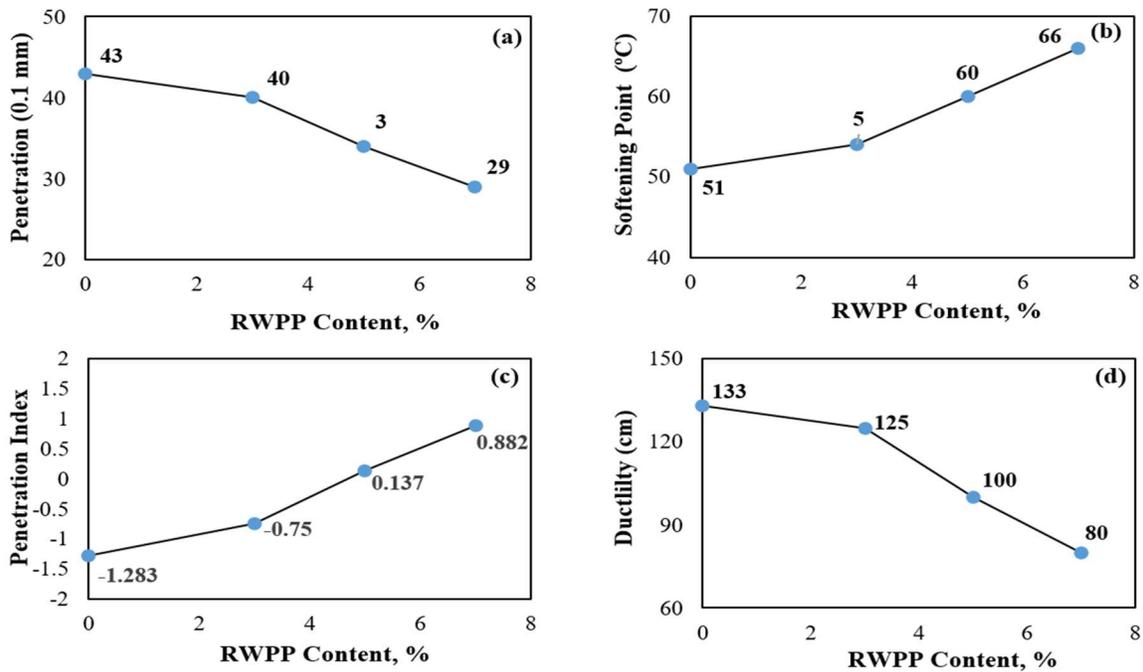


Figure 6 Physical properties of RWPP-modified binder: (a) penetration; (b) softening point; (c) penetration index, and (e) ductility

B. Storage Stability of RWPP-Modified Binder

The softening point values of the top and the bottom sections of modified binders with the addition of 0.15%, 0.25%, and 0.35% of RWPP were identified. The difference in the softening point values (ΔT) between the top and the bottom sections was determined to assess the stability of RWPP-modified binders in storage conditions. The modified sample can be considered if it has ΔT value equal or less than 2.5 °C. As presented in Figure 7, the binder with 0.15% RWPP had a softening point differential (ΔT) within the maximum limit (2.5°C), whereas, the modified binders with 0.25% and 0.35% RWPP have ΔT of 4.5 °C and 6 °C,

respectively, which are more than accepted limit. Higher ΔT values can indicate a potential for incompatibility and separation between RWPP and asphalt binder.

Overall, the phase separation and storage stability of modified binder are dependent on RWPP content. In other words, increasing RWPP content more than 0.15% can negatively affect the stability of modified binder during high-temperature storage conditions. This outcome is inconsistent with the findings of early investigation by Javadi et al, (2024), which stated that 0.25% PP-modified asphalt binder passed the maximum segregation limit, and it was stable at storage condition. However, as reported by

Javadi et al, (2024), this result was unexpected since there is an evident agglomeration on the surface of the top section specimen of the tube before performing softening point test.

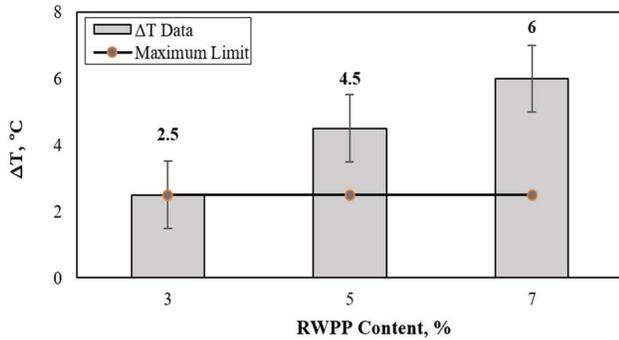


Figure 7 Softening point differential of RWPP-modified binders

C. Marshall Properties

Table 2 provides stability and flow outcomes for base and modified mixtures using S-WP and WP modification techniques. According to the data in Table 2, the stability

values of all RWPP-modified mixtures made by WP and S-WP are higher than that of base mixture. Obviously, incorporating RWPP into asphalt mixture increases stability by almost 32%, 57%, and 20% at addition of 0.15%, 0.25%, and 0.35% RWPP, respectively, through WP modification. Whereas, it rises by 24%, 36% and 1% at addition of 1%, 3%, and 5% RWPP, respectively, using S-WP modification. Additionally, it prevents rutting. WP modification shows the greatest results, and the modified combination with the 0.25% RWPP polymer addition had the highest stiffness value in WP discovered that the maximum stability for modified mixture were roughly 16.98 kN for WP at addition of 0.25% RWPP and 14.7 kN for S-WP at addition of 3% RWPP.

In general, flow results for base and modified mixtures are within the specification limits as provided in Table 2. The flow values of RWPP-modified mixtures are lower than that of a base mixture, offering better resistance to deformation under load like rutting distress. The outcome of the early study (Fattah et al., 2021) supports this finding.

Table 2. Stability and flow results of base and modified mixtures

Property	Base Mixture	Modified Mixture						Requirements	
		WP			S-WP			Minimum	Maximum
		RWPP Content, %							
		3	5	7	1	3	5		
Stability, kN	10.75	14.24	16.98	12.95	13.41	14.7	10.88	8	-
Flow, mm	3.7	3.2	3.0	2.8	3.0	2.8	2.75	2	4

The Marshall stiffness (MS) is the ratio between stability to flow and it is an indicator to evaluate the propensity of asphalt mixture to depression (rut). The ability of mixture to resist permanent deformation, like rutting, will improved with higher values of MS (Mohsin & Latief, 2025 (b)). The correlation between the RWPP content and MS for both base and modified mixtures using WP and S-WP is shown in Figure 8. Mixtures become more rigid when RWPP are used, which prevents rutting. WP modification shows the greatest results, and the modified combination with the 0.25% RWPP polymer addition had the highest stiffness value in WP.

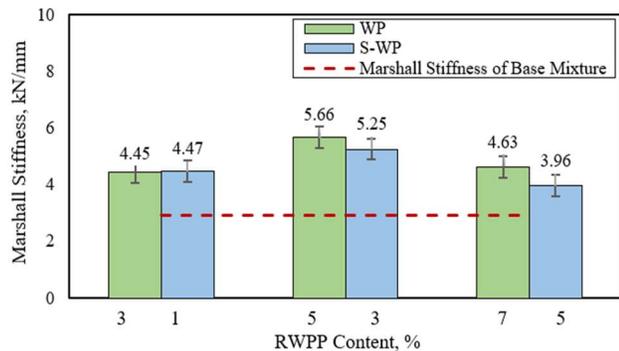


Figure 8 Marshall Stiffness for Base and Modified Mixtures

The results of volumetric characteristics for RWPP-modified mixtures using WP and S-WP are given in Table 3. It was observed that the volumetric characteristics of all mixtures (base and modified) satisfied the specification limit for asphalt concrete mixtures (General Specification for Roads and Bridges, 2023). The RWPP mixtures will have a lower bulk density than the base mixture. Consequently, the mixture's bulk density decreases when the RWPP ratio is increased. The difference in specific gravity between the RWPP polymer, the aggregates, and modified binder, is usually the cause of this reduction in density.

As the percentage of RWPP in the modified mixture rises, the percentage of air voids tends to rise significantly in all mixture. The paradox of increased air voids alongside enhanced mechanical strength in asphalt mixtures modified with RWPP can be explained through a series of interrelated mechanisms. The addition of RWPP facilitates the formation of a three-dimensional network within the asphalt matrix, strengthening structural cohesion through particle interlocking because WPP forms physical bonds that reinforce the mixture's integrity despite the presence of voids (Buruiana et al., 2023). Additionally, RWPP chemically interacts with the asphalt binder to produce a hybrid compound that improves both flexibility and viscosity. This transformation results in an internal polymer

network that enhances binder performance and offsets the adverse effects of porosity (Xia et al., 2025).

Also, the voids in mineral aggregate have risen with the addition of RWPP. Thus, the binder films can more easily be accommodated on the aggregate particles and provide thicker film to coat the aggregate, resulting in a mixture with better strength. Also, it has been noted that when asphalt

mixture is modified with RWPP using both modification methods (WP and S-WP), the voids filled with asphalt parameter tends to drop as the RWPP content increases. This is because of the RWPP polymer's flexibility, which enables it to fill in the gaps in the mixture.

Table 3 Volumetric characteristics of modified mixtures

Modification Process	RWPP Content, %	Density (gm/m ³)	Air Voids (%)	Voids in Mineral Aggregate (%)	Voids Filled with Asphalt (%)
WP	0	2.327	3.7	14.20	74.00
	3	2.319	3.8	14.27	73.37
	5	2.315	3.9	14.42	72.95
	7	2.305	4.1	14.79	72.20
S-WP	0	2.327	3.7	14.20	74.00
	1	2.312	3.9	14.21	72.55
	3	2.280	4.0	14.25	71.85
	5	2.270	4.2	14.30	70.62
Requirements	Minimum	Not Limited	3.0	14.00	Not Limited
	Maximum	Not Limited	5.0	Not Limited	Not Limited

D. Water Damage Resistance

Table 4 outlines the ITS results under dry and wet conditions for both base and RWPP-modified asphalt mixtures. Based on the experimental data, the RWPP-modified mixture achieves higher tensile strength in WP and S-WP for both conditions (dry and wet) when compared to those of base mixture. More precisely, modification with 0.25% RWPP in WP and 3% RWPP in S-WP have the

significant impact on the tensile characteristics in the modified mixture. This is because polymer granules that are distributed throughout the asphalt mixture serve as an extra layer of bonding between the aggregate and the binder. This enhancement in ITS for modified mixtures is in line with the findings of previous study (Vamegh et al., 2020).

Table 4 ITS outcomes for base and modified mixtures

Modification Process	RWPP Content, %	ITS, kPa	
		Condition	
		Dry (Unconditioned)	Wet (Conditioned)
Without Modification	0	1175.99	948.32
	3	1831.00	1582.33
	5	2055.00	1852.33
	7	1985.73	1699.13
S-WP	1	1746.00	1453.66
	3	1762.66	1563.66
	5	1194.45	967.30

The TSR results for base and RWPP-modified mixtures are shown in Figure 9. TSR calculates the ratio of strength in wet to dry circumstances to assess moisture-induced deterioration in hot asphalt mixture. Greater resistance to strength deterioration during water immersion is indicated by a higher TSR, which reflects improved water resistance. Therefore, mixtures with TSR values above 80% show greater resistance to such deterioration, whereas, those with values below 80% are vulnerable to moisture-induced harm. According to the TSR values in Figure 9, all mixtures obtained TSR values above 80%.

The results show that adding RWPP enhanced the resistance of mixture to water damage. Obviously, 0.25% RWPP in WP

and 3% RWPP in S-WP produced the best TSR values, showing 11.7% in WP and 10% in S-WP increase in water damage resistance over base mixture. Higher viscosity of modified asphalt is the reason of this improvement in moisture damage resistance, which strengthens the bond and improves adherence between the aggregate and modified binder. Consequently, this reduces the probability of adhesive failure (stripping) in asphalt pavement.

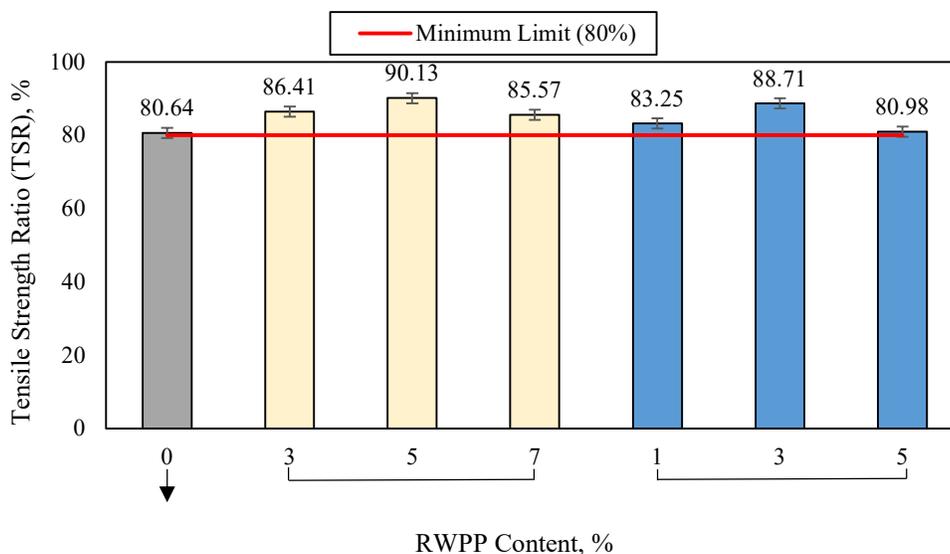


Figure 9 Tensile strength ratio of base and RWPP-modified mixtures

This study offered a reasonably thorough evaluation of the impact of adding RWPP polymer into asphalt mixture using two modification processes: WP and S-WP. New recycling process was used to produce RWPP in three sizes. The following are the main discussion drawn from the study:

(i) RWPP has a considerable effect on altering the physical properties of asphalt binder through applying WP modification. As a clarification, the inclusion of RWPP results in a decrease in penetration values (an increase in consistency). Also, RWPP-modified binder was less ductile (less resistant to thermal cracks) but more viscous (more resistant to permanent deformation). RWPP-modified binders have greater softening point values, thus, they are more resistant to high temperatures, indicating a greater resistance to long-term deformation. Furthermore, RWPP-modified binder is more consistent against temperature changes.

(ii) The storage stability results revealed that softening point difference for 0.15% RWPP-modified binder sample was 2.5 °C which represented the maximum acceptable requirement. Thus, adding more than 0.15% RWPP in WP modification can cause phase separation between RWPP and asphalt especially during storage at high temperature condition.

(iii) In general, the mechanical properties of asphalt mixtures are greatly improved by the addition of RWPP. The stability values of the RWPP-modified mixtures were higher compared to base mixture. However, the stability was declined at RWPP addition of 0.35% in WP and 5% in S-WP but it still higher than base mixture. The highest stability values for WP and S-WP was obtained at a RWPP concentration of 0.25% and 3%, respectively. Additionally, compared with S-WP, RWPP-modified mixtures prepared in WP modification show higher stability values. In addition, modified mixtures exhibit stronger resistance to permanent

deformations than base mixture since they have higher MS values.

(iv) The increasing in ITS values for both conditions (dry and wet) was more noticeable for modified binder with 0.25% RWPP applying WP. In addition, RWPP-modified mixtures achieved TSR above 80%, demonstrating their ability to withstand moisture-induced deterioration. In addition, compared to base mixture, it can be found that the TSR values of RWPP-modified mixtures prepared using WP increased by 7.2%, 11.8%, and 6.1% for RWPP addition of 0.15%, 0.25%, and 0.35%, respectively. At the same time, the TSR values of RWPP-modified mixtures prepared using S-WP increased by 3.2%, 10%, and 0.42% for RWPP addition of 1%, 3%, and 5%, respectively. Correspondingly, WP is more effective in improving the moisture damage resistance than S-WP and the optimal contents of RWPP were 0.25% and 3% for WP and S-WP, respectively.

(v) During the modification process, increasing the RWPP content beyond specific thresholds negatively impacted the workability and properties of the asphalt mixture. These thresholds are 0.15% and 3% of RWPP for WP and S-WP, respectively. Maintaining RWPP content below these limits is crucial to ensure the mixture's optimal performance.

(vi) This research provides a new recycling process to convert WPP into high-quality artificial aggregate with controlled dimensions, which can significantly enhance the overall performance of asphalt mixture, addressing the technical problem of the WPP in flake form. In addition, S-WP is adopted to saving energy, reducing gas emissions, providing economic benefits, solving the environmental pollution issues, and finally achieving the sustainability goals.

(vii) In conclusion, RWPP can be used as an artificial aggregate utilizing S-WP that delivers positive outcomes with speed of implementation and minimizes the cost arising from applying the WP, using a large amount of RWPP to reduce the pressure on the environmental and to avoid

stability issue for RWPP-modified binder during storage condition. As a result, S-WP is a promising process that could be used to produce eco-friendly and sustainable asphalt pavement.

IV. CONCLUSION

This study demonstrates that recycled waste polypropylene (RWPP) can significantly enhance the performance of asphalt mixtures through two viable modification processes, each suited to different practical applications. The findings confirm that while the Wet Process (WP) yields superior mechanical properties including higher stability, greater resistance to permanent deformation, and improved moisture damage resistance its effectiveness is constrained by storage stability issues, limiting optimal RWPP content to 0.15%. In contrast, the Solid-State Wet Process (S-WP), which utilizes a novel recycling method to convert waste plastic into artificial aggregate, allows for a higher incorporation rate (up to 3% RWPP) and delivers positive performance outcomes with greater practicality and cost-effectiveness, as it requires no specialized equipment and can be implemented in traditional asphalt plants. Ultimately, this research offers a strategic choice: adopt WP with chemical additives for high-performance pavements subjected to heavy traffic and high temperatures, or embrace S-WP as a sustainable, eco-friendly solution for low to moderate traffic applications thereby addressing both technical performance goals and environmental sustainability objectives. Future research should focus on extending this approach to other waste polymers, such as polyvinyl chloride and crumb rubber, while also evaluating the economic viability of the recycling process.

Authors Contributions

I. S. Daryul: Conceptualization, Manuscript preparation, Writing -original draft, Data, Experimentation. **R. H. Latief:** Conceptualization, Supervision, Validation, Literature, Analysis, Writing –review and editing.

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