Eco-Friendly Asphalt Mixture: Utilization of Waste Polypropylene as a Partial Replacement of Aggregate

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ABSTRACT: Recently, many techniques have been developed to improve the properties of asphalt pavement and to reduce environmental pressure. Adding waste polypropylene (WPP) to asphalt mixtures is one of the most often used and effective techniques. Nevertheless, waste plastic aggregate in flake form exhibited the worst performance in the asphalt mixture, as demonstrated in previous investigations. Therefore, a new recycling process is used in this research to produce crushed and angular WPP aggregate (WPPA) with controlled dimensions, usually ranging from 0.075 mm to 12.5 mm, similar to those of natural aggregate. WPPA is used as a partial replacement for coarse aggregates, fine aggregates, and mineral filler, replacing all aggregate sizes from 12.5 mm to less than 0.075 mm. Modified asphalt mixture was designed with replacement proportions of 4%, 6%, and 8% for coarse WPPA; 2%, 4%, and 6% for fine WPPA; and 0.5%, 0.75%, and 1.0% for filler WPPA by the weight of the asphalt mixtures. An abrasion test was performed to assess the resistance and durability of WPPA to tearing and wear. Marshall and indirect tensile strength tests were employed to assess the performance of control and WPP-modified mixtures. Compared to the control mixture, WPPA incorporation provided greater stability and higher stiffness. For instance, notable increases in stability (up to 34.8%) and stiffness (up to 42.8%) were observed upon replacing fine aggregates with 2% WPPA in the asphalt mixture. In addition, a significant enhancement in the resistance of WPPA-modified mixture against moisture damage was achieved as the tensile strength ratio (TSR) was increased substantially, especially at replacement ratios of 4% coarse WPPA, 2% fine WPPA, and 0.75% filler WPPA, where TSR was increased by 14.4%, 10.9%, and 8.8%, respectively. In conclusion, WPPA-modified mixtures are less susceptible to moisture damage with higher stability and stiffness.

ABSTRAK: Dalam beberapa tahun terakhir, banyak teknologi telah dikembangkan untuk meningkatkan sifat-sifat pengaspalan asfalt dan mengurangkan beban alam sekitar . Penambahan sisa polipropilena (WPP) kepada campuran asfalt adalah salah satu teknik yang paling kerap digunakan dan berkesan. Dalam kajian ini, agregat WPP (WPPA) digunakan sebagai penggantian separa agregat kasar, agregat halus, dan pengisi mineral, menggantikan semua kecerunan agregat daripada saiz 12.5 mm kepada saiz kurang daripada 0.075 mm. Kompaun plastik terpakai dalam bentuk kepingan menunjukkan prestasi yang lebih buruk untuk campuran aspal seperti yang dibuktikan dalam penyelidikan sebelum ini. Oleh itu, satu proses kitar semula baru sedang digunakan untuk menghasilkan WPPA dengan dimensi yang terkawal, biasanya antara 0.075 mm hingga 12.5 mm. Campuran asfalt diubah suai telah direka bentuk dengan perkadaran gantian 4%, 6%, dan 8% untuk WPPA kasar; 2%, 4% dan 6% untuk WPPA halus; dan 0.5%, 0.75% dan 1.0% untuk pengisi WPPA mengikut berat campuran asfalt berat. Ujian lelasan dilakukan untuk menilai rintangan dan ketahanan WPPA untuk koyak dan haus. Marshall dan ujian kekuatan tegangan tidak langsung telah digunakan untuk menilai prestasi campuran kawalan dan campuran asfalt yang diubah suai dengan WPP. Berbanding dengan campuran kawalan, penggabungan WPPA memberikan kestabilan yang lebih tinggi dan kekukuhan yang lebih baik, yang masing-masing meningkat sebanyak 7-35%

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dan 1-43%. Menurut ujian kekuatan tidak langsung, peningkatan ketara dalam rintangan campuran diubah suai WPPA terhadap kerosakan lembapan telah dicapai kerana nisbah kekuatan tegangan (TSR) telah meningkat dengan ketara terutamanya pada nisbah penggantian 4% WPPA kasar, 2% WPPA halus dan 0.75% pengisi WPPA. Secara kesimpulannya, campuran yang diubah suai WPPA kurang terdedah kepada kerosakan lembapan dengan kestabilan dan kekakuan yang lebih tinggi.

KEYWORDS: *Waste polypropylene, Recycling process, Aggregate replacement, Dry process, Asphalt binder.*

1. INTRODUCTION

In recent decades, large quantities of plastic waste have been generated worldwide, negatively affecting the environment. In some regions, such as European countries, approximately 30% of total plastic waste is recycled, while the remaining 70% is disposed of in landfills [1]. Globally, around 9% of waste plastic was recycled, while the remaining quantities were landfilled, leaked into the environment, were mismanaged, or were incinerated [2]. As the push for sustainability grows stronger, scientists are increasingly exploring innovative approaches to recycling and repurposing waste plastic. Therefore, pavement researchers have extensively investigated the use of various types of plastic in asphalt mixtures as a binder modifier, additive, partial replacement for aggregates, or a combination of these [3].

Currently, polymer-modified asphalt mixtures achieve more desirable pavement performance, enabling them to resist heavy loads and harsh environmental conditions. For instance, modifying the asphalt binder with 6% high-density polyethylene increased stability by approximately 113% and improved resistance to water damage by more than 10% in modified asphalt mixtures [4]. In addition, incorporating waste plastic in asphalt pavement contributes to sustainability by lowering costs and reducing pollution. For clarification, using waste plastic after recycling in the pavement sector can help save energy, preserve natural resources, lower harmful emissions, and reduce landfill waste. The first use of waste plastics in the pavement field originated in the 1990s, primarily in fiber form to modify the properties of asphalt mixtures [5-6].

In fact, polymers can be categorized into two groups: elastomers, such as styrene-butadiene rubber, polybutadiene, and styrene-butadiene-styrene, which enhance both elasticity and strength, and plasterers, such as polyethylene, polypropylene, and ethylene vinyl acetate, which only enhance strength [7]. Polypropylene is the second-most-produced plastic globally, accounting for 21% of the total plastic market [8]. Its widespread use highlights its importance in various industries. Polypropylene, discovered in 1951, gained rapid popularity due to its low density among commodity plastics. It offers excellent chemical resistance and can be processed using various methods, such as injection molding and extrusion, making it highly versatile and widely used in packaging, medical supplies, automotive components, housewares, and consumer goods [9].

Hot-mix asphalt primarily consists of aggregates and asphalt binder. Thus, incorporating waste plastic into asphalt mixtures as a partial replacement for aggregates reduces dependence on traditional virgin aggregates, helping conserve vital natural resources. Waste plastic is added using a dry process, meaning these wastes are incorporated into the aggregate prior to encountering the binder. This method forms a thin plastic coating around the aggregate, and when the coated aggregate is combined with the binder, it delivers outstanding performance in the asphalt mixture because polymers typically have higher viscosity than asphalt binders and better adhesion to the aggregate [10]. In addition, chemical interactions can form between high-viscosity polymers and polar components on the natural aggregate surface, thereby forming an additional adhesion layer. Thus, the mechanical interlocking of the aggregates, internal strength, cohesion, and the resistance of asphalt pavement to water stripping were improved [11, 12]. In general, the degree of interaction of the polymers with any material depends on their softening temperature, as well as on the time of digestion and mixing [10].

In this research, waste polypropylene (WPP) is used as a partial replacement of aggregates in an asphalt mixture. Incorporating WPP-modified aggregate (WPPA) into asphalt mixtures is an effective and practical option, not only from an environmental perspective but also from an economic perspective, since aggregates comprise nearly 95% of the asphalt mixture. Generally, incorporating WPPA as an artificial aggregate in asphalt mixtures is an economical choice due to reduced energy consumption, lower waste disposal costs, decreased transportation needs, lower material costs, and improved pavement performance, leading to long-term savings [13]. Several studies have examined the use of waste plastic as a partial replacement for natural aggregates in asphalt mixtures; however, WPPA has been used in only a limited number of investigations. Thus, it is imperative to highlight the significance and originality of this study on environmentally friendly asphalt mixtures made from waste plastic.

In fact, the dry process is more appropriate for incorporating WPP into the asphalt mixture, since WPP has a melting point above 160 °C. In turn, WPP faces difficulties during blending with the binder via the wet process because its melting point is higher than the binder's mixing temperature; thus, it is difficult to melt completely within the binder structure, leading to premature binder aging and making the pre-mixing process difficult [14]. The asphalt binder becomes brittle and stiff due to premature aging during the modification process with plastic, leading to a severe reduction in pavement service life by increasing its susceptibility to various distresses, particularly cracking [15]. Whereas WPP was added into asphalt mixtures in a dry process as an artificial aggregate at typical mixing temperatures, avoiding separation and melting issues. In addition, the dry process is more cost-effective than the wet process because it eliminates the need for specialized equipment and pre-melting [16].

Hence, Kim et al. [17] studied the incorporation of waste plastic aggregate, including WPPA, as a partial replacement of natural coarse aggregate at 10% and 20% by aggregate weight. The WPPA sizes ranged between 5 and 13 mm. The outcomes revealed that the WPPA-mixture exhibited a 23% higher Marshall stability than the control mixture. Also, the tensile strength of the WPPA mixture increased by 20% and 18% for dry and wet conditions, respectively. Whereas Bumruiana et al. [18] used WPP, at sizes ranging from 0.1 mm to 2 mm, as a mixture modifier, adding it at three proportions: 0.1%, 0.3%, and 0.6% by weight of the mixture. Adding 0.3% WPP raised the Marshall stability of the asphalt mixture by 32% compared to the control mixture.

Lee et al. [19] opted to use WPP in a fine size (less than 5 mm) as an artificial aggregate in lower pavement layers, which was added at 3%, 5%, 7%, and 10% to conserve natural resources of natural aggregate and to reduce pressure on the environmental, it was combined with the addition of magnesium powder (particle size less than 0.075 mm) to improve the performance of the mixture. The results reveal that the asphalt mixture with 5% fine WPPA demonstrated excellent water damage resistance, greater strength, and higher resistance to plastic deformation, with improvement rates of 31%, 39%, and 60%, respectively, compared to the control mixture prepared with natural aggregates.

Dione et al. [20] used 50% WPPA and 50% waste low-density polyethylene as partial replacements for natural aggregate, with contents ranging from 2% to 8%. Also, these waste plastics are incorporated into asphalt mixtures in a flake shape with a fine size between 2 mm and 5 mm. The research showed that asphalt mixture performance improved with the addition of waste plastic at percentages below 7%, with increased Marshall stability, enhanced moisture damage resistance, and an 80% reduction in rut depth compared to the mixture without waste plastic. This performance enhancement can be achieved through two main mechanisms. The first mechanism is to improve asphalt-aggregate adhesion by effectively coating the aggregate surfaces. The second mechanism uses WPPA as a reinforcement material within the aggregate skeleton [21]. However, in other studies, using waste plastic in flake form as a partial replacement for aggregate had a negative impact on the mixture's performance, contributing to lower permanent deformation, indirect tensile strength, stiffness, and moisture damage resistance [22-23].

Although promising outcomes have been obtained, these studies have often overlooked crucial gaps and shortcomings. The significant gap is the limited use of WPPA as a partial replacement for aggregates in asphalt mixtures at different ratios. In addition, the literature lacks sufficient in-depth research examining the effects of varying WPPA sizes and angular shapes on asphalt mix performance. Researchers have observed that the irregular structure, sharp edges, and higher surface area of angular aggregates can improve mechanical interlocking and bonding between aggregate particles within the asphalt mixture more than those of rounded aggregates and flake-shaped plastic aggregates. This mechanical interlocking is crucial for forming a strong aggregate skeleton and effective load transfer, leading to higher stability, better workability, higher shear strength, and superior resistance to deformation, particularly under elevated temperatures and heavy traffic loads [24, 25].

These gaps motivate this research, which aims to systematically assess and enhance WPPA to increase the sustainability and viability of asphalt mixtures. The aim of this research was to assess the feasibility of replacing natural aggregates with WPPA using a dry process, without compromising the performance of the asphalt mixture while preserving natural aggregate resources. A new recycling process is employed to produce WPPA with different sizes, controlled dimensions, and angular shapes. Three WPPA sizes (coarse, fine, and filler) were considered. Pavement performance was evaluated using a variety of tests, including abrasion, Marshall, and water damage resistance tests.

2. MATERIALS

2.1. Asphalt Binder

Asphalt binder Type (40–50) is sourced from the Al-Dora refinery oil in Baghdad, Iraq, and is commonly used in local paving works because it has relatively high hardness and stiffness compared to other types, such as 50-60 and 60-70. Thus, it is better suited for withstanding high-traffic loads and hot climates, especially in the middle and southern regions of Iraq. Laboratory tests were conducted in accordance with ASTM standards, and the results were compared with Iraqi road and bridge specifications [26]. In this study, asphalt binder (Type 40-50) was utilized to produce both conventional and modified asphalt mixtures. Before its application in mixtures, the physical properties of the asphalt binder, including specific gravity, ductility, softening point, flash point, and penetration, were thoroughly analyzed, as shown in Table 1. Also, the penetration and ductility tests were repeated on the residue from the thin-film oven test to assess changes in the asphalt binder's flexibility and consistency at high temperatures during production and construction. Correspondingly, this can help predict the pavement's performance, particularly in terms of durability and cracking resistance.

Table 1. Physical properties of asphalt binder

Property	Test Method	Results	Requirements [26]
Penetration, 1/10 mm	ASTM D-5	43	40-50
Specific Gravity, unit-less	ASTM D-70	1.04	-
Ductility, cm	ASTM D-113	133	≥100
Flash Point, ºC	ASTM D-92	324	232 min
Softening Point, ºC	ASTM D-36	51	-
Thin Film Oven Test (TFOT)	ASTM D-1754	-	-
Retained Penetration after TFOT, %	ASTM D-5	75	> 55
Ductility after TFOT, cm	ASTM D-113	95	> 25

2.2. Aggregates

The fine and coarse aggregates utilized in this study were sourced from the Al-Nibaai quarry. Coarse aggregates were defined as those retained between sieves No. 3/4 and No. 4, while fine aggregates were classified as those retained between sieves No. 4 and No. 200. In the road laboratory, these aggregates were sieved and blended to conform to the local specification [26]. In addition, limestone dust, obtained from a local factory, was used as the mineral filler in this study. Generally, this filler is used in conventional asphalt mixtures. The physical properties of the filler were examined, revealing a bulk specific gravity of 2.70 and a passing percentage of 88% through sieve No. 200. Physical tests were performed to evaluate the properties of both fine and coarse aggregates, and their results are presented in Table 2. In addition, Fig. 1 shows the selected gradation of aggregates, including coarse, fine, and filler materials, for conventional asphalt mixtures used in the surface layer, which aligns with the criteria limits. These limits were stipulated by the local specification [26].

Table 2. Physical properties of coarse and fine aggregates

Property	Coarse Aggregate		Fine Aggregate	
	Results	Test Method	Results	Test Method
Bulk Specific Gravity	2.58	ASTM C-127	2.6	ASTM C-128
Apparent Specific Gravity	2.61	ASTM C-127	2.72	ASTM C-128
Water Absorption, %	1.024	ASTM C-127	1.731	ASTM C-128
Clay Lumps, %	0.509	ASTM C-142	0.98	ASTM C-142
Passing Sieve No. 200, %	0.46	ASTM C-117	0.94	ASTM C-117

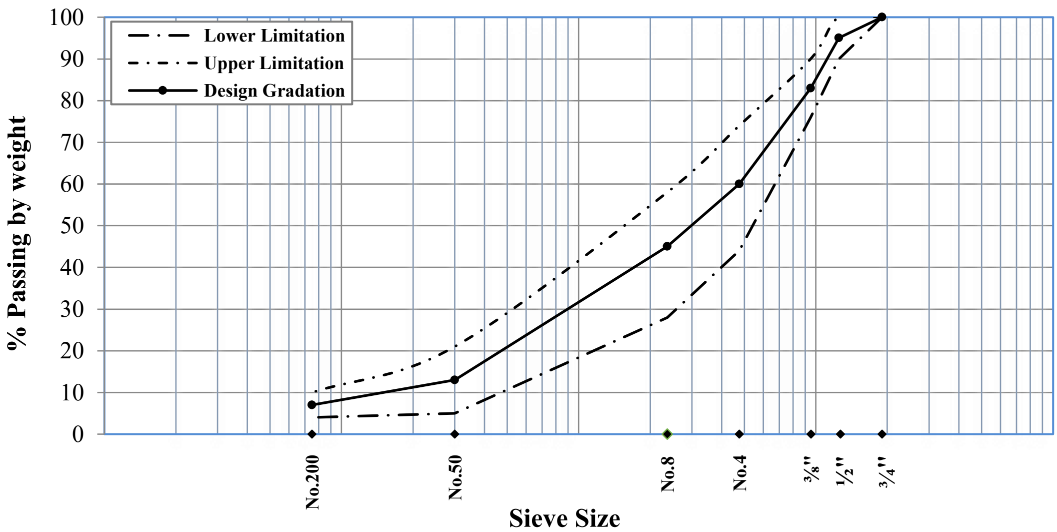

Figure 1. Aggregate gradation for the surface layer.

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2.3. Waste Polypropylene

In this work, WPP was sourced from local disposable plates, food packaging, microwave food containers, automotive parts, and cups. ASTM C128 was followed and used to measure the water absorption of WPP. The physical characteristics of WPP are listed in Table 3.

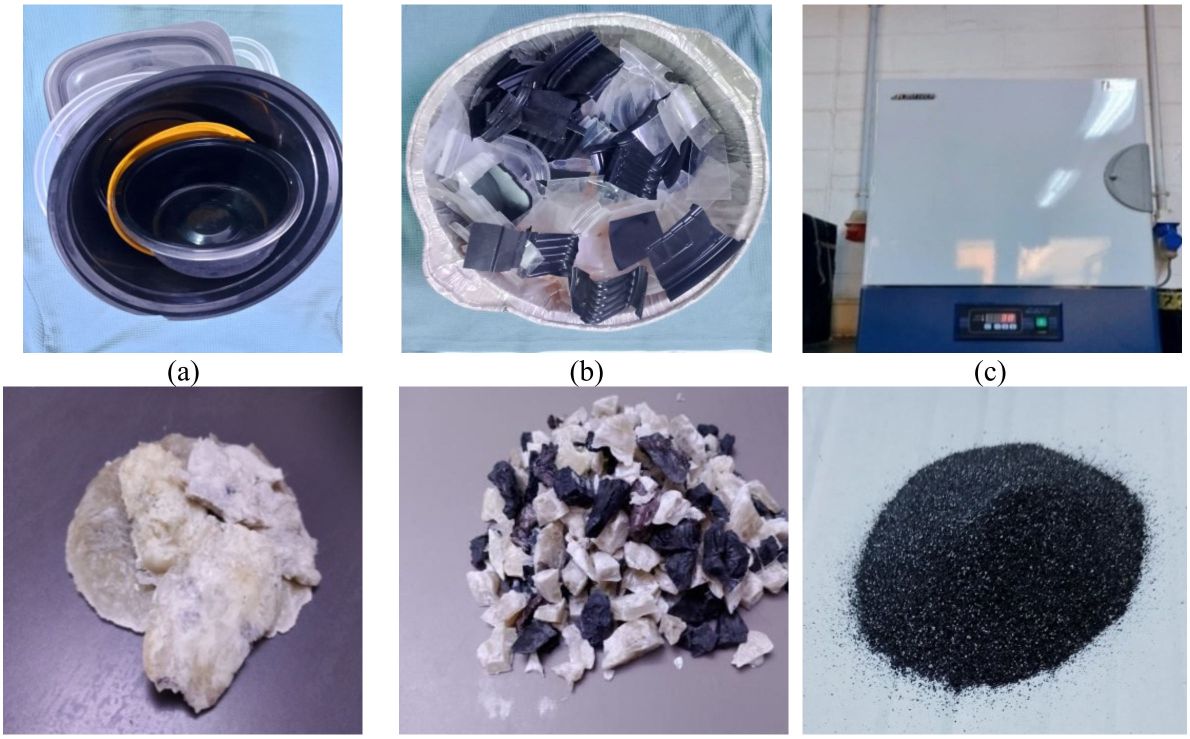
Table 3. Physical properties of WPP

Property	Value
Color	Transparent
Melting Point, °C	150-165
Water Absorption (%)	1.3

3. Experimental Methods

3.1. Production of WPP Aggregates

Figure 2 illustrates the production stages of WPPA. Firstly, WPP undergoes manual sorting (Fig. 2a). The sorted plastics are then cleaned thoroughly, shredded into small flakes, and soaked and dried to eliminate dirt and dust, as shown in Fig. 2b. The plastic resin is melted at temperatures of 160–180 °C (Fig. 2c) [17, 19], transforming it into a molten form ready for further processing, as presented in Fig. 2d. Following that, molten WPP is carefully extruded through a custom-designed die, producing WPPA with controlled dimensions, typically ranging from 12.5 mm to 0.075 mm (Fig. 2e). These WPPA have sharp edges and an irregular surface similar to the shape of natural aggregate particles. To use WPP as a filler material, the molten WPP is cooled to room temperature, collected in a flat pan, and mechanically ground for approximately 5 min into a fine powder with particle sizes below 0.075 mm, as illustrated in Fig. 2f.



(a) (b) (c)

(d) (e) (f)

Figure 2. Manufacturing WPPA: (a) collection of WPP; (b) shredded WPP; (c) melted WPP; (d) cooled WPP; (e) WPPA in coarse and fine sizes; and (f) WPPA powder.

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This process ensures consistency in size and quality, making WPPA suitable for use in construction roads. In this study, the replacement proportions (by the weight of asphalt mixture) were used as follows: 4%, 6%, and 8% for coarse WPPA; 2%, 4%, and 6% for fine WPPA; and 0.5%, 0.75%, and 1% for filler WPPA. The replacement contents of WPPA for fine and coarse aggregates were selected based on findings from previous studies [19, 20, 27]. Whereas the replacement contents of WPPA for the filler size have been selected by the authors, no previous studies have replaced the filler materials with recycled plastic waste. The natural aggregates and WPPA sizes are depicted in Fig. 3.

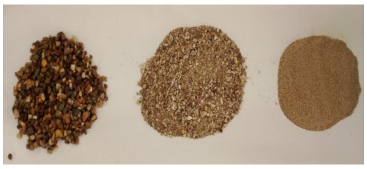
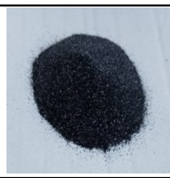
Type of Aggregate	**Type of Particle**						
	Coarse			Fine			Filler
Natural Aggregate							
WPPA							
Particle Size, mm	12.5	9.5	4.75	2.36	0.3	0.075	Less than 0.075

Figure 3. Surface appearance and sizes of natural aggregate and WPPA.

3.2. Abrasion Test

One of the goals of this research was to partially substitute natural aggregates retained on sieve sizes (12.5-9.5 mm) with WPPA at replacement proportions of 4, 6, and 8%. The Los Angeles test was used to calculate aggregate wear resistance, and the abrasion loss value should be less than 30% for pavements, as specified by the local specification for roads and bridges [26]. The Los Angeles abrasion test, following the ASTM C-131 standard, is presented in Fig. 4. This test is performed to evaluate the resistance of a mixture of WPPA and natural aggregate to abrasion and impact. There are six types of aggregate grading (A, B, C, D, E, and F) in the ASTM C-131 standard. Among these types, grading type B is more appropriate for local aggregate gradation for the surface layer, as specified by the local specification [26]. For grading type B, a sample of coarse aggregate at a weight of 5000 gm (2500 gm retained on a sieve with a size opening of 12.5 mm (½ inch) and 2500 gm retained on a sieve with a size opening of 9.5 mm (⅜ inch)) is combined with eleven steel spheres and placed inside a rotating steel drum. The drum rotates for a designated number of revolutions (typically 500 for grading type B), subjecting the aggregate to continuous crushing, abrasion, and grinding. After completing the rotation, the aggregate is removed, sieved through a No. 12 sieve, and the weight retained on the sieve is measured. The percentage of material loss, known as the Los Angeles abrasion or abrasion loss, is calculated using the formula:

$$\textit{Abrasion Loss (\%)} = \frac{W_{Original} - W_{Final}}{W_{Original}} \; x \; 100 \qquad (1)$$

where $W_{Original}$ is the original weight of the aggregate sample before the Los Angeles test in gm, and W_{Final} is the retained weight of the aggregate sample after the Los Angeles test in grams.

Figure 4. Los Angeles abrasion test: (a) sample of natural aggregate and WPPA; (b) Los Angeles drum; and (c) sample after test.

3.3. Asphalt Mixture Sample Preparation

The established combinations total 102 samples. Marshall samples, measuring 101.6 mm in diameter and 63.5 mm in height, are used in asphalt mixture design tests to assess key properties. Firstly, density and air voids (AV) were measured to evaluate the mixture compaction and to determine the percentage of air-filled spaces, respectively, which mainly influence durability. Secondly, voids in mineral aggregate (VMA) were computed to assess the asphalt film thickness on aggregate surfaces, which is vital for durability. Whereas voids filled with asphalt (VFA) were calculated to determine the percentage of air voids filled with asphalt, which is crucial for achieving the desired balance among permeability, compaction, and durability in the asphalt mixture. Thirdly, Marshall stability was measured to evaluate the strength of the asphalt mixture, which indicates load capacity. At the same time as measuring Marshall stability, the flow was recorded to assess deformation under load, which represents deformation prior to failure. Finally, the resistance of asphalt mixtures (modified and unmodified) to moisture (water) was assessed.

Table 4. Number of samples for control and WPPA-modified mixtures distributed based on Marshall and water damage tests

Mixture Type		Replacement Proportions of WPPA (%), by the Weight of Asphalt Mixture	Sample Number		
			Marshall Test	Water Damage Test	
				Dry Condition	Wet Condition
Control Mixture		-	15	3	3
Modified Mixture	WPPA Coarse	4	3	3	3
		6	3	3	3
		8	3	3	3
	WPPA Fine	2	3	3	3
		4	3	3	3
		6	3	3	3
	WPPA Filler	0.50	3	3	3
		0.75	3	3	3
		1.00	3	3	3
Total Number of Samples			102 sample		

For the control mixture, the aggregate was blended with asphalt and stirred for three minutes. This ensured that the aggregate was thoroughly coated by the binder, achieving uniform coverage [28]. For mixtures modified with WPP, the mix of natural aggregates and WPPA was placed in an oven for three to fifteen minutes at a temperature of 170-180 °C [29]. It formed a uniform coating around the aggregates after hot bitumen at 160°C was incorporated into the mixture. The samples were compacted to 75 blows per side for the Marshall test. Meanwhile, for water damage test samples, 54 blows per side are applied to achieve the required air voids. After compaction, samples were left to cure in the molds for 24 hours at room temperature. Table 4 provides the total number of samples by mixture type, the WPPA replacement ratio for the modified mixture, and the number of tests conducted.

3.4. Marshall Test

According to ASTM D6927, the Marshall mix design is commonly used in Iraq to optimize hot asphalt mixtures. The asphalt content for hot mixtures used in surface and binder layers was specified as 4%-6% in the local criteria [26]. Therefore, these mixtures were designed using five asphalt content levels: 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%. A total of 15 specimens were prepared, three for each asphalt percentage, to determine the optimal asphalt content (OAC). The Asphalt Institute's method was employed to calculate the OAC that achieved maximum density, maximum stability, and 4% air voids. For each sample, the bulk density, AV, VMA, and VFA were determined. Following this, the samples were conditioned at 60 °C for 30-40 minutes. These samples were tested using the Marshall loading device at a rate of 50.8 mm/min until the maximum load was reached, which indicates Marshall stability. At that load, the flow is measured, which indicates the deformation in mm. The relationship between flow and stability represents a delicate balance and trade-off between the asphalt mixture's flexibility and its ability to resist deformation. For the selected gradation, the OAC was found to be 5% for the control mixture, and it was also used for WPPA-modified mixtures.

3.5. Indirect Tensile Test

The indirect tensile test is a widely used method for evaluating the water-damage performance of flexible pavements. In this research, sixty specimens were prepared and tested under two conditions: dry and wet. Six specimens represented a control mixture with no WPPA addition, while fifty-four specimens were prepared for WPPA-modified mixtures.

The stages of performing this test are presented in Fig. 5. Specimens were compacted using an automatic Marshall impact compactor to achieve a target air void of 7±1%. The test was conducted in accordance with ASTM D 4867 M. Specimens were divided into two groups: unconditioned and conditioned. For conditioned specimens, water saturation was achieved using vacuum desiccators, with a saturation level between 55% and 80%. Saturated samples were then wrapped in stretch film, placed in plastic bags containing 10 ml of water, and stored at -18°C for 16 hours. Afterward, these samples were moved to a water bath at 60 °C for 24 hours. Unconditioned samples were simply submerged in a water bath for 20 minutes, while conditioned samples were immersed in a 25°C water bath for one hour prior to testing. The samples were subjected to an indirect tensile splitting test in a vertical orientation to assess their resistance to water damage. Tensile Strength Ratio (TSR) of asphalt mixtures was determined using the formula:

$$TSR\ (\%) = \frac{ITS_{condition}}{ITS_{uncondition}}\ x\ 100 \tag{2}$$

$$ITS = \frac{2000 * P}{\pi\ t\ D} \tag{3}$$

where ITS is the indirect tensile strength in kPa; P indicates the maximum load to fracture the sample in N; t refers to the thickness of the sample in mm, and D is the sample diameter in mm.

(a) (b)

(c) (d)

(e) (f)

Figure 5. Stages of water damage test: (a) samples before test; (b) saturation process; (c) freezing cycle; (d) thawing cycle; (e) sample testing; and (f) fractured samples.

4. Results and Discussion

4.1. Abrasion Resistance

Figure 6 presents the results of abrasion loss for both mixtures. The results reveal that the abrasion loss was reduced by approximately 10.2% in the sample with 8% WPPA compared with the natural aggregate sample. As coarse WPPA content increased, the aggregate proportion decreased equivalently, leading to reduced wear and corrosion. The higher polymer content results in a lower percentage of abrasion loss. The WPP is classified as a thermoplastic polymer, and it has a plastic nature. Thus, after the recycling process, WPP retains high strength, preventing its particles from shattering or breaking during the abrasion test. In addition, replacing portions of natural aggregate with WPPA reduces crushing between the steel balls and the natural aggregate particles because WPPA partially surrounds the aggregate particles. This improvement in aggregate abrasion resistance is similar to that reported in a previous study [30], which used polyethylene as a partial replacement for aggregates. Also, all samples fulfilled the maximum requirement (30%).

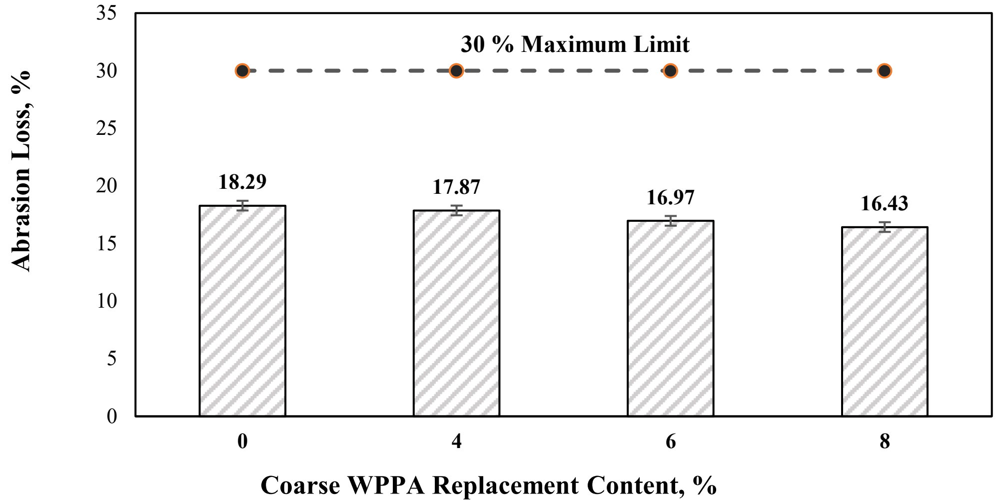


Figure 6. Abrasion loss results of natural aggregate and WPPA.

4.2. Marshall Characteristics

4.2.1. Mechanical Properties

As observed in Fig. 7, most modified mixtures with WPPA showed higher stability values than the control mixture. In addition, WPPA, in coarse, fine, and mineral filler sizes, enhances the stability of the asphalt mixture due to improved aggregate interlock, but excessive amounts reduce the stability value. More precisely, the stability at the addition of 6% fine WPPA and 8% coarse WPPA was reduced by approximately 21% and 33%, respectively, compared to the addition of 2% fine WPPA and 4% coarse WPPA.

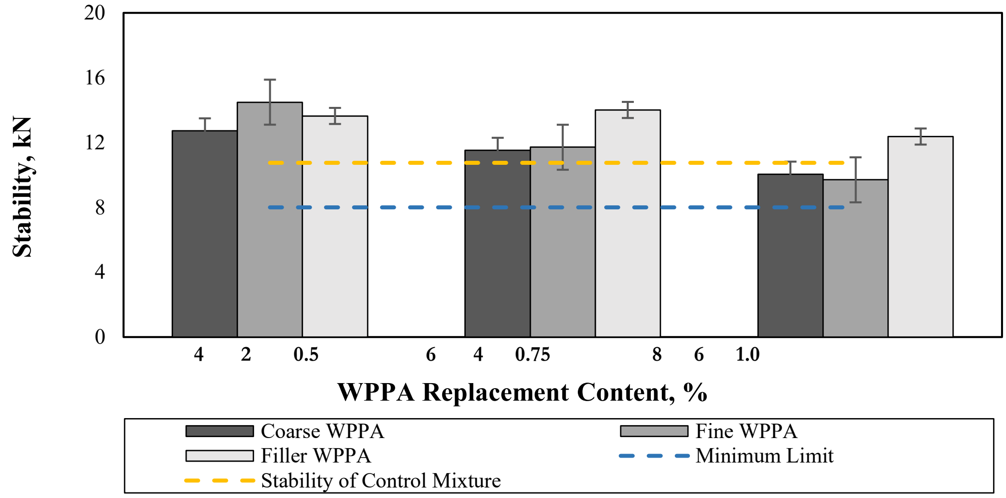


Figure 7. Marshall stability of control and WPPA-modified mixtures.

The drop in stability occurs because WPPA has a lower specific gravity, which weakens aggregate bonding, especially at higher concentrations. To clarify, the overall bulk density of the asphalt mixture decreases when portions of natural aggregate are replaced with WPPA, resulting in a higher air void percentage in the compacted mixture. In addition, excessive WPPA content may reduce the mechanical interlocking of the aggregate skeleton, as WPPA is more flexible and can deform under load and heat more than crushed stone. Correspondingly, the previous reasons make the asphalt pavement more susceptible to deformation and reduce its stability under heavy traffic loads, as excessive air voids and poor interlock between aggregates compromise its structural integrity [27, 31]. This finding is aligned with the results of a previous investigation [18]. Also, WPP (plastic) has a higher stiffness than the asphalt binder at 60 °C, the temperature of the Marshall test. The stiffnesses of WPP and the asphalt binder were determined from their softening points. Consequently, higher compression strength values were achieved for WPPA-modified samples [29].

In addition, the highest stability value was achieved for the modified mixture with fine WPPA at a replacement content of 2%, an increase of 34.8% compared to the control mixture. This is because the small WPPA coats the aggregate more readily, functioning similarly to the binder, while the coarse WPPA is attached to the aggregate particles, acting similarly to the natural aggregate [19, 32]. When mixed at high temperatures, the small particles of WPPA (less than 4.75 mm) can effectively coat the natural aggregates by forming a comprehensive and uniform thin film of softened or melted WPP around the aggregates, mainly because of their increased surface area-to-volume ratio, which improves the chemical and physical interactions with the aggregate particles as well as enhances overall binding [33].

Figure 8 shows that flow decreases as WPPA content increases across all modified mixtures, resulting in a less deformable, more rigid mixture. This is explained by polypropylene's lower specific gravity than pure asphalt, which allows particles to interpenetrate and improves aggregate interlock, increasing stability and reducing flow. Asphalt mixtures with moderate flow and high stability can significantly resist rutting distress and withstand heavy traffic loads. This result was aligned with the findings in the previous investigation [17]. However, the results for all modified mixtures met the minimum stability limit (minimum 8 kN) and the flow limit (allowed range 2-4 mm) specified in the local criteria [26].

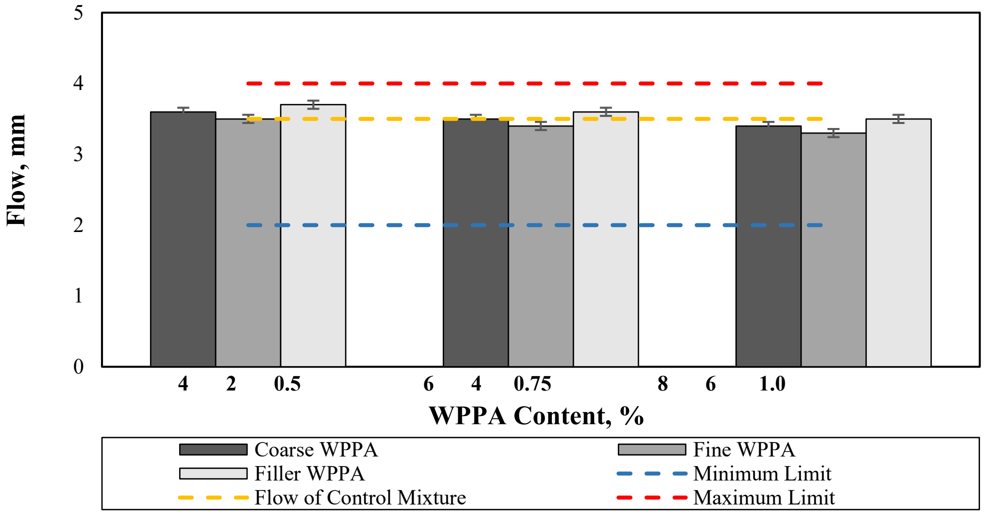


Figure 8. Marshall flow of control and WPPA-modified mixtures.

Furthermore, the Marshall test measures the stiffness or rigidity index of an asphalt mixture. The rigidity index is a ratio of stability to flow that evaluates the mixture's rut-proneness. In other words, it refers to the asphalt mixture's resistance to deformation under traffic loads. Higher rigidity index values, which indicate greater stiffness, enhance the mixture's ability to withstand prolonged deformation [34-35]. Table 5 shows the relationship

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between WPPA concentration and rigidity index for both control and modified mixtures for filler, fine, and coarse WPPA. Mixtures become stiffer and rut-resistant when WPPA is added. The maximum rigidity index value for the WPPA-modified combination with 2% fine WPPA was 4.14 kN/mm. It was nearly 43% higher than that of the control mixture. The increase in the rigidity index is attributed to the distinctive impact of the rough surface texture and angular shape, which promote better mechanical interlock between aggregate particles and improve adhesion within the asphalt mixture's structure.

Table 5. Rigid index of control and WPPA-modified mixtures

Mixture Type	Control	WPPA-Modified								
		Coarse Replacement			Fine Replacement			Mineral Filler Replacement		
		WPPA Content, %								
		4	6	8	2	4	6	0.50	0.75	1.00
Rigid Index, kN/mm	2.90	3.53	3.29	2.95	4.14	3.44	2.93	3.68	3.89	3.53

4.2.2. Volumetric Properties

The bulk density (unit weight) values declined with the addition of WPPA in coarse, fine, and filler size replacements, as shown in Fig. 9. The density of the mixture decreases with increasing the content. For example, the density of the modified mixtures decreased by 3.7%, 7.5%, and 10.2% for coarse WPPA content of 4%, 6%, and 8%, respectively, compared to the control mixture. This pattern emphasizes the lightweight properties of WPPA and their impact on the mixture's bulk density. This implies that the WPPA-modified mixture is lighter than the control mixture. In general, asphalt mixtures with lower bulk density have lower stability. Despite this, WPPA-asphalt mixtures provide higher stability than the control mixture because WPPA enhances the bond between the natural aggregates and the asphalt binder. This unique bond improves cohesion and increases the stiffness of the asphalt mixture. In addition, the reduction in density can likely reduce asphalt mixture transportation and placement costs [36].

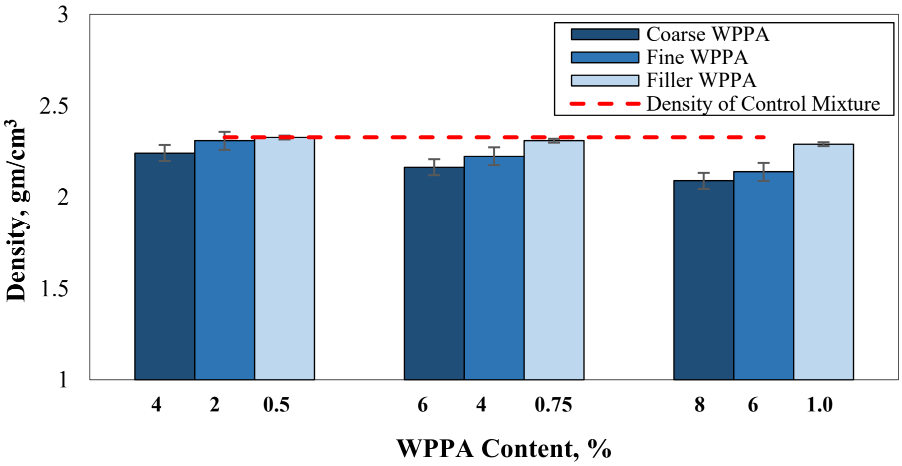

Figure 9. Bulk density of control and WPPA-modified mixtures.

Replacing natural aggregates with WPPA significantly affects the volumetric properties of the asphalt mixture, and a preliminary analysis of this effect was conducted. Table 6 provides the volumetric properties of control and WPPA-modified mixtures. The AV in the control mixture was almost 3.7%. Although there was an increase in AV across the modified mixtures, it remained within the limited range of the surface layer (3–5%). This range was specified by the local road pavement specification to resist pavement distress such as fatigue cracking, bleeding, raveling, and water damage [37]. Obviously, the introduction of WPPA significantly increases the AV and VMA contents of asphalt mixtures of all sizes that were replaced, because, for the same weight, the low-density WPPA occupies a larger volume than natural aggregates, thereby affecting the overall volumetric properties of the asphalt mixtures. Overall, when WPPA enhances certain characteristics, excessive amounts compromise structural integrity.

Table 6. Volumetric properties of control and modified mixtures.

	Mixture Type	Control	WPPA-Modified								
			Coarse Replacement			Fine Replacement			Mineral Filler Replacement		
			WPPA Content, %								
			4	**6**	**8**	**2**	**4**	**6**	**0.50**	**0.75**	**1.00**
Volumetri	AV, %	3.7	3.8	4.1	4.3	3.9	4.1	4.3	4.1	4.2	4.4
	VMA, %	14.2	14.25	14.31	14.35	14.75	14.81	15.09	15.85	15.98	16.01
	VFA, %	74	73	71	70	73	72	71	74	73	72

4.3. Indirect Tensile Strength

The impact of WPPA on the ITS for both control and modified asphalt mixtures is shown in Fig. 10. Based on the results, wet-conditioned samples exhibited lower values of ITS than dry-conditioned samples, reflecting the expected impact of moisture on the mixture's strength. Also, both dry and wet ITS readings were considerably enhanced by the addition of WPPA. This is attributed to the fact that the polypropylene polymer demonstrated higher resistance to aging and tensile degradation, making it the most appropriate option for high-performance applications, particularly for maintaining high moisture resistance. In addition, stronger bonding between the WPP polymer and aggregate prevents water from causing further damage in the asphalt mixture and enhances mixture strength in wet conditions, as the resulting bonding is hydrophobic. To clarify, the WPP is hydrophobic due to its non-polar molecular structure, which helps repel water and improve the asphalt mixture's resistance to moisture damage [38]. The WPPA also fills the microscopic voids between natural aggregate particles, thereby reducing pathways for water to enter the asphalt mixture structure and promoting better mechanical interlocking [19]. This bonding between WPP and aggregate creates a more cohesive, stronger matrix that enhances adhesion and resists water stripping. Accordingly, the pavement would be less susceptible to moisture damage. In conclusion, modified mixtures with 6% fine WPPA and 4% coarse WPPA exhibited the greatest dry ITS (1423 kPa) and wet ITS (1303 kPa), respectively.

The TSR results for the control and modified mixtures are presented in Fig. 11. TSR values, which range from 81.42% to 92.28% in the modified mixtures, indicate less susceptibility to moisture than in the control mixture. This improvement is likely due to the strong adhesion between the asphalt binder and WPPA, thereby reducing the moisture-induced stripping effect. In addition, the WPPA forms a three-dimensional network within the asphalt binder and creates a hydrophobic coating on the aggregate. Eventually, this strengthens the bond between the asphalt binder and aggregate particles, thereby improving the resistance of asphalt mixtures to moisture damage [39].

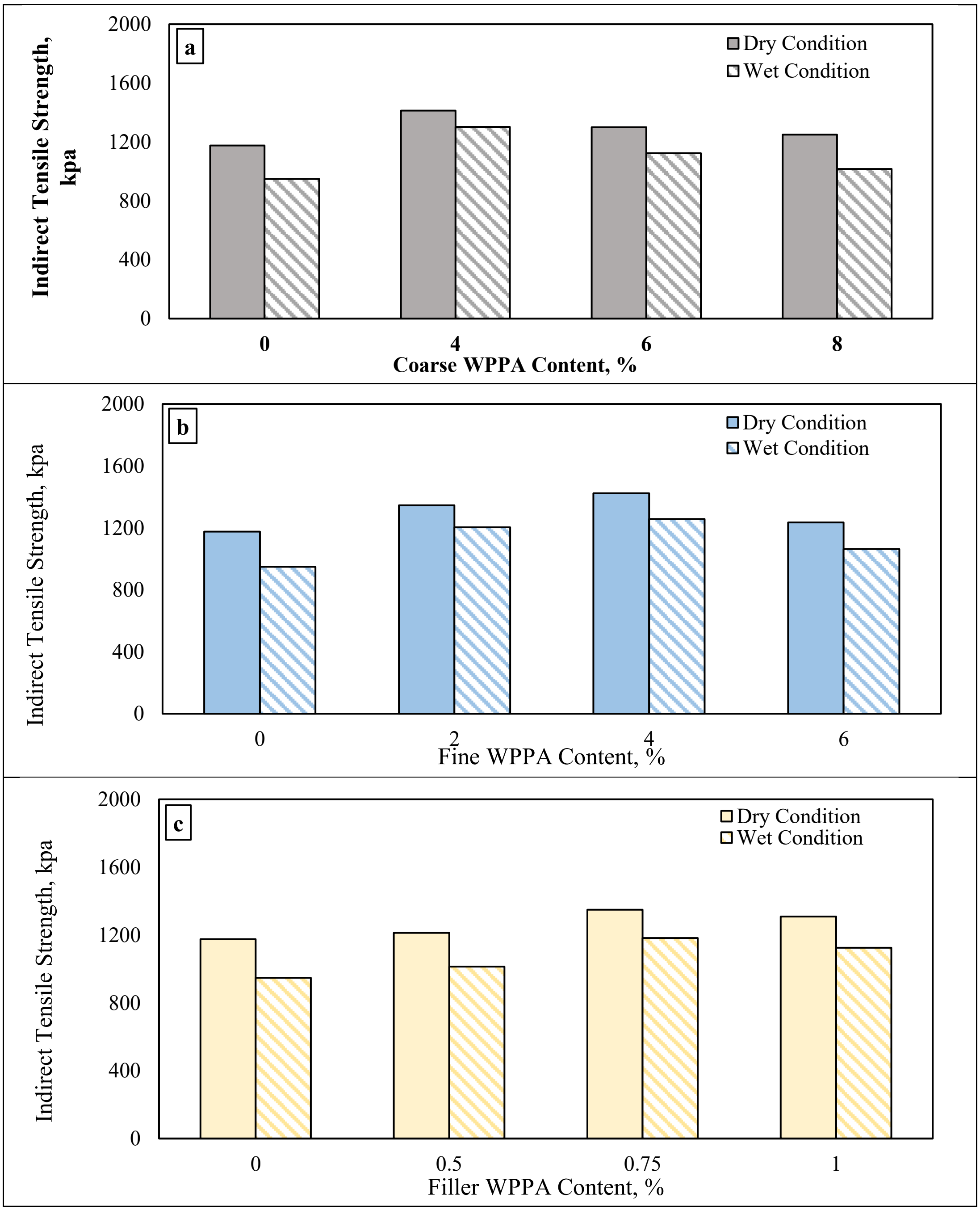

Figure 10. ITS results at dry and wet conditions: (a) coarse WPPA; (b) fine WPPA; and (c) filler WPPA.

ITS and TSR outcomes are consistent with the findings of the earlier work conducted by Lee et al. [19]. It is clear that when the WPPA content for all sizes increased, the TSR values decreased. Nevertheless, this finding does not coincide with previous research [29], which indicates a reduction in the TSR value with the addition of WPPA. This is due to the much stronger affinity between the asphalt binder and the natural aggregate than between the asphalt binder and waste plastic. Also, WPP in flake shape can negatively affect the water damage resistance of asphalt pavement because flake-shaped particles may reduce load-carrying capacity and increase voids. The acceptable TSR limit specified by Superpave requirements must be at least 80% for the wearing course. All modified mixtures fulfilled that requirement; even the control mixture had a TSR of 80.64%.

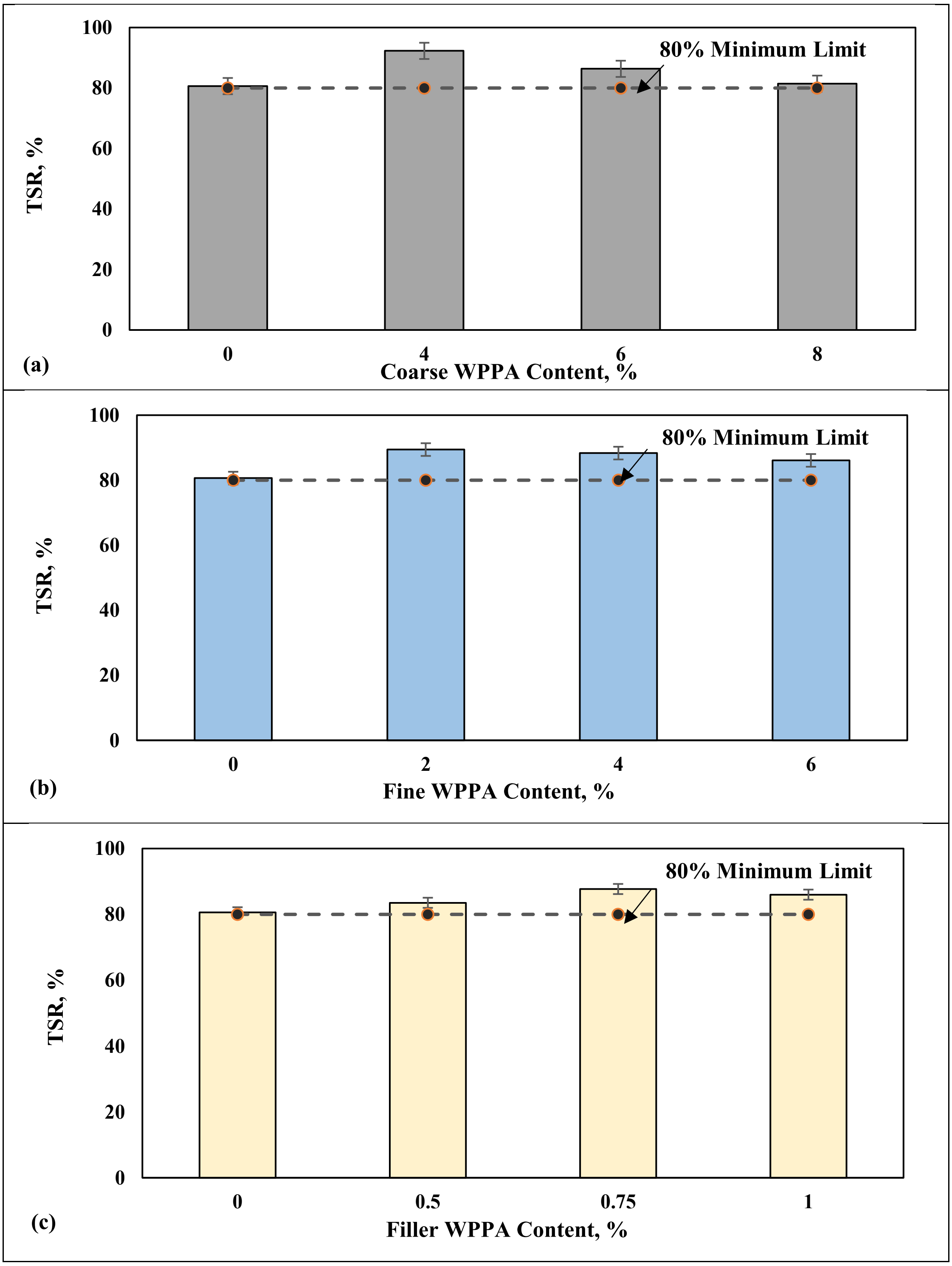

Figure 11. TSR of WPPA-modified mixtures: (a) coarse WPPA; (b) fine WPPA; and filler WPPA.

5. CONCLUSION

This study examined the influence of waste polypropylene plastic aggregate (WPPA) on the properties of asphalt mixtures and found that, when used at appropriate replacement levels, WPPA can improve abrasion resistance, Marshall stability, moisture resistance, and overall pavement performance. The hardness and resistance to tearing and wear increased with higher coarse WPPA contents, showing improvements of 2.3%, 7.2%, and 10.2% at 4%, 6%, and 8% coarse WPPA replacement, respectively, compared with the natural aggregate mixture; this improvement is attributed to the lower surface roughness of WPPA, which reduces surface abrasion. However, the incorporation of WPPA also reduced the bulk density of the modified mixtures because natural aggregates with higher unit weight were partially replaced by lighter WPPA, resulting in a lighter aggregate skeleton. As the WPPA content increased, voids filled with asphalt (VFA) decreased, while air voids (AV) and voids in mineral aggregate (VMA) increased, mainly due to the lower density of WPPA and its tendency to rise or separate from heavier aggregate particles during mixing, placing, and compaction, particularly when excessive dosages or inadequate compaction are involved. In terms of mechanical performance, mixtures modified with coarse and fine WPPA generally showed improved Marshall stability, although higher replacement levels reduced stability by 6.5% for 8% coarse WPPA and 9.8% for 6% fine WPPA compared with the control mixture. In contrast, all mixtures containing WPPA as a filler material below 0.075 mm achieved higher stability than the control, likely because the fine WPPA particles formed a uniform, thin, molten film around the aggregates, thereby improving binder–aggregate interaction. The tensile strength ratio (TSR) also improved by approximately 14%, 11%, and 9% for mixtures containing 4% coarse WPPA, 2% fine WPPA, and 0.75% filler WPPA, respectively, and all WPPA-modified mixtures exceeded the 80% TSR threshold, confirming enhanced resistance to moisture-induced damage through stronger physical and chemical bonding between the binder and aggregate. The angular shape of WPPA further contributed to improved load-carrying capacity, mechanical interlocking, aggregate skeleton bonding, and adhesion within the asphalt mixture, suggesting the potential for longer pavement service life. Overall, the optimal WPPA replacement contents were identified as 4%, 2%, and 0.75% for coarse, fine, and filler sizes, respectively, because these proportions produced the best balance between strength, stiffness, stability, and moisture resistance, while higher dosages negatively affected mixture performance. Compared with the wet process, the dry-process incorporation of WPPA as an aggregate replacement may also more effectively support sustainability goals by enabling greater amounts of waste polypropylene plastic to be reused and diverted from landfills. Nevertheless, the study has three main limitations: high WPPA contents may reduce mixture homogeneity because WPPA, especially in fine sizes, tends to cluster with aggregate particles; producing WPPA with controlled sizes and dimensions may be more costly than conventional cutting and shredding methods; and the use of WPP collected from different sources may introduce contamination and material variability, making quality control difficult and potentially causing unpredictable pavement performance when WPPA is incorporated into asphalt mixtures.

6. RECOMMENDATIONS

Based on the findings of this research, several recommendations are proposed to strengthen the future development and practical application of waste polypropylene plastic (WPP) in asphalt mixtures. Future studies should investigate alternative approaches for incorporating WPP, including modified mixing techniques that can improve mixture performance while controlling production cost and environmental impact. For example, the use of a semi-wet process to modify asphalt binders with WPP may offer a practical alternative to conventional dry mixing by reducing emissions and improving binder–polymer interaction. Since the present findings are mainly derived from laboratory experiments, field trials are strongly recommended to validate the long-term performance of WPPA-modified asphalt pavements under actual traffic loading, weather exposure, and construction conditions. Further research should also include additional mechanical performance tests, particularly fatigue resistance and rutting evaluation, to better understand the durability of asphalt mixtures incorporating WPPA produced through the recycling process adopted in this study. In addition to technical performance, future work should examine the environmental implications of using WPP in asphalt mixtures through comprehensive assessments such as life cycle assessment, with specific attention to carbon emissions, energy consumption, and potential microplastic release. Such evaluation is necessary to provide a more balanced understanding of the sustainability benefits and possible environmental risks associated with WPP utilization in pavement materials. Finally, advanced chemical and physical characterization of WPP should be conducted before its incorporation into asphalt mixtures to ensure material consistency, quality control, and predictable pavement performance.

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