

Research Article

Effect of Waste Thermoplastics on Properties of Warm Mix Asphalt

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ABSTRACT

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Since road projects are among the largest projects and can consume large quantities of materials, and given the significant accumulation of plastic waste worldwide, using this waste in road construction projects contributes to sustainability. In the context of sustainability in the road sector, the use of warm asphalt mixes (WMA) instead of hot mixes comes to mind, as they consume less energy, thereby reducing carbon emissions and lowering costs. Combining these two factors maximizes sustainability benefits. Accordingly, this study aims to investigate the effects of three types of thermoplastic waste materials (TPWM), namely Polyethylene Terephthalate (PET), Polypropylene (PP), and High-Density Polyethylene (HDPE), in addition to a blend of these three materials in equal proportions (abbreviated as BL), on the properties of WMA. These TPWMs were mixed with WMA at aggregate weight percentages of 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, and 1.2%. The properties studied included Marshall properties, rutting resistance, and tensile strength. The study showed that adding the optimal doses of TPWMs increases the mix's density, stability, stiffness, rutting resistance, and tensile strength. The study revealed that the optimal percentages are 0.4%, 0.6%, 0.6%, and 0.6% for PET, PP, HDPE, and BL, respectively. It also showed that HDPE is the best, as adding the optimal percentage of it to WMA increases its G_{mb} , Marshall Stability, Marshall Stiffness, unconditioned ITS, and conditioned ITS by 0.4%, 25%, 42%, 13%, and 18%, respectively, whereas decreasing rut depth by about 28%.

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1. Introduction

Generally, effective flexible pavement dominates the serviceability of a highway, as it controls drivability [1, 2]. Enhancing drivability on highways improves transportation efficiency [3]. Highways dominate transportation modes [4–6], supporting economic growth, especially in developing countries such as Iraq. The [4] efficiency of flexible pavement depends heavily on the quality of the asphaltic layers, which in turn depends on the quality of the mixture [5, 6]. Hot mixes are widely used in this direction. However, these mixes are mostly costly. The nearest alternative is WMA, as it provides quality comparable to that of hot mixes but with lower production energy, since it requires lower mixing and compaction temperatures and is aided by low-cost foaming additives [7]. Reducing energy consumption, in addition to reducing costs, also reduces carbon emissions and supports sustainability [8]. In the context of sustainability, the use of waste materials is evident [9–11]. Among the types of waste, plastic has become one of the most abundant in recent years [12]. Therefore, finding ways to recycle it benefits the environment and turns it into a useful material rather than the opposite. Since road paving projects are among the largest and most resource-intensive [13, 14], they could incorporate this waste into the paving materials. Thus, combining WMA with plastic waste would be a beneficial hybrid. However, the effects of these wastes on WMA properties must be studied to avoid adverse outcomes.

Several studies have shown that waste plastics in asphalt mixtures enhance stiffness, rutting resistance, and durability. Initial research confirms that polymer-modified binders with waste plastics increase mixture stability and pavement lifespan [15, 16]. Later studies indicate that waste plastics can improve Marshall stability, moisture resistance, and high-temperature performance, with outcomes varying by polymer type and modification method [17, 18]. Polyethylene-based modifiers such as LDPE and related polyolefins increase stiffness and reduce deformation, but their effects depend on dispersion and compatibility with the asphalt binder [19–21]. Among thermoplastics, polyethylene terephthalate (PET) is extensively studied for its abundance and rigidity. PET improves the rutting resistance, Marshall stability, and fracture behavior of asphalt mixtures when incorporated [22–24]. High-density polyethylene (HDPE) has the potential to enhance high-temperature performance, moisture resistance, and deformation resistance due to its molecular stability and stiffness [25, 26]. Excessive HDPE content can cause phase separation and reduced workability [27]. Polypropylene (PP) is investigated as both a direct modifier and a wax-based WMA additive, reducing binder viscosity and improving stiffness upon cooling [28, 29]. Waste plastic-derived waxes are effective WMA additives that improve workability and lower production temperatures [30–32]. Recent research has examined blended plastic systems, which may combine the benefits of polymers and enhance the mixture [33, 34]. Despite the recorded advantages of TPWM in asphaltic mixtures, the previous studies generally covered investigations about PET, PP, and HDPE separately under various materials, mixture designs, and testing conditions eliminating the direct comparisons of their relative influence and performance in a unified platform. In addition, no evidence is available on their comparative and blended influences under identical WMA conditions. Despite extensive research on waste plastic-modified asphalts, a critical gap remains: most studies test PET, PP, and HDPE separately using different materials and procedures. Research on WMA conditions is limited, even though the temperature sensitivity of thermoplastics can affect performance. Also, the blended effects of PET, PP, and HDPE—typical of municipal plastic waste—are not evaluated under identical conditions. Thus, the comparative effectiveness and optimal dosage of thermoplastics for WMA remain unclear. This study aims to address the identified gap by systematically comparing the effects of PET, PP, HDPE, and their blends under identical WMA conditions. Specifically, the research investigates how these thermoplastic waste materials influence

Marshall properties, rutting resistance, and tensile strength. The objective is to identify the most effective type of waste plastic and the optimal dosage to enhance sustainable pavement performance under WMA conditions. Attaining the objective of this study bridges the gap of knowledge and exposes its novelty.

2. Research Method

As previously mentioned, three different TPWM types were used in this study: PET, PP, and HDPE. In addition, a blend of these three materials in equal proportions (abbreviated as BL) was used. PET can be found in water and fresh drink bottles. PP is usually used for food containers and caps. HDPE is normally used in milk bottles and detergent containers. These types differ from one another in certain properties. Among the most important differences are density and melting point. To reduce the complexity of the study and for practical purposes, two parameters were held constant. First, six TPWM doses (0.2%, 0.4%, 0.6%, 0.8%, 1.0%, and 1.2% by aggregate weight) were selected for blending with WMA. Second, asphalt content was fixed at 5% of the total mix weight for both the control mixture and all TPWM-blended mixtures. This approach was adopted to eliminate the effect of asphalt content variations on the mixture's engineering properties and to ensure that any performance changes were primarily attributable to the addition of TPWMs. This asphalt content was selected based on a previous study by the same research team using the same materials and aggregate gradation, which identified 5% as the optimum asphalt content. To simplify the description in this paper, several abbreviations were adopted in addition to those previously used. Table 1 summarizes these abbreviations. WMA-CTRL represents the control warm mixture. WMA-TPWM represents warm mixtures of any thermoplastic adopted in this study (PET, PP, HDPE, and BL) at any dose. WMA-PET, WMA-PP, WMA-HDPE, and WMA-BL represent warm mixtures blended with any adopted doses of PET, PP, HDPE, and BL, respectively. WMA-PET-X%, WMA-PP-X%, WMA-HDPE-X%, and WMA-BL-X% represent warm mixtures blended with a specific dose (X%) of PET, PP, HDPE, and BL, respectively. For example, WMA-PET-0.6% denotes a warm mixture containing 0.6% PET.

Table 1
Description of abbreviations used

Abbreviation	Meaning
WMA-CTRL	Control WMA
WMA-TPWM	WMA + TPWM
WMA-PET	WMA + PET at any dose
WMA-PP	WMA + PP at any dose
WMA-HDPE	WMA + HDPE at any dose
WMA-BL	WMA + BL at any dose
WMA-PET-X%	WMA + PET at X% dose
WMA-PP-X%	WMA + PP at X% dose
WMA-HDPE-X%	WMA + HDPE at X% dose
WMA-BL-X%	WMA + BL at X% dose

2.1 Materials Used

The materials used in this study include aggregate, asphalt binder, Aspha-min, and TPWM materials. The properties of these materials are described in the following sub-subsections.

2.1.1 Aggregate

The aggregate gradation is shown in Figure 1. It was selected to fall within the limits of the Iraqi specifications. Proper gradation of aggregates indicates several desirable mixture properties, such as a tight skeleton that provides particle-to-particle contact, leading to load transfer within the mixture. Consequently, this leads to high stability and resistance to permanent deformations such as rutting. Moreover, proper gradation ensures high density, low air voids, and low permeability, thereby increasing durability and resistance to water damage. In addition, it decreases segregation during hauling and increases workability during spreading. Furthermore, it ensures a preferable surface texture and surface friction. The aggregate used complies with the other requirements of Iraqi specifications, including toughness and particle shape, as shown in Table 2. Table 2 shows that the gypsum content and plasticity index values are 0% and 0, respectively. This reflects the absence of harmful gypsum and clay impurities in the aggregate, which reduce asphalt adhesion to the aggregate and cause pavement weakness due to swelling or subsequent water washing away. Low flakiness content ensures good interlock among the particles and increases stability. The soundness of the aggregate indicates low susceptibility to water absorption, indicating high water-damage resistance. A low abrasion value indicates high resistance to surface polishing and high stability. The specific gravity of coarse aggregate, fine aggregate, and filler was found to be 2.651, 2.747, and 2.716, respectively. The specifications for Iraq did not stipulate specific density values, but these densities can be considered relatively high, ensuring high density and stability of the mixture.

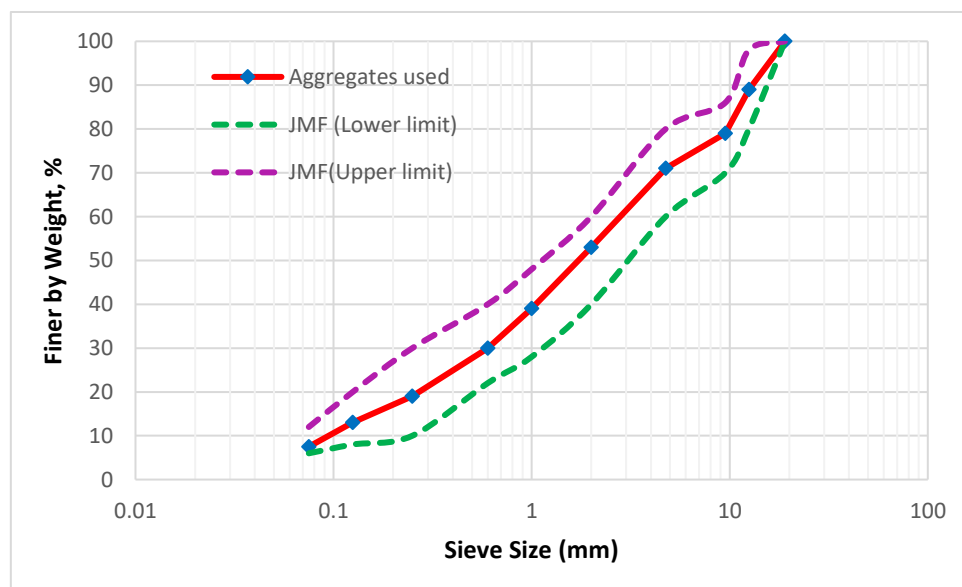


Fig. 1. Aggregate gradation

Table 2

Properties of aggregate used

Property	Adopted Test	Iraqi Specifications	Attained Result	Evaluation
Gypsum Content	BS 1377	Less than 1%	0%	OK
Plasticity Index	AASHTO T-89	Less than 3	0	OK
Flakiness	BS 812	Less than 20%	3%	OK
Soundness	AASHTO T-104	Less than 12%	2.1%	OK
Los Angeles Abrasion Value	AASHTO T-96	Less than 30%	14%	OK

2.1.2 Asphalt and Aspha-min

A sufficient quantity of asphalt was supplied from the local Dora refinery. Table 3 summarizes the properties of asphalt. The Iraqi specifications were considered as a reference. The asphalt penetration value was measured at 47 units, which falls within the specification limits (40–50). The values of ductility, softening point, purity, and specific gravity were measured as 103 cm, 54 °C, 99.9%, and 99.9%, respectively. All these properties comply with Iraqi specifications. Using asphalt that conforms to local specifications ensures good properties for the asphalt mix. By guaranteeing a penetration value within the range of 40–50, the mix can be made hard enough to prevent deformations such as rutting and soft enough to prevent cracking, under Iraqi conditions. These properties are further confirmed by the asphalt's compliance with softening point requirements, which indicate its low-temperature susceptibility across varying temperatures and thus high resistance to deformation, as well as its high ductility, which reflects high resistance to cracking. Meeting the specifications of asphalt properties after applying the procedure specified by AASHTO T-179 indicates the asphalt's resistance to aging. The specific gravity of asphalt was found to be 1.02; this value was adopted in the calculations of Marshall properties.

Commercial Aspha-min available in the Iraqi market was used as a foaming agent to produce the WMA. It was added to the mixes at 0.30% of the total mix weight, as instructed by the producer.

Table 3

Asphalt properties

Properties	Test	Conditions	Specifications	Asphalt Used	Evaluation
Penetration	AASHTO	25 °C, 100g, 5 Sec,	40–50	47	OK
Penetration After Heating	T-49	units: 0.1 mm	Less than 52%	61%	OK
Flash Point	AASHTO T-78	Open Cup	Higher than 240 °C	267 °C	OK
Loss on Heating	AASHTO T-47	5hrs., 163 °C	Less than 0.75%	0.50%	OK
Ductility	AASHTO T-51	25 °C, 50 mm/min	Higher than 100cm	>100cm	OK
Softening Point	AASHTO		54–60 °C	54 °C	OK
Increase in Softening Point	T-53	Ring and Ball	Less than 10 °C	8 °C	OK
Purity (Solubility)	AASHTO T-44	Organic Solvent (Trichloroethylene)	Less than 99%	99.99%	OK
Specific Gravity	ASTM D-70	Pycnometer, 25 °C	NA	1.02	NA

2.1.3 TPWMs

TPWMs were collected from local trash, classified, and cleaned. The cleaning process involved manually removing dirt and foreign materials, then washing with water, and then drying with a hot dryer. The cleaned TPWMs were ground mechanically into fine particles. Afterward, the products were sieved on sieve No. 8 (2.36 mm). Several studies adopted this procedure [35, 36]. Table 4 summarizes the properties of TPWMs. As shown in Table 4, a uniform size was adopted for the four types of TPWMs to eliminate the effect of size on the results and isolate the effect of plastic type. The differences in properties among the four types include density and melting point. The density values of PET, BL, HDPE, and PP are 1.35, 1.07, 0.96, and 0.90, respectively. The melting points of PET, BL, PP, and HDPE are 251 °C, 245 °C, 165 °C, and 130 °C, respectively. Clear differences in density and melting point can be observed among the different types of TPWM. These differences may affect the properties of WMA in different ways.

Table 4
Properties of TPWMs

Particles finer than	2.36 mm	AASHTO T27	All TPWM types	100 %
	1.18 mm			50%
	0.425 mm			0%
Specific Gravity		ASTM D792	PET	1.35
			BL	1.07
			HDPE	0.96
			PP	0.90
Melting Point		ASTM D3418	PET	251°C
			BL	245°C
			PP	165°C
			HDPE	130°C

2.2 Preparation of Specimens

2.2.1 Determination of mixing and compaction temperatures

The viscosity of asphalt foamed by Aspha-min was measured in accordance with AASHTO T316 to determine the mixing and compaction temperatures. The test involved measuring the viscosities at 120 °C, 135 °C, 150 °C, and 165 °C. To improve the accuracy of the results, three tests were conducted at each temperature, and the average value was used. The measured viscosities were converted to kinematic viscosities by multiplying by the asphalt's specific gravity (1.02). The relationship between temperature and viscosity was used to obtain the asphalt viscosity curve for the study, as shown in Figure 2. The temperature range for mixing, given a target of 150–190 centistokes, was found to be 137–149 °C. The temperature range for compaction, given a target of 250–310 centistokes, was found to be 123–129 °C. These temperatures were used to prepare the mixes and to compact the laboratory specimens, ensuring proper mix homogeneity and achieving suitable workability and compatibility.

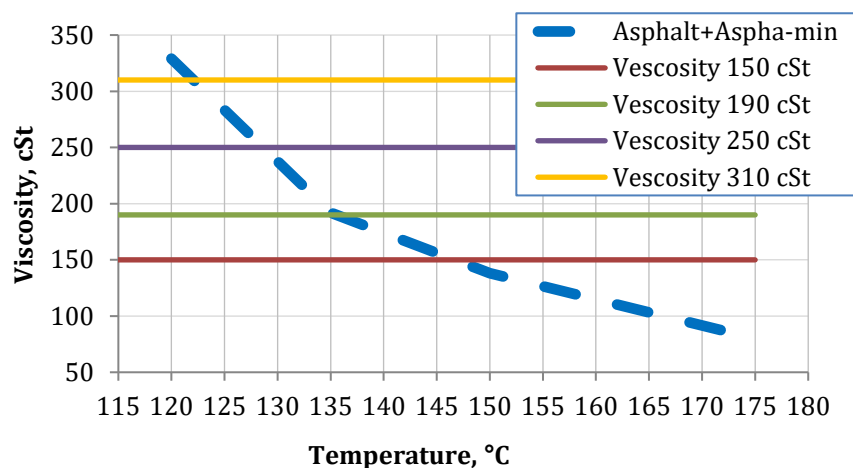


Fig. 2. Asphalt viscosities at different temperatures

2.2.2 Mixing preparation

The control mix was produced by heating the aggregates and asphalt separately to the predetermined temperatures as described in sub-subsection 2.2.1. The heated aggregates were then placed in a mixer, after which the hot asphalt binder and the required percentage of Aspha-min (0.3%) were added. The mixing process was maintained for 2–3 minutes to ensure complete, homogeneous coverage of the aggregate particles. Precautions were taken to ensure that the mixing temperatures were maintained.

The same procedure was used to produce TPWM-blended mixtures. However, there is one additional step: replacing a percentage of the fine aggregate with TPWM. The added TPWMs were completely blended with the aggregate in dry conditions. The resulting mixtures were subsequently used to prepare and compact the required test specimens.

2.2.3 Preparation of Marshall specimens

Marshall specimens were prepared according to AASHTO T245 using cylindrical molds with diameters and heights of 101.6 mm and 63.5 mm, respectively. After preparing the mixes at viscosity-based temperatures, the mixes were first placed in the Marshall compactor and compacted with a standard hammer for 75 blows per face.

Three independent samples, each involving 3 identical specimens, were prepared for WMA-CTRL. Similarly, 3 samples, each containing 3 identical specimens, were prepared for each TPWM-blended mix. In total, 90 specimens were prepared.

These specimens were used to determine the Marshall properties, including Stability, Flow, bulk density, air voids, and void-in-mineral-aggregate (VMA). For each property, the average value of each of the three specimens represents the value of one sample. Each sample represents one testing repetition. The average of the three samples was used as the final value.

2.2.4 Preparation of rutting specimens

To implement the rutting test in accordance with AASHTO T324 using a double-wheel tracker, specimens measuring 600 mm × 200 mm × 75 mm were prepared. The temperatures specified in subsection 2.2.1 were used in preparing the rutting specimens. For WMA-CTRL, 4 specimens were prepared to be sufficient for 2 repetitions each, including 2 side-by-side specimens. The average of each pair of specimens represents the value of one sample. Each sample represents one testing repetition. The average of each pair of samples was used as the final value. A similar procedure was adopted for TPWM-blended mixes. This brings the total to 28 specimens.

2.2.5 Preparation of ITS specimens

Indirect tensile strength (ITS) test specimens were prepared according to AASHTO T283, using cylindrical specimens with a diameter of 100 mm and a thickness of 63.5 ± 2.5 mm, targeting an air void ratio of $7 \pm 0.5\%$. Trial compaction attempts were conducted to determine the optimal number of blows required to achieve the desired void ratio. For each mix (control and TPWM-blended mixes), 3 independent test repetitions were implemented. Each repetition consists of 6 specimens, including 3 unconditioned specimens and 3 conditioned ones, resulting in a total of 18 specimens per mixture. For each repetition, the average ITS value of the three specimens was computed individually for the unconditioned and conditioned subsets. The final recorded ITS values are the average of the three independent repetitions. TSR values were computed as the ratio of the conditioned to unconditioned ITS values. The conditioning process involves subjecting the specimens to vacuum saturation, followed by freezing at -18 ± 3 °C, and then immersion in a water bath at 60 ± 1 °C for 24 hours. This simulated the effects of moisture and harsh environmental conditions on asphalt mixture performance.

2.3 Testing Program

To apply the testing program for this study, samples were prepared according to the standard methods described in subsection (2.2). The testing program includes Marshall properties, rutting resistance, and tensile strength for unconditioned and conditioned specimens to investigate the effects of TPWM types on WMA. Marshall specimens were tested using the standard method to determine the relevant properties. Stability and Flow were measured using a standard machine at 60 °C in accordance with AASHTO T245. Bulk density (G_{mb}) and maximum density (G_{mm}) of the specimens were measured using the standard method adopted in AASHTO T166 and AASHTO T209, respectively. Based on these measurements, the air void and VMA values were calculated.

Rutting tests were conducted in accordance with the standard method described in AASHTO T324 under full-immersion conditions at 50 °C and a contact pressure of approximately 730 kPa to simulate tire loading. Rutting depth measurements were recorded up to 20,000-wheel passes, and the average values were calculated as described in sub-subsection 2.2.4. ITS of unconditioned and conditioned specimens was determined based on AASHTO T283 using indirect tensile testing at 25 °C. The average values for each set of 3 specimens were treated as a single sample. Afterward, the averages of each set of 3 samples were used to represent one set. The tensile strength ratio (TSR) was calculated as the tensile strength of the conditioned specimens divided by that of the unconditioned specimens. This was done to evaluate the mixtures' resistance to moisture damage and the effect of TPWM

addition on the durability and performance of WMA mixtures. Table 5 summarizes the testing program.

Table 5

Testing program

Property	Standard	Specifications
Marshall Stability		More than 8.0 kN
Marshall Flow	AASHTO T245	8.0–14.0 units (2–3.5 mm)
Marshall Stiffness	Calculated	-
G_{mb}	AASHTO T166	-
G_{mm}	AASHTO T209	-
Marshall Air Voids	Calculated	3.0–5.0 %
Marshall VMA		Equal to or more than 14.0 %
Rutting Resistance	AASHTO T324	More than 20%
Indirect Tensile Strength (ITS)	AASHTO T283	TSR more than 80%

2.4 Determination of the Optimum TPWM Doses

To determine the optimal doses of TPWMs, the overall engineering performance of each mix was considered instead of requiring all properties to attain their individual optimum at the same dose. Priority was given to maximum Marshall stability and minimum rut depth, whereas ITS and TSR values were considered as supporting performance indicators. In addition, the selected dose was required to satisfy the specified limits of the other Marshall properties.

3. Results and Discussion

3.1 Viscosity Results

Viscosity testing was performed on Aspha-min foamed asphalt to determine the mixing and compaction temperatures, aiming for 150–190 and 250–310 centistokes for mixing and compaction, respectively, in accordance with the Marshall method standards, as illustrated in Figure 2. These temperatures were found to be 137–149 °C and 123–129 °C for mixing and compacting, respectively.

3.2 Marshall Test Results

Tables 6, 7, 8, and 9 present the Marshall properties of WMA blended with different TPWM types at varying doses. For WMA-CTRL and WMA-TPWM mixes, all values were within the acceptable ranges specified in the Iraqi specifications. The changes in the values can be traced in the tables. Some properties, such as G_{mb} , were barely affected in all mixes (WMA blended with different doses of PET, PP, HDPE, or BL). This can be attributed to the fact that only a small portion of fine aggregate was replaced with TPWMs, whose effect on the density is almost negligible. By focusing on stability, the key Marshall property as mentioned in subsection 2.4, the trend of values increases with increasing TPWM doses until reaching a maximum. Afterward, the values decrease as the dose increases (Figure 3). The maximum Marshall stability values correspond to the optimal TPWM doses. The optimal doses are 0.4%, 0.6%, 0.6%, and 0.6% for WMA mixes blended with PET, PP, HDPE, and BL, respectively. Several possible reasons can explain this trend. First, TPWM may increase friction and interlock within the mixture structure due to its rough texture, which is created during the mechanical shredding process. Second, it may act as reinforcement in the mixture, increasing overall

strength by controlling micro-cracks. Third, when partially melted (softened) by heating, it may act as an adhesive that glues the aggregate particles together; upon cooling, it regains its stiffness, strengthening the bonds. Fourth, the stiffness of TPWM, which is higher than that of asphalt at the test temperature, may increase the mix's overall stiffness [25]. However, increasing TPWM doses beyond the optimum reduces stability for several reasons. First, excess TPWM may absorb asphalt, depriving the mix of its primary adhesive and consequently reducing bond. The presence of TPWM increases heterogeneity in the mixture structure, thereby reducing its stability.

Table 6
Marshall properties for WMA mixed with PET

PET %	G_{mb}	Stability (kN)	Flow (mm)	Stiffness (kN/mm)	Air Voids (%)	VMA (%)
0.00%	2.443	13.0	3.00	4.33	4.0	14.0
0.20%	2.444	13.7	2.92	4.69	3.9	14.1
0.40%	2.446	14.5	2.82	5.14	3.8	14.2
0.60%	2.445	14.3	2.85	5.02	3.9	14.3
0.80%	2.443	13.9	2.92	4.76	4.0	14.4
1.00%	2.441	13.4	3.00	4.47	4.1	14.6
1.20%	2.439	13.0	3.10	4.19	4.3	14.8

Table 7
Marshall properties for WMA mixed with PP

PP %	G_{mb}	Stability (kN)	Flow (mm)	Stiffness (kN/mm)	Air Voids (%)	VMA (%)
0.00%	2.443	13.0	3.00	4.33	4.0	14.0
0.20%	2.444	13.4	2.96	4.53	3.9	14.1
0.40%	2.446	13.9	2.90	4.79	3.9	14.2
0.60%	2.447	14.3	2.84	5.04	3.8	14.3
0.80%	2.447	14.2	2.85	4.98	3.8	14.4
1.00%	2.445	13.9	2.90	4.79	3.9	14.5
1.20%	2.443	13.5	2.98	4.53	4.0	14.6

Table 8
Marshall properties for WMA mixed with HDPE

HDPE %	G_{mb}	Stability (kN)	Flow (mm)	Stiffness (kN/mm)	Air Voids (%)	VMA (%)
0.00%	2.443	13.0	3.00	4.33	4.00	14.0
0.20%	2.447	14.2	2.86	4.97	3.80	14.1
0.40%	2.450	15.4	2.74	5.62	3.60	14.2
0.60%	2.453	16.3	2.64	6.17	3.50	14.3
0.80%	2.452	16.1	2.66	6.05	3.50	14.4
1.00%	2.450	15.7	2.72	5.77	3.60	14.5
1.20%	2.448	15.2	2.80	5.43	3.80	14.6

Table 9
Marshall properties for WMA mixed with BL

BL %	G_{mb}	Stability (kN)	Flow (mm)	Stiffness (kN/mm)	Air Voids (%)	VMA (%)
0.00%	2.443	13.0	3.00	4.33	4.0	14.0
0.20%	2.446	13.9	2.90	4.79	3.8	14.1
0.40%	2.448	14.9	2.80	5.32	3.7	14.2
0.60%	2.450	15.5	2.72	5.70	3.6	14.3
0.80%	2.449	15.3	2.74	5.58	3.7	14.4
1.00%	2.447	14.9	2.80	5.32	3.8	14.5
1.20%	2.445	14.4	2.88	5.00	3.9	14.6

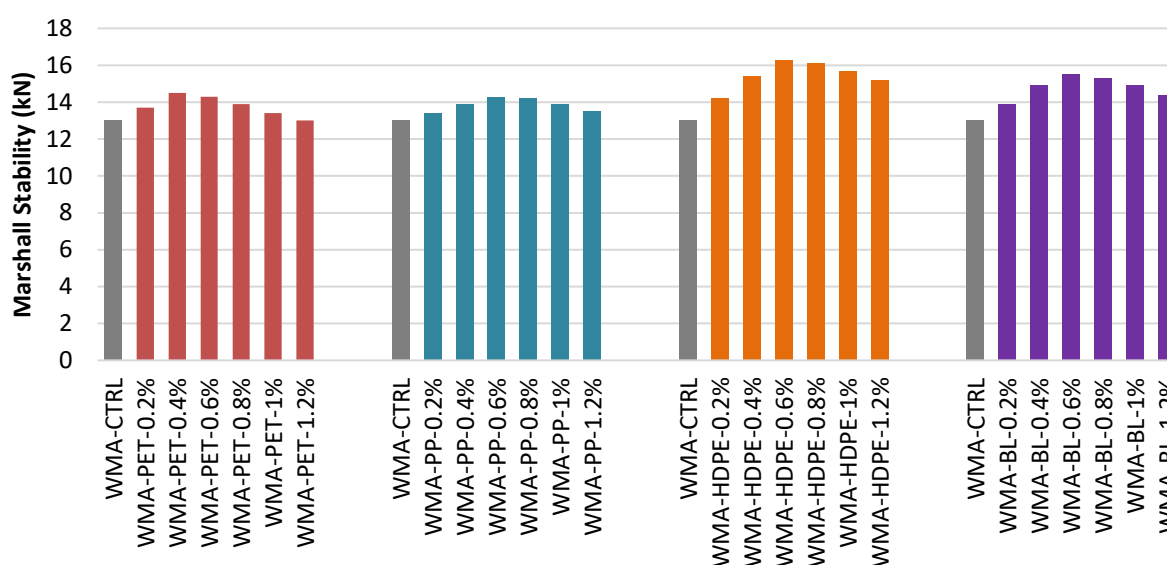


Fig. 3. Marshall Stability of control mix and mixes blended with different doses of TPWMs

The values of Marshall properties at optimum doses of different TPWM types are presented in Figure 4. The stability values were 14.5 kN, 14.3 kN, 16.3 kN, and 15.5 kN for WMA blended with PET, PP, HDPE, and BL at their respective optimum doses. WMA-HDPE-0.6% registered the highest stability value (16.3 kN) compared to the other mixes. It also registered the highest G_{mb} and stiffness values, indicating the greatest improvement in WMA properties, as high density indicates high rutting resistance and high stiffness indicates high resistance to various distresses. Since TPWM replaces fine aggregate by weight, difference in its specific gravity may also affects the volumetric composition of the mix. This behavior can be justified in the context of the melting-point values of the TPWM types. HDPE has a melting temperature (about 130 °C) lower than the range of mixing temperatures of the Marshall specimens (137–149 °C), as previously mentioned. This may promote HDPE melting during mixing, enabling it to act as an adhesive that strengthens the bond among the aggregate particles, thereby increasing stability and, consequently, stiffness, since stiffness is a function of stability [28]. Melting may also provide some lubricating effect during compaction, as asphalt does, enhancing mixture compatibility and increasing G_{mb} . However, the average melting points of PET and PP are about 240 °C and 165 °C, respectively. Those temperatures are higher than those adopted in the mixing process. This means that no complete melting occurs; only partial melting or softening is

probable. This softening may provide some potential for PET and PP to adhere, leading to less bonding than with HDPE and resulting in lower stability and stiffness. Nevertheless, WMA-BL exhibited moderate values (less than those of HDPE but higher than those of PET and PP). This behavior is expected because each TPWM type within BL acts independently, yielding an average effect.

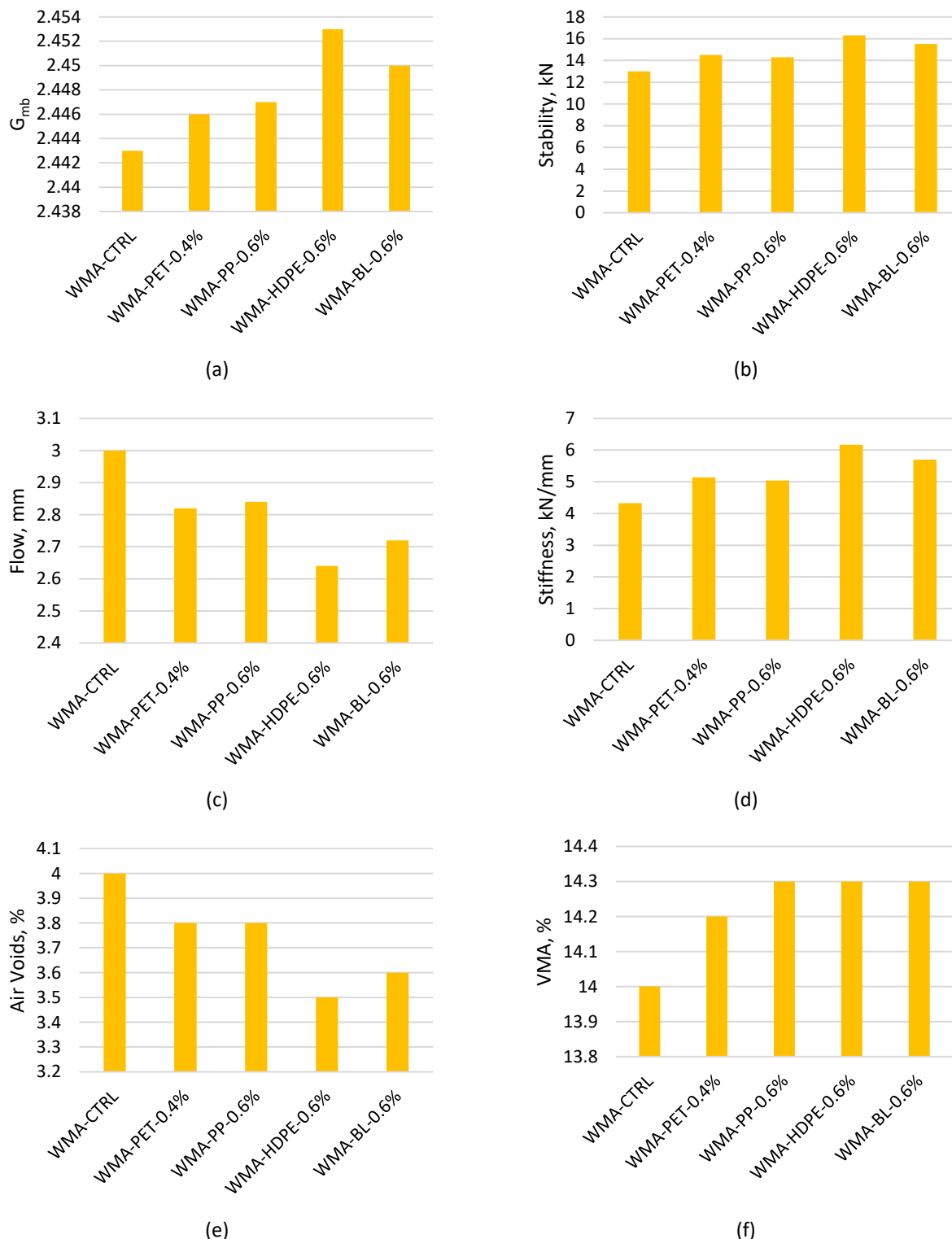


Fig. 4. Marshall properties at optimum doses of TPWM: (a) G_{mb} , (b) Stability, (c) Flow, (d) Stiffness, (e) Air voids, (f) VMA

3.3 Rutting Results

Figures 5–8 show the rut test results for WMA-PET, WMA-PP, WMA-HDPE, and WMA-BL mixes, respectively, using a track wheel. The figures exhibited typical trends in all mixtures. The rutting depth increases sharply in the first stage. Afterward, the increase in rut depth flattens. This behavior is expected, as rutting depends not only on WMA properties but also on repetitive loading. In the first stage, rapid densification and particle rearrangements occur due to wheel passes. In the second stage, the internal structure of the mix stabilizes and exhibits more resistance to deformation.

To focus on the effects of different TPWM types and doses, the rut depth after 20,000-wheel passes is considered. Rut depth values were found to be 8.92 mm, 8.16 mm, 8.36 mm, 8.58 mm, 8.82 mm, and 9.06 mm for WMA-PET-0.2%, WMA-PET-0.4%, WMA-PET-0.6%, WMA-PET-0.8%, WMA-PET-1.0%, and WMA-PET-1.2%, respectively. All these values are less than the measured WMA-CTRL (9.8 mm). However, the lowest rut depth was measured in WMA-PET-0.4%, which was selected to have the optimum PET dose as mentioned in subsection 3.2. For PP, rut depth values were 9.02 mm, 8.38 mm, 8.08 mm, 8.27 mm, 8.5 mm, and 8.74 mm for WMA-PP-0.2%, WMA-PP-0.4%, WMA-PP-0.6%, WMA-PP-0.8%, WMA-PP-1.0%, and WMA-PP-1.2%, respectively. For HDPE, rut depth values were found to be 8.52 mm, 7.57 mm, 7.04 mm, 7.21 mm, 7.49 mm, and 7.8 mm for WMA-HDPE-0.2%, WMA-HDPE-0.4%, WMA-HDPE-0.6%, WMA-HDPE-0.8%, WMA-HDPE-1.0%, and WMA-HDPE-1.2%, respectively. For BL, rut depth values were 8.68 mm, 7.85 mm, 7.47 mm, 7.65 mm, 7.9 mm, and 8.18 mm for WMA-BL-0.2%, WMA-BL-0.4%, WMA-BL-0.6%, WMA-BL-0.8%, WMA-BL-1.0%, and WMA-BL-1.2%, respectively. Overall, the lowest rut depths were observed in mixes corresponding to the optimum doses. This is reasonable, as the optimal doses were selected based on the highest stability and stiffness values, which indicate the greatest rutting resistance.

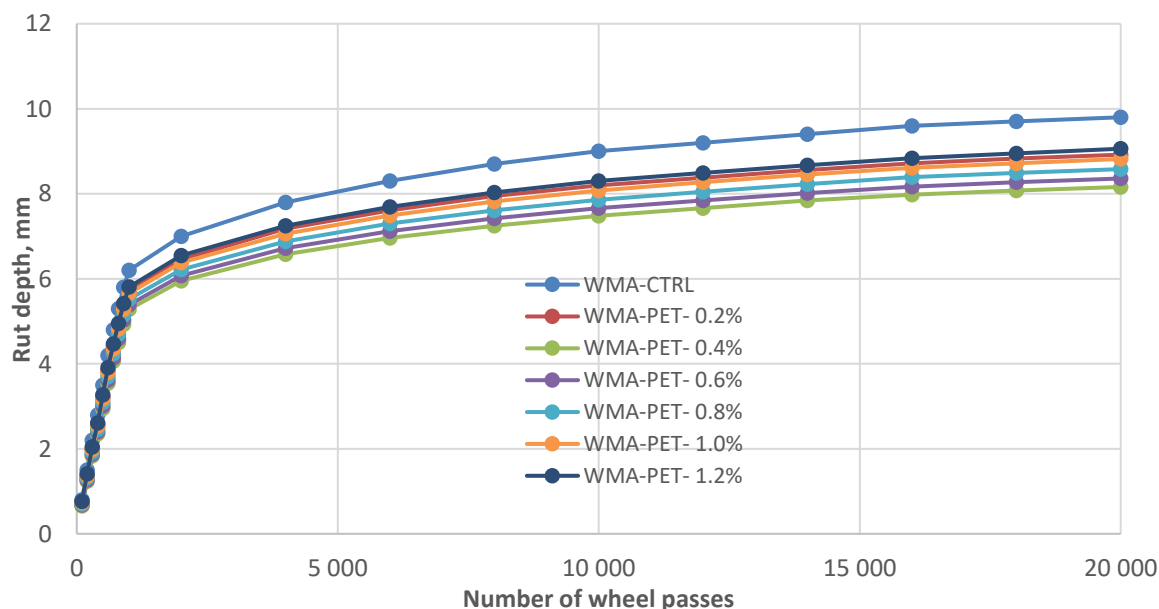


Fig. 5. Rut depth of WMA-PET

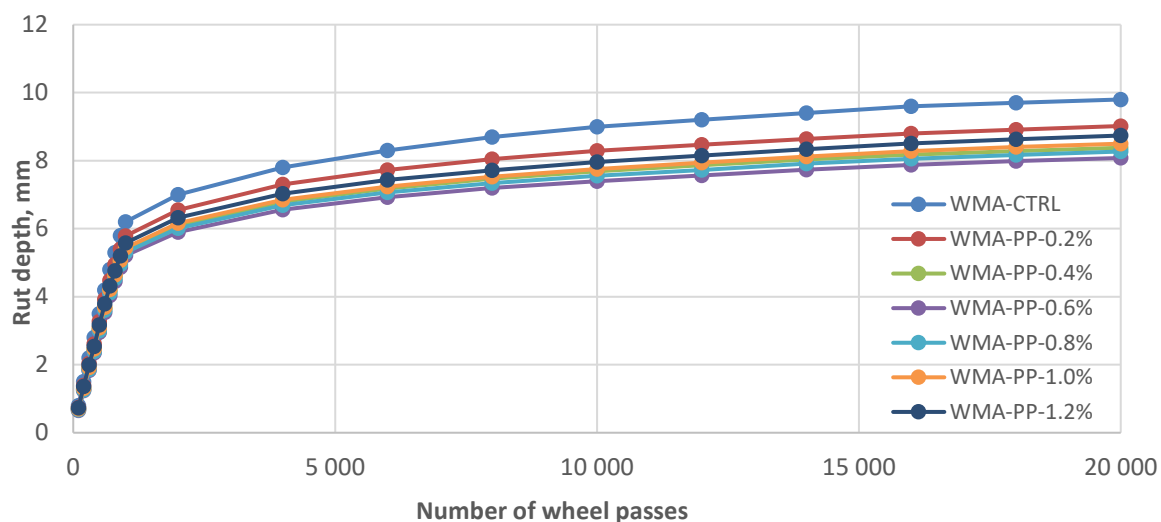


Fig. 6. Rut depth of WMA-PP

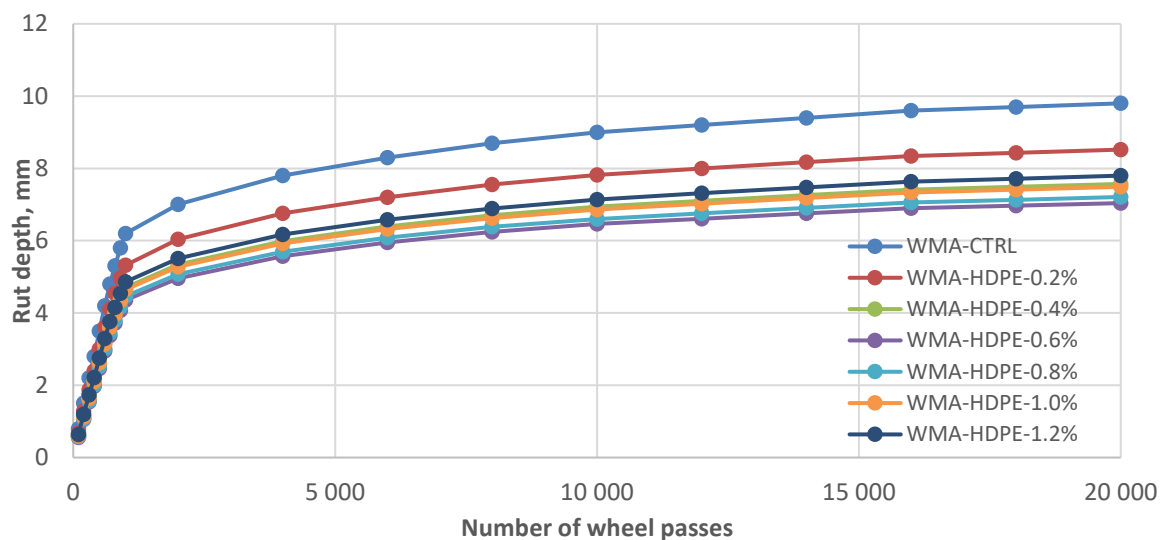


Fig. 7. Rut depth of WMA-HDPE

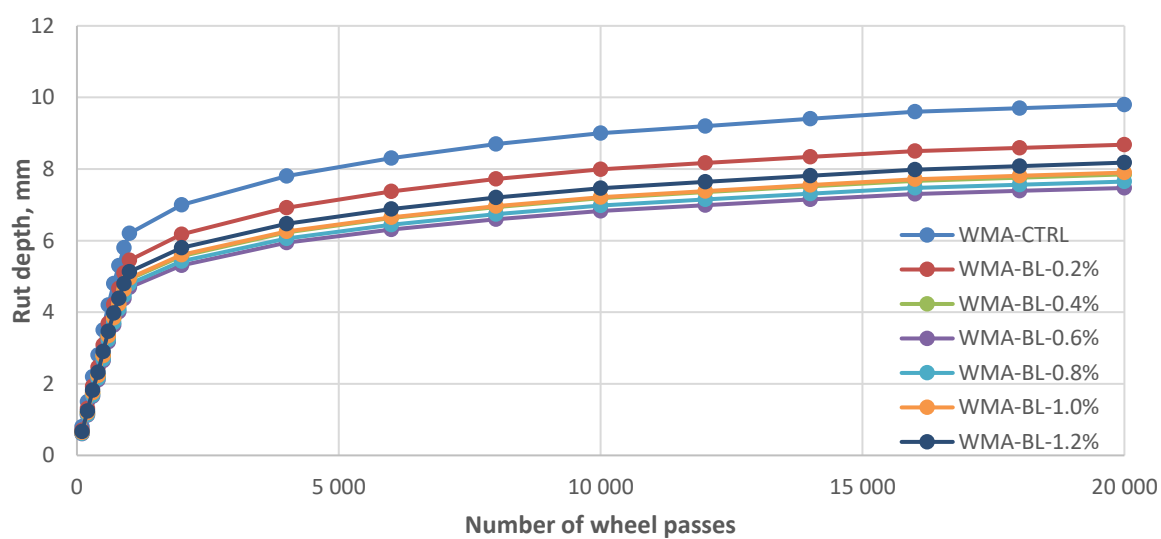


Fig. 8. Rut depth of WMA-BL

To understand the effects of different TPWM types, a special focus is placed on the optimum doses, as shown in Figure 9. The figure shows that the WMA-HDPE-0.6% mixture has the lowest value among the other mixes. Two reasons can justify this. First, its highest G_{mb} , highest stability, and highest stiffness among the other mixtures increase its rutting resistance. Second, its lowest air voids among the other mixtures decrease its rutting susceptibility. The differences between the mixtures contain different TPWM types probably related to their responses at the preselected mixing temperatures. HDPE, which exhibits the lowest melting temperature, was more likely to soften and participate to enhance bonding and ability to compact. In contrast, PET and PP exhibit higher melting temperatures and may remain solid or partially softened during mixing process. The intermediate behavior of BL may consequently reflect the combined behaviors of its various components.

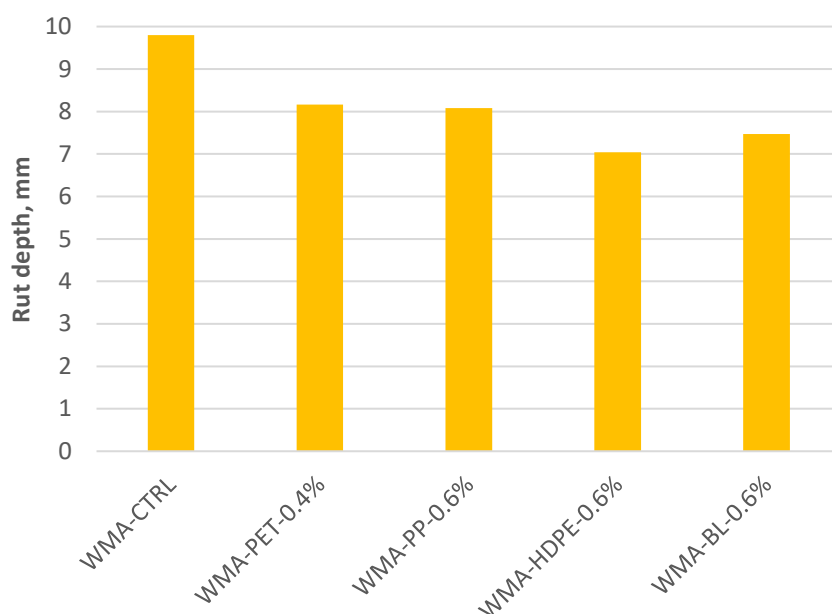


Fig. 9. Rut depth after 20,000 wheel passes

3.4 ITS Results

The values of ITS of unconditioned samples, ITS of conditioned samples, and TSR values for WMA-PET, WMA-PP, WMA-HDPE, and WMA-BL mixtures are shown in Tables 10, 11, 12, and 13, respectively. The results exhibited behavior similar to that observed in Marshall stability (as previously stated in subsection 3.2). The values increase with increasing TPWM doses until reaching the optimum, then decrease. With respect to PP, even though the highest unconditioned ITS value is found at 0.8%, 0.6% was adopted based on better overall performance in the other considered criteria as mentioned in section 2.4. This trend can be justified by reasons similar to those described in the previous subsections (3.2 and 3.3). However, one reason that may be more significant in this context is the reinforcing effect of the TPWM fibers within the mixture structure, as it is directly related to the tensile strength of the WMA mixture. This action increases the tensile strength of mixtures. However, its influence diminishes in mixes with excessive TPWM (beyond the optimum) due to increased mixture inhomogeneity and decreased asphalt adhesion resulting from TPWM absorption. Focusing on WMA-HDPE, adding the optimum dose increases ITS by 13% and 18% for

unconditioned and conditioned samples, respectively. This difference (about 5%) may be attributed to the plastic's water resistance, thereby increasing the mixture's resistance to wet conditions.

Table 10
ITS and TSR values for WMA-PET mixture

PET %	ITS Unconditioned (kPa)	ITS Conditioned (kPa)	TSR (%)
0.00%	510	408	80.0
0.20%	528	421	79.7
0.40%	548	442	80.7
0.60%	542	433	79.9
0.80%	533	421	79.0
1.00%	522	407	78.0
1.20%	512	394	77.0

Table 11
ITS and TSR values for WMA-PP mixture

PP %	ITS Unconditioned (kPa)	ITS Conditioned (kPa)	TSR (%)
0.00%	510	408	80.0
0.20%	516	412	79.8
0.40%	526	424	80.6
0.60%	542	433	79.9
0.80%	545	430	78.9
1.00%	541	422	78.0
1.20%	531	409	77.0

Table 12
ITS and TSR values for WMA-HDPE mixture

HDPE %	ITS Unconditioned (kPa)	ITS Conditioned (kPa)	TSR (%)
0.00%	510	408	80.0
0.20%	535	433	80.9
0.40%	558	457	81.9
0.60%	578	480	83.0
0.80%	572	475	83.0
1.00%	562	461	82.0
1.20%	550	446	81.1

Table 13
ITS and TSR values for WMA-BL mixture

BL %	ITS Unconditioned (kPa)	ITS Conditioned (kPa)	TSR (%)
0.00%	510	408	80.0
0.20%	530	427	80.6
0.40%	548	445	81.2
0.60%	562	460	81.9
0.80%	558	456	81.7
1.00%	548	443	80.8
1.20%	536	428	79.9

Figure 10 summarizes ITS and TSR values related to WMA-CTRL, WMA-PET-0.4%, WMA-PP-0.6%, WMA-HDPE-0.6%, and WMA-BL-0.6%. WMA-HDPE-0.6% registered the highest values for ITS in unconditioned samples and conditioned samples, as well as TSR. Based on the previously described results, the behavior is expected to be related to similar factors.

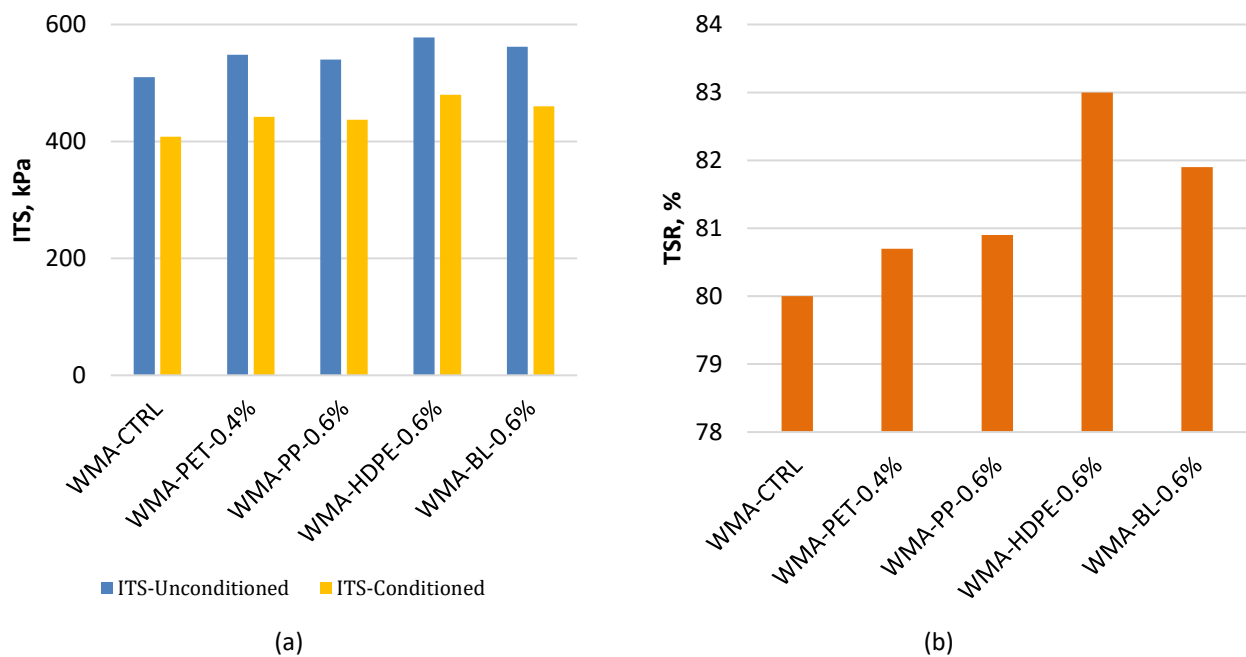


Fig. 10. ITS and TSR values at optimum doses of TPWM: (a) ITS, (b) TSR

4. Limitations and Future Work

This study was implemented under laboratory scale by utilizing local materials considering specific aggregate gradation, asphalt binder, WMA additive, and limited range of TPWM doses. Accordingly, the results must be interpreted within these experimental conditions. Future research is recommended to cover other materials and mixture conditions and to investigate long-term aging,

fatigue, and low-temperature performance, field-scale behavior, and the environmental and economic implications of using TPWMs in WMA.

5. Conclusions

This study investigates the effects of three types of TPWM, as well as a blend of these three types in equal proportions, on the Marshall properties, rutting resistance, and tensile strength of WMA. Special focus was placed on selecting the best type and specifying the optimal dose. The following conclusions were drawn from the results:

1. The three types of TPWM have positive effects on the properties of WMA. However, the effects differ based on the TPWM type and the dose added to the mixture.
2. Among the types used in this study, HDPE has the best effects on the properties of WMA in terms of increases in G_{mb} , Marshall Stability, Marshall Stiffness, rutting resistance, and tensile strength. This behavior is related to its ability to form cohesive bonds due to its relatively low melting temperature compared to other types.
3. The optimum doses of PET, PP, HDPE, and BL are 0.4%, 0.6%, 0.6%, and 0.6%, respectively.
4. Adding the optimum dose of HDPE to WMA can increase its G_{mb} , Marshall Stability, Marshall Stiffness, unconditioned ITS, and conditioned ITS by 0.4%, 25%, 42%, 13%, and 18%, respectively, whereas decreasing rut depth by about 28%.
5. Using a blend of these three types (BL) has an average effect on the properties of WMA, which indicates that each portion of the blend works separately. However, the blend of different TPWM types is inconsistent, increasing the mixture's inhomogeneity, which is already somewhat heterogeneous. In addition, the blending process consumes effort and energy. Therefore, this study does not recommend it.

Author Contributions

Conceptualization, A.M.M.; methodology, A.M.M.; investigation, K.H.S.; formal analysis, L.A. and M.F.A.; writing—original draft preparation, A.M.M. and K.H.S.; writing—review and editing, A.M.M. and K.H.S; All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data generated and analyzed during this study are available from the authors upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval and Informed Consent

Not applicable.

Declaration on the Use of Artificial Intelligence

The authors declare that no generative artificial intelligence tool was used in the preparation of this manuscript.

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