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Mechanical and Durability Performance of Dry-Process Hybrid LDPE-PET Modified Hot-Mix Asphalt

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ABSTRACT

Plastic waste valorization has increased interest in using low-density polyethylene (LDPE) and polyethylene terephthalate (PET) in hot mix asphalt (HMA), yet their combined behavior under dry processing remains largely undocumented, especially for hot-climate pavements. Twelve mixtures containing 4–10% LDPE–PET blends (< 2 mm) were prepared to examine hybrid dry process modification of HMA. Marshall stability and flow, volumetric properties, indirect tensile strength (ITS), and tensile strength ratio (TSR) were used to assess performance. The control mix recorded a Marshall stability of 10.78 kN, an ITS850 kPa, and a TSR of 83%. LDPE enhanced cohesion and compaction, whereas PET contributed stiffness at moderate contents; when combined, they produced a balanced effect with LDPE providing uniform coating and PET serving as dispersed reinforcement. Statistical analysis confirmed significant differences among mixtures ($p < 0.001$) and identified the LDPE5-PET3 blend at 8% total polymer as the most effective, achieving approximately 17% higher stability, 14% higher ITS, and a TSR of about 93%, while maintaining acceptable flow values and a favorable void structure. Systems dominated by PET or containing 10% polymer exhibited reduced compressibility and lower moisture resistance. The paper gives a practical range of dosages for hybrid modification of HMA. Although laboratory testing has inherent limitations, the results offer valuable insights for future research on performance improvement and the utilization of recycled plastic waste.

1. INTRODUCTION

Plastic waste is identified as one of the most severe global environmental issues today [1]. In 2019, around 370 million tons of plastic waste were generated worldwide, most of which was disposed of in landfills or incinerated. These two methods create environmental and economic issues. Two of the most well-known plastic wastes types include low-density polyethylene (LDPE) used in packaging films and plastic bags, and polyethylene terephthalate (PET), used in beverage bottles. These types of plastics prompted the highway industry to explore ways of combining waste plastics into hot mix asphalt (HMA). This becomes particularly relevant in hot climate regions, such as Iraq, where pavements experience elevated temperatures that can surpass the limitations for most conventional binders. Previously published research has reported observable performance improvements when (LDPE) and (PET) were used in asphalt mixtures. LDPE has been shown to reduce air void content, improve pavement stability, and decrease rutting susceptibility at moderate dosages, typically in the range of 2-6% by weight of binder [2-4]. On the other hand, PET has a much higher melting point and stiffer structure, that can lead to improved mixture strength and enhanced high-temperature stability. PET does not usually melt at regular HMA temperatures, so it typically remains as a rigid particle, which presents dispersion and bonding issues with the bitumen. At higher contents, PET could also increase mixture brittleness and reduce workability [5, 6]. The success of the dry mixing process, where plastic particles are directly added to hot aggregates, is, for the most part, influenced by particle size, usually less than 2 millimeters, and a mixing temperature of about 175-180°C [1, 7]. However, there has been little insight into the combined performance of both LDPE and PET in HMA despite the research interest in both. Their combined use can provide a more holistic solution where the flexibility from LDPE can balance out the brittleness from PET. Moreover, mixed plastic waste streams are more accessible and economically viable compared to single polymer waste sources [8, 9]. This research fills the knowledge gap by investigating the combined utilization of LDPE and PET in HMA using the dry mixing method. Plastic particles (< 2 mm) were dry-mixed with aggregates heated to 175°C for 30 s and then mixed with penetration-grade 40-50 bitumen, which was chosen based on its suitability to the region. Mixes were prepared with total plastic contents of 4-10% by binder weight at different LDPE-PET ratios. Performance characterization was conducted using Marshall stability and flow, volumetric properties, and indirect tensile strength (ITS) in both dry and wet conditions. Moisture susceptibility was investigated in terms of the tensile strength ratio (TSR).

This study advances understanding of LDPE-PET use in dry-processed HMA, outlining their interaction and practical dosage ranges. The results are based on short-term laboratory evaluation, reflecting the standard scope adopted in most research on plastic-modified asphalt.

2. LITERATURE REVIEW

Interest in adding waste plastics to HMA is based on their potential to help improve the performance of HMA while simultaneously diverting plastic waste from landfills. Among the commonly used methods of adding plastic waste to HMA, the dry mixing method involves adding plastic into heated aggregates before binder addition. LDPE typically demonstrates excellent benefits at 8–10% by binder weight, which offers 20–30% increases in Marshall stability and reduced flow values, though similar improvements were reported even at 2% [10-13]. The LDPE effect on volumetric properties is mild and primarily related to its dispersion quality. Evenly dispersed LDPE causes negligible differences in air voids (VA) and voids in mineral aggregate (VMA), while large or poorly dispersed particles slightly raise both, typically below 0.5% [4, 14]. Generally, LDPE acts as a binder-extending modifier, providing an increase in the mechanical performance of the asphalt matrix without significant changes in its internal structure. The LDPE is also beneficial for its water resistance because of its hydrophobicity, improving the bonding between the binder and aggregate. Mohanty [13] showed a rise in TSR from 78% for the unmodified mixes to 85–88% with 2% LDPE. Similar values of improvement have been presented in Singh and Gupta's study [3] and later confirmed under different test conditions in several studies [2, 15-17]. Above dosages of 10-12% by binder weight, LDPE reduces performance by causing problems with workability, inadequate dispersion, and unmelted clusters. These circumstances generally reduce flow values, tensile strength, and Marshall stability. Khadka et al. [5] detected the reduction in stability from 18.3 to 16.5 kN at 8–10% LDPE and attributed this to the coarseness of the flakes and low energy used in mixing, as echoed by Sabina et al. [18] and Awwad and Shbeeb [16]. Such findings show that careful control regarding particle size, heating, and dosage is important. However, PET behaves differently than LDPE due to rigidity and a higher melting point; it stays in a solid form during conventional HMA production. Thus, PET is not a binder modifier, but rather is more like a fine aggregate. While PET also has limited interaction with the binder, it can improve strength and stiffness as long as appropriate dosages are used. Most studies have indicated that the effective dosage of PET, in terms of binder weight, is generally between 6–8%, which includes several significant increases in Marshall stability, stiffness, and lower flows [19-21]. This has also been reported by Mashaan et al. [22] and Birega et al. [23], who reported an enhancement up to 10% in marshall stability. The volumetric effects of PET vary, depending on dosage and particle size. Modestly dosed micronized PET can reduce VA slightly and increase density [19]. The higher doses or coarse flakes increase VA and VMA, leading to low workability and poor compaction [24, 25]. There is some evidence regarding gains in strength with up to 12–15% PET [26, 27]; however, this is offset in various works due to an increase in voids and permeability. For example, Movilla-Quesada et al. [25] noticed TSR levels above 80% at 10% PET, but the reduction in TSR occurred at 14% PET, which was linked to the excess voids and poor cohesion. Agha et al. [28] identified an increase in TSR from the low 70s to near 90% at 10% PET, using a modified dry process treatment (pre-coated aggregate). While dos Santos Ferreira et al. [29] reported TSR values above 80% at low PET contents, Agha et al. [28] showed that more uniform dispersion generated TSR values near 96%. These findings indicate that the positive impact of PET on moisture resistance is more closely related to the effects of its mixing quality and particle uniformity than to its chemistry. Poorly dispersed PET may behave like an inert filler, and its performance is lower than that of LDPE, depending on the initial mixing conditions to which each was subjected. In summary, the literature regarding the behavior of PET is rife with contradictions: high stability and strength are observed when PET is well dispersed (a fiber network with close void spacing), while studies that tested coarse or uneven PET particles invariably reported more void space, poorer compressibility, and worse moisture resistance. The observed differences are a function of the processing conditions used, not of the base material properties. LDPE and PET work differently in an asphalt mixture. LDPE softens at 108℃, causing a bonding effect that improves binder ductility, cohesion, and compaction of the asphalt, whereas PET remains rigid; as such, PET will stiffen the asphalt, resist rutting, and act as a mineral filler [30]. Multiple investigations have demonstrated that LDPE has the capability of improving rutting resistance of up to 6% [31, 32], whereas poorly ground PET can contribute to increased VA and reduced compaction [24]. A combination of LDPE and PET may promote high-performance asphalt due to their complementary properties. Research in this area with dual modifiers is limited but still noteworthy. Khadka et al. [5] found that PET outperformed LDPE at 8–10%, with comments that a combination of the two could be beneficial. Agha et al. [28] found high TSR and stability in well-dispersed PET flakes in dry-mixed systems, while Revelli et al. [30] saw LDPE outperform PET in both stability and moisture resistance, likely because of the better binder compatibility. Recent discussions have also begun to take into consideration the life-cycle and recyclability implications of polymer-modified asphalt, especially for long-term reuse of reclaimed asphalt pavement. Though still developing, these studies point out the need to balance performance benefits with environmental and life-cycle considerations.

3. METHODOLOGY

3.1 Materials

3.1.1 Aggregates

Crushed stone and manufactured sand were used as coarse and fine aggregates. Gradation was designed to meet surface course requirements according to the Specifications of the State Corporation for Roads and Bridges (SCRB) [33] and ASTM D3515 [34], as illustrated in Figure 1. Ordinary Portland Cement (OPC) was used as the mineral filler in compliance with ASTM D242 [34]. Aggregate physical and chemical properties are presented in Table 1.

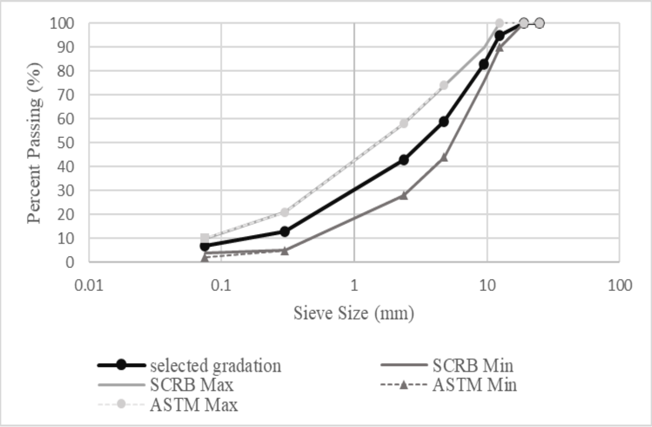

Figure 1. Aggregate gradation of selected mix compared with SCRB and ASTM specification limits

Note: ASTM and SCRB limit curves overlap in certain sieve ranges, resulting in visually merged lines.

Table 1. Physical and chemical properties of the coarse and fine aggregates used in the asphalt mixtures

Test Parameter	Fine Agg.	Coarse Agg.	SCRB Limits
Specific gravity	2.57	2.6	N/A
Absorption (%)	0.85%	0.69%	N/A
(SO_3%)	0.323%	0.07%	≤ 0.5% (Fine), ≤ 0.1% (Coarse)
Aggregate Impact Value (AIV) (%)	N/A	14%	N/A
Los Angeles Abrasion Value (%)	N/A	8%	≤ 30%

Table 2. Physical and rheological properties of the bitumen

Property	Test Value	Test Method	SCRB Limits	ASTM Limits
Penetration (25℃, 100g, 5 s)	43.5 mm	ASTM D5	40–50 mm	40–50 mm
Softening point	52.5℃	ASTM D36	≥ 50℃	≥ 50℃
Specific gravity at 25℃	1.03	ASTM D70	N/A	N/A
Ductility (25℃, 5 cm/min)	120 cm	ASTM D113	> 100 cm	> 100 cm
Viscosity (135℃)	0.7 Pa.s	ASTM D4402	N/A	N/A
Flash point	265℃	ASTM D92	> 232℃	> 230℃

Table 3. Composition of asphalt mixtures with varying LDPE and PET contents (by binder weight)

Mix ID	LDPE (%)	PET (%)	Total (%)
C-0	0	0	0
LDPE-4	4	0	4
PET-4	0	4	4
BLEND-4	2	2	4
LDPE4-PET2	4	2	6
LDPE2-PET4	2	4	6
BLEND-8	4	4	8
LDPE5-PET3	5	3	8
LDPE3-PET5	3	5	8
BLEND-10	5	5	10
LDPE6-PET4	6	4	10
LDPE4-PET6	4	6	10

3.1.2 Bitumen

A 40/50 penetration-grade bitumen from the Beiji Refinery (Iraq) was used, selected for its suitability under the region's high-temperature climate. Its physical and rheological properties were evaluated according to SCRB and ASTM standards, and the results (Table 2) confirmed compliance with specification requirements for surface course asphalt mixtures.

3.1.3 Plastic modifiers

Two recycled plastics were used as dry-process modifiers: PET from post-consumer beverage bottles and LDPE in pellet form from a local recycling facility handling industrial films, shopping bags, and packaging waste. Before use, both plastics were cleaned and ground to pass a 2 mm sieve, ensuring uniform particle size for dry mixing.

3.2 Determination of optimum asphalt content

The optimum asphalt content (OAC) of the control mixture was determined using the Marshall mix design method, with specimen preparation and testing in accordance with ASTM D6926 and ASTM D6927. Following Asphalt Institute guidelines, the OAC was selected by balancing 4% target VA, peak Marshall stability, maximum bulk density, and voids filled with asphalt (VFA) value within 65–75%. Trial specimens were produced at binder contents of 4–6% by total mix weight, and the OAC was established at 4.9%, providing the most favorable balance of volumetric and mechanical properties. This value was applied to all LDPE-PET mixtures to isolate the effects of LDPE and PET, under the fixed-binder approach commonly adopted in polymer-modified asphalt studies [4, 35-38].

3.3 Mixing and sample preparation

Asphalt mixtures were prepared using the dry process. Mixing duration and temperatures followed established dry-process procedures to minimize polymer clustering and promote uniform particle embedding in the aggregate skeleton. Aggregates were oven-heated to approximately 175 C, then PET and LDPE particles (≤ 2 mm) were dry-mixed with the hot aggregates for 30 s to ensure dispersion [16, 39]. Preheated bitumen (160–170℃) was added, and the blend was mixed for another 90 s to ensure uniform coating. Specimens were compacted by the Marshall method (ASTM D6927), applying 75 blows per face to form cylindrical samples (101 mm × 63.5 mm). Twelve mixtures were produced: one unmodified control (C-0), two individually modified with 4% LDPE or 4% PET, and nine PET-LDPE blends with total plastic dosages of 4–10% by binder weight. This range was selected based on previous investigations, which had tested LDPE and PET separately, reporting optimum performance in the range of 4–10% [3, 4, 24, 40]. Three replicates were used following ASTM recommendations for repeatability, and the resulting coefficients of variation are sufficiently small that this sample size delivers adequate statistical stability. Mixture compositions are fully detailed in Table 3.

3.4 Testing procedures

Laboratory tests were performed according to the standard procedures of ASTM to assess the mechanical behavior and durability of the control and polymer-modified mixtures. The Marshall stability and flow of the compacted specimens with

75 blows per face and tested at 60 ± 1°C were determined in accordance with ASTM D6927. Stability was the maximum load at failure, while the corresponding deformation was measured as flow. For volumetric properties such as VA, VMA, and VFA, bulk specific gravity determined by ASTM D2726 and theoretical maximum specific gravity obtained from ASTM D2041 were used, giving information about mix compressibility and binder distribution. ITS was measured in accordance with ASTM D6931 on cylindrical specimens of dimensions 100 mm × 63.5 mm. Dry samples were conditioned at 25°C before loading. Moisture susceptibility was assessed in terms of TSR by following ASTM D4867, where the wet ITS is divided by the dry ITS after conditioning the specimens in a water bath at 60°C for 24 h. All the aforementioned tests were carried out on three replicate specimens, and the mean values are presented.

4. RESULTS AND DISCUSSION

4.1 Marshall stability and flow

According to SCRB [33], surface-course asphalt should reach ≥ 8 kN stability and 2–4 mm flow. This aligns with the specifications of Asphalt Institute MS-2 and FAA P-401. Test outcomes, measured against the control mix, are given in Figure 2. Error bars represent standard deviation (n = 3), which do not show much variation in stability CV from 2.2-5.1% and flow CV from 0.6-3.8%, lending confidence to the data reliability. Control mix C-0, with a 10.78 kN stability and 3.87 mm flow, was used as a benchmark for data comparisons. ANOVA revealed significant differences among groups (Stability: F (11,24) = 15.05, $p < 0.001$; Flow: F (11,24) = 142.36, $p < 0.001$). The inclusion of 4% LDPE raised stability to 11.73 kN (a 9% increase above control) and reduced flow to 3.48 mm. This can be attributed to the softening of LDPE during mixing and better performance as it pertains to increased cohesion of the binder [3]. The post-hoc analysis also showed LDPE-4 was one of the stronger combinations and still had reasonable flow. Conversely, adding 4% PET had only minimal stability improvements (11.06 kN), while the samples exceeded the SCRB flow limitation of 4.14 mm. Since PET has a higher melting point than LDPE, it does not blend into the binder in the same manner as LDPE; this means that PET acts as a filler in the mixture, resulting in localized slippage and permanent deformation [24]. Statistical Analyses indicated that PET-4's stability was not statistically different from the control ($p > 0.05$), however, its flow was significantly greater than both the control and all compliant mixes ($p < 0.05$). A properly proportioned blend of 2% LDPE and 2% PET increased stability to 11.60 kN (5% stronger than PET-4) and returned flow to acceptable levels of compliance (3.58 mm) by combining LDPE's adhesive properties to PET's structural rigidity [3, 27]. LDPE-PET composites were most optimal at a total polymer usage of 6–8%, with LDPE providing the bulk contribution. The 5% LDPE and 3% PET blend achieved the highest stability, at 12.65 kN, with acceptable compliance flow (3.67 mm). The observed stability demonstrated a synergistic contribution of binder reinforcement and structural effects, favorably aligning with the proposed usage of LDPE-rich systems in the literature [27]. Tukey's HSD confirmed the (LDPE5-PET3) blend advantage over PET-4 and PET-heavy blends in both stability ($p = 0.006$) and flow ($p < 0.01$). At 10% polymer, however, performance declined sharply, with stability dropping below the control mix (< 9.2 kN) and flow exceeding 5 mm due to poor dispersion and polymer-rich zones [5]. Statistical modeling confirmed a nonlinear response: performance peaked near 8% and deteriorated when one polymer dominated. Overall, 8% total polymer with LDPE ≥ 60% offered the best stability-flow balance. Higher dosages or PET-rich blends reduced rutting resistance by increasing deformation. This optimal window is further evaluated in the following sections on tensile strength and moisture susceptibility.

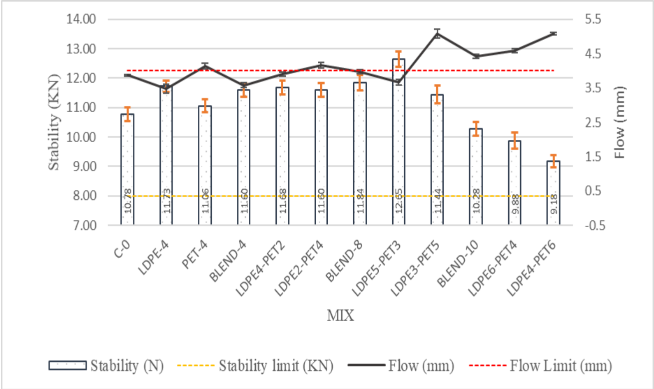

Figure 2. Marshall stability and flow values for all asphalt mixtures compared to SCRB specification limits

4.2 Volumetric properties

According to SCRB [33], surface-course mixtures must contain 3–5% VA, at least 14% VMA, and 65-75% VFA, consistent with Asphalt Institute MS-2 specifications for 12.5 mm NMAS. These volumetric parameters govern compaction, durability, and resistance to moisture and oxidation. The control mix (C-0) satisfied all volumetric requirements (VA = 4.12%, VMA = 14.49%, VFA = 71.53%) and served as the benchmark, as shown in Figure 3. With the 4% LDPE blend, VA slightly decreased to 3.97%, while VMA and VFA rose to 14.69% and 72.95%, respectively, which is indicative of improved compaction and binder distribution. These trends align with findings reported in studies [31, 32] and match the stability and flow enhancements described in Section 4.1. The use of 4% PET contributed to an increase in VA (4.45%), VMA (15.67%), and a minimal increase in VFA (71.52%), demonstrating poor compactability due to PET rigidity, as also reported in the study [24]. In addition, the volumetric response of the blended mixes varied by polymer ratio. At a total of 4% polymer (BLEND-4), VA (4.36%), and VFA (71.96%) were comparable to the control mix, although the dual modification showed favorable behavior, even at low dosages. However, with the use of 6%, the PET-dominant blend (LDPE2-PET4) resulted in increased VA (5.27%) and reduced VFA (68.76%), which indicates lower compressibility. The LDPE-rich blend (LDPE4-PET2) resulted in acceptable volumetric values (VA = 4.64%, VFA = 70.13%). The volumetric patterns support the mechanical outcomes from Section 4.1, since blends containing a higher content of LDPE had lower void contents and overall better performance. Blends with a higher concentration of PET had a more open matrix and less stability. The optimal volumetric results occurred at 8% total polymer (LDPE5-PET3), with VA = 3.94% and VMA = 15.43% (all within SCRB limits), and the best VFA at 74.5%. The improved results in this study align with previous studies of hybrid systems and are attributed to the binder extending abilities of LDPE and micro-reinforcement capabilities of PET [27, 30]. At a total polymer content of 10%, the volumetric values decreased (VA > 5%, VMA > 16%, and VFA < 68%), indicating that additional plastic beyond the optimal total polymer range negatively affects stability by breaking down the mastic structure and increasing porosity [30]. These volumetric variations were concurrent with the mechanical behavior noted: lower VA and consistent VMA supported higher ITS and TSR values, whereas higher VA resulted in lower moisture resistance. The volumetric response was most balanced when an 8% total polymer dosage was used with dominant LDPE, meeting SCRB specifications, and long-term mix durability.

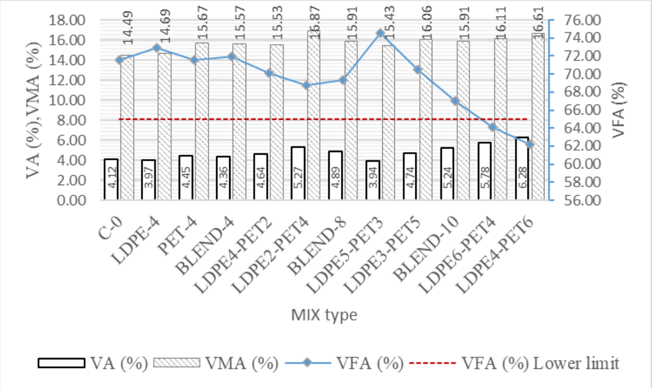

Figure 3. Volumetric properties (VA, VMA, VFA) of control and polymer-modified asphalt mixtures

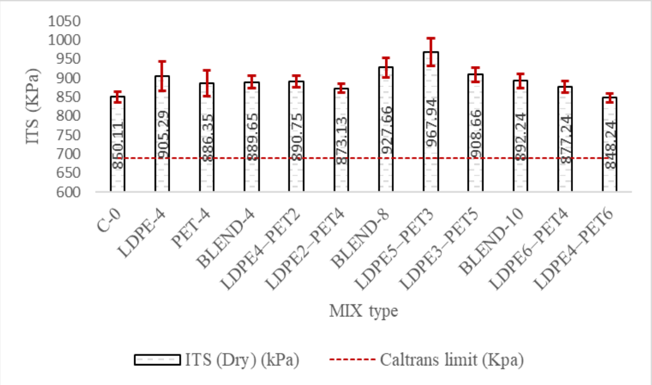

Figure 4. ITS of control and polymer-modified asphalt mixtures

4.3 ITS

The control mixture (C-0) reached 850 kPa, which is greater than the Caltrans minimum requirement of 690 kPa. C-0 was subsequently utilized as the reference mixture to evaluate the polymer influences, as shown in Figure 4. The one-way ANOVA test confirmed significant differences existed between the mixtures [F (11,24) = 7.18, $p < 0.001$], indicating that the observed variances were statistically significant. The addition of 4% LDPE raised the ITS to 905 kPa (a 6% improvement over control). This coincides with earlier observations that LDPE softens at higher mixing temperatures, thickening the binder film, improving aggregate coating, and bridging micro-voids that help redistribute tensile stresses [3, 31, 41, 42]. The PET-4 mix achieved an ITS of 886 kPa (4% greater than control), but it was still lower than the LDPE-4. It is noteworthy that for dry-process experiments, PET consistently provided modest strength gains of 2–4%; however, beyond this range, the stiffening effects of PET and binder starvation reduced the strength gains [2, 11, 25, 28]. Because PET remains solid at typical mixing temperatures, it acts as a rigid inclusion rather than a film-forming polymer. Under diametral loading, poorly wetted or clustered particles thin the asphalt film and concentrate stresses, thereby reducing fatigue resistance and increasing flow at higher contents [24]. These mechanisms clarify why PET-4 achieved only modest improvement compared to LDPE-4. The combination of 2% LDPE and 2% PET achieved 890 kPa (4.7% over the control mix), which lies between the results of the 2% LDPE and 2% PET and does not exhibit synergistic effects. This behavior is attributed to the lower amount of LDPE, which weakened the binder film, while the 2% PET contribution provided limited stiffening [3, 43]. At 6%, the LDPE-dominant (4LDPE,2PET) blend capped out at 891 kPa, while the PET-heavy (2LDPE,4PET) blend dropped to 873 kPa (2.7% gain) as a result of having rigid inclusions and micro-voids [44, 45]. At 8% total polymer, the LDPE-dominant (5LDPE,3PET) revealed the highest ITS value of 967 kPa (13.8%) higher than the control mix, significantly higher than PET-4, LDPE-4, and several blends ($p < 0.05$). These results are attributed to the melt film of the LDPE leading to a stronger cohesion and moisture tolerance [46, 47] as well as the PET stiffening below a threshold amount [43, 45]. This complementary interaction supports recent findings on the behavior of dual-polymer asphalt systems [27]. The PET-dominant 3:5 blend reached 909 kPa (7% above control), while the balanced 4:4 blend achieved 928 kPa (9.2%). The results show two main pathways: A minimum of 4% LDPE is required for film continuity, while PET provides rigidity to the material up to 5%. Beyond that range, an excessive void content develops [24, 48]. Although both tested blends were statistically similar to the 5:3 optimum ($p > 0.05$), they produced smaller improvements, reinforcing that LDPE-dominant ratios yield better tensile performance. In the case of 10% total polymer, all blends showed indications of over-saturation, where the binder could not fully coat the plastic particles, leaving extremely high voids and less tensile strength [25]. PET exacerbated the issue since the flakes had low adhesion, and contents above 6% led to reduced ITS and Marshall quotient values [48]. The LDPE-rich 6:4 also had a poor performance converting excessive LDPE into a lubricated film that impaired load transfer. All blends that were at 10% also performed less than the 8% blends ($p < 0.01$), establishing an upper limit of 8% polymers as the best ratio.

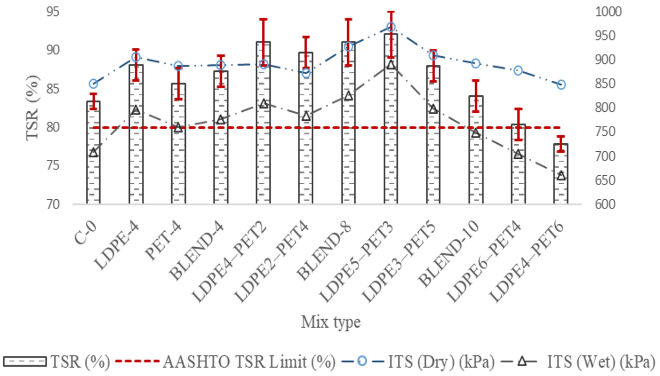

Figure 5. TSR of control and polymer-modified asphalt mixtures

Table 4. Summary of key statistical results across performance metrics

Property	ANOVA Results	Post-Hoc Tukey Comparisons	Regression Model and Fit
Stability (kN)	F (11,24) = 15.05, $p < 0.001$	LDPE5-PET3 significantly higher than PET-4 (+2.1 kN, $p = 0.002$) and LDPE-4 (+1.7 kN, $p = 0.013$); also exceeded weaker blends ($p < 0.01$)	Quadratic model: $R^2 = 0.75$, Adj-$R^2 = 0.53$
Flow (mm)	F (11,24) = 142.36, $p < 0.0001$	PET-4 and PET-5-LDPE3 showed significantly higher flow than LDPE5-PET3 ($p < 0.05$); PET-rich mixes approached upper specification limit	Quadratic model: $R^2 = 0.82$, Adj-$R^2 = 0.67$
ITS (kPa)	F (11,24) = 7.18, $p < 0.001$	LDPE5-PET3 exceeded PET-4 (+82 kPa, $p = 0.004$) and LDPE-4 (+63 kPa, $p = 0.048$); also superior to weaker blends ($p < 0.01$)	Quadratic model: $R^2 = 0.49$, Log-transformed model: $R^2 = 0.84$, predictions stable but wider CI
TSR (%)	F (11,24) = 9.50, $p < 0.001$	LDPE5-PET3 > PET-4 (+8.4%, $p = 0.006$) and LDPE-4 (+7.2%, $p = 0.015$); PET-dominant mixes < 80% threshold	Quadratic model: $R^2 = 0.76$, Adj-$R^2 = 0.55$

4.4 Water susceptibility

The TSR was used to assess moisture resistance, which has an established minimum requirement of 80% in accordance with AASHTO T-283 [49]. The control mixture (C-0) had a TSR of 83%. While this value is above the minimum requirement, it still indicates relatively low moisture resistance, as illustrated in Figure 5. One-way ANOVA confirmed significant differences in TSR across the mixtures [F (11,24) = 9.50, $p < 0.001$]. At 4%, the LDPE increased TSR to 88%, with wet ITS exceeding 900 kPa, significantly higher than control ($\Delta = +4.7$ percentage points, $p = 0.006$). The improvement is attributed to partial melting of the LDPE during mixing, forming a hydrophobic film that mitigated moisture-induced stripping [46, 47]. PET-4 achieved a smaller increase in TSR (86%, $\Delta = +2.3$ percentage points, $p = 0.020$). Since PET remains solid at mixing temperatures, it does not form a continuous film to act as a moisture barrier, explaining the lesser performance [43, 45]. Blended systems, however, demonstrated clear signs of synergy. The 2% LDPE and 2% PET mix reached a TSR of 87% (wet ITS 890 kPa), while LDPE-dominant blends exhibited the highest performance: LDPE4-PET2 and LDPE5-PET3 achieved 92–93% TSR with wet ITS values > 920 kPa. This behavior is attributed to the formation of a cohesive, moisture-resisting film from LDPE, while PET primarily contributes structural stiffening [3, 27, 43, 45]. The effects of a high proportion of PET led to diminished performance compared to mixtures with less PET. Although the 10% combinations had TSR values just below 90%, a mixture like LDPE4-PET6 (60% PET) dropped below the 80% TSR mark at 78%, which was significantly lower than both the control and LDPE-rich combinations ($p < 0.001$). This decrease is likely due to excess PET acting as a rigid, poorly-wetted inclusion, which contributed to micro-voids and moisture ingress. These findings are consistent with previous research with high proportions of PET [28, 44, 45]. Two-way ANOVA confirmed significant main effects for both LDPE% ($p = 0.006$) and PET% ($p < 0.001$), along with a notable interaction effect ($p = 0.013$), indicating that moisture resistance is influenced more by the LDPE:PET ratio than by total polymer content alone. Additionally, visual evaluation of conditioned samples provided support for these conclusions: samples that included LDPE after the wet conditioning process had a uniform coating of the binder, whereas mixes that contained PET showed some aggregate exposed (particularly at the edges). This is related to the increased VA and decreased tensile strength following conditioning. LDPE was the main driver: 4–5% LDPE lifted TSR into the 88–90% range, PET contributed stiffness only up to 3%, and the optimum occurred at 8% total polymer with a 5:3 LDPE-PET (TSR = 93%, wet ITS = 920 kPa).

4.5 Statistical validation

To verify the robustness of the observed performance trends, global ANOVAs, post-hoc contrasts, factorial tests, and regression models were conducted across all mechanical and durability indicators [50]. As shown in Table 4, homogeneity of variance was supported (Levene's $p > 0.26$ for all outcomes), and replicate variability remained low (CV $\leq$ 5%). Global tests indicated significant differences between groups for stability, flow, ITS, and TSR (all $p < 0.001$). The post-hoc Tukey comparisons ranked LDPE5-PET3 in the highest group consistently, while other blends that were PET-heavy or high-total blends ranked lower. Factorial analysis: The two-way ANOVAs revealed significant effects for LDPE, PET, and interaction for all outcomes ($p < 0.05$), and demonstrate that performance is defined by the LDPE:PET ratio, not just total polymer amount. Multivariate analysis. PERMANOVA across all four outcomes confirmed strong separation among mixes (pseudo-F = 14.15, $R^2 = 0.866$, $p < 0.0001$). Through regression analysis, the statistical tests confirmed an additional layer through the understanding of the increases in performance measure relative to each variable across the LDPE-PET mixing range. The responses for stability, flow, and TSR were reasonably estimated with quadratic models for each measure, with coefficients of determination of 0.75, 0.82, and 0.76, respectively. The coefficients of determination demonstrate a consistent curvature pattern of behaviour in these properties as polymer proportions are altered. When examining the surface fit of the model, the pattern becomes clearer: mixtures that are near the centre of the LDPE-PET distribution tend to be close to the predicted optimal area, while those that favour the structural compositions of PET or LDPE are outside of optimality. The ITS response was notably different; while it was direct in the quadratic model, it resulted in considerable scatter seen by a low overall R^2 of 0.49. However, when the response was logarithmically transformed, it was found that the fit improved considerably to an overall R^2 of 0.84, which is also consistent with the nature of ITS and its sensitivity to changes in the mixture composition of the modified asphalt systems.

5. CONCLUSION

The research focused on the effect of waste-based LDPE and PET on dry process HMA under elevated temperature conditions. LDPE enhances the cohesive strength of the mastic and improves compaction, while PET acts as a rigid inclusion that increases stiffness at moderate levels. The optimal performance of blended systems occurs when LDPE forms a continuous film and PET acts as a reinforcing agent without disrupting film continuity. Mixtures containing a mid-range total polymer fraction performed better than both single-polymer and PET-dominant mixes. The key stable formulation was composed of approximately 8% total polymer, with LDPE as the major phase and a 5:3 LDPE-to-PET ratio. This formulation resulted in high tensile strength, acceptable flow within specification limits, and a desirable void structure. On the other hand, PET-heavy blends and 10% polymer mixtures exhibit poor compaction and increased susceptibility to moisture. Overall, the results suggest that maintaining a continuous LDPE film, with PET in a subordinate reinforcing role, is essential for long-term performance. the results suggest that LDPE-PET hybrids could indeed improve the performance of surface course HMA and stand as an effective mixed plastic waste recycling solution. Several limitations should be recognized. The experiments were conducted at the laboratory scale, the conditioning period was short, and the study relied on a single aggregate-binder pairing. A broader environmental evaluation, ideally through life-cycle assessment, is still pending. Future work should incorporate rutting and fatigue tests, aging protocols calibrated to service temperatures, field validation under actual traffic, and a comprehensive environmental analysis to weigh performance benefits against ecological costs.

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