

Evaluating the Curing Effects on PET-Enhanced Asphalt Mixtures in Hot-Climate Conditions

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ABSTRACT

Asphalt pavements in Iraq face intense summer heat, often exceeding 50 °C, accelerating the binder aging and reducing the pavement life. This study investigates how recycled Polyethylene Terephthalate (PET), added via the dry process, affects the asphalt performance—and how the curing time and temperature influence that effect. A total of 195 Marshall specimens were prepared using five PET dosages (0, 1, 5, 10, and 20% by bitumen weight), cured at two temperatures (50 °C and 70 °C) over three periods (7, 14, and 30 days), plus a control mix with no curing. The results show that 5% PET consistently delivered the best performance. At 70 °C after 14 days, the Marshall stability increased from 14.04 kN to 17.86 kN (27%), and the Marshall Quotient (MQ) rose from 3.41 to 4.28 (over 25%), compared to the control mix, while the flow values remained within the SCRB limits. The statistical analysis confirmed that the PET dosage had the most significant impact ($p < 0.0001$), accounting for up to 91% of flow variation. The curing temperature affected the flow but not other properties, while the curing time had no significant effect. However, the performance declined sharply with PET contents above 10%. Higher dosages led to reduced density, increased voids, and weaker structural integrity—signaling a clear upper limit for effective PET use. In conclusion, adding 5% PET and curing for at least one week at 50 °C or higher produces a more durable and heat-resistant asphalt mix. The approach not only enhances the mechanical properties, but also offers a sustainable solution by recycling plastic waste into long-lasting pavements. This study investigates the PET modification and controlled curing conditions under extreme climate settings—bridging two underexplored variables in the asphalt performance research.

Keywords-hot mix asphalt; PET; curing conditions; Marshall properties; volumetric properties; sustainability

I. INTRODUCTION

Asphalt pavements in regions like Iraq face rapid

deterioration due to extreme temperature fluctuations, with surface temperatures exceeding 50 °C in summer and dropping below 10 °C during winter nights [1]. These harsh conditions

accelerate the binder aging, leading to rutting and cracking under repeated loading [2, 3]. Achieving a mix that balances stiffness and flexibility is critical, particularly when considering the influence of the curing time and temperature on the performance. Recycled PET, derived from plastic waste, has been studied as a sustainable asphalt modifier. PET’s hydrophobic nature, nonabsorbent structure, and semi-elastic behavior improve the binder cohesion and reduce the binder demand, particularly in Hot Mix Asphalt (HMA) applications [4]. Research has explored the incorporation of PET waste into asphalt mixtures, demonstrating improvements in the mechanical properties and sustainability aspects [5, 6]. It has been reported that PET can improve the rutting resistance, delay oxidation, and enhance the structural stiffness at dosages up to 5% [7-9]. However, beyond 10%, challenges have been noted, such as increased Air Voids (Va) and reduced compaction [10], while high dosages may also introduce issues, like thermal softening or poor dispersion [11]. The effect of the PET content on stability, flow, and stiffness has been explored. Authors in [12] found that the particle size and mixing methods significantly influence performance, while in [13], an optimal behavior was observed at 14% PET beyond which the cohesion declined. Authors in [14] reported increased binder viscosity and reduced rutting depth at 15–20%.

Meanwhile, the curing conditions play a key role in simulating field aging. An increased curing time enhances the rutting resistance and stiffness [15, 16], while short-term oven aging can replicate the long-term field conditions [17]. However, the exposure above 150 °C significantly alters the binder properties [18], and aging reduces the healing ability under repeated loading [19, 20]. While previous studies address high-temperature performance, they overlook the specific roles of curing time and temperature [10]. The absence of standardized protocols further limits comparability. While numerous studies have explored PET modification or thermal conditioning independently, few have assessed their combined influence under controlled curing regimes. Moreover, no previous research has evaluated this interaction in the context of Iraq’s extreme summer climate. This study addresses that gap by examining PET-modified mixtures cured at 50 °C and 70 °C for 7, 14, and 30 days, assessing PET’s potential as both a plastic waste solution and a performance-enhancing additive against oxidative aging in hot, arid conditions.

II. MATERIALS

A. Aggregates

Locally available crushed stone and manufactured sand were used as coarse and fine aggregates in this study. All aggregates were tested according to the SCRB binder course specifications [21] and ASTM D3515 [22], as shown in Table I, to confirm their suitability for hot mix asphalt. Gradation compliance with the specification limits is illustrated in Figure 1. Limestone powder, meeting ASTM D242 requirements, was used as a mineral filler to improve the binder retention and mix compactness [22].

B. Bitumen

The bitumen used was 40/50 penetration grade, sourced from the Beiji Refinery in Iraq. It was selected for its suitability

in high-temperature environments. To ensure performance reliability, its physical and rheological properties were tested according to [21, 22], as depicted in Table II. The results confirmed compliance with the required specifications for binder course applications.

TABLE I. PHYSICAL AND CHEMICAL PROPERTIES OF AGGREGATES

Test Parameter	Fine Aggregate	Coarse Aggregate	SCRB Limits [21]	ASTM Limits [22]
Specific Gravity	2.57	2.6	N/A	N/A
Absorption (%)	0.85%	0.69%	N/A	N/A
Sulfate Content (SO ₃)(%)	0.32%	0.07%	≤ 0.5% (Fine), ≤ 0.1% (Coarse)	N/A
Aggregate Impact Value (AIV) (%)	N/A	14%	N/A	N/A
Los Angeles Abrasion Value (%)	N/A	8%	≤ 30% (Surface Course)	≤ 50%

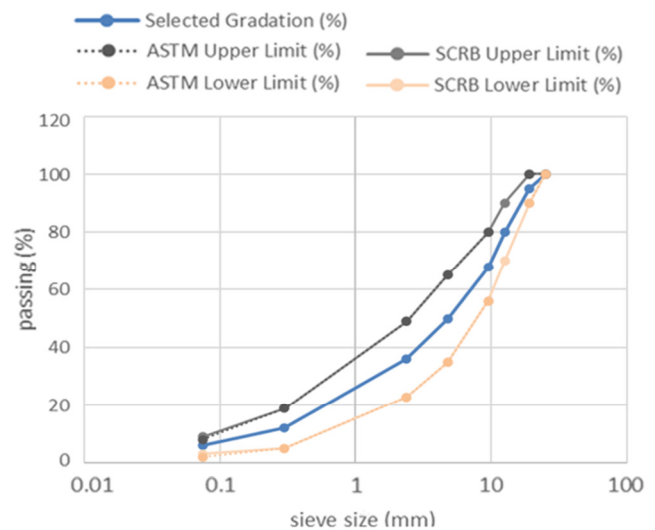


Fig. 1. Aggregate gradation curve compared with SCRB and ASTM specification limits

TABLE II. PHYSICAL AND RHEOLOGICAL PROPERTIES OF BITUMEN

Property	Test Value	Test Method	SCRB Limits [21]	ASTM Limits [22]
Penetration (25°C, 100 g, 5 s)	43.5 mm	ASTM D5	40-50 mm	40-50 mm
Softening Point (Ring & Ball)	52.5°C	ASTM D36	≥ 50°C	≥ 50°C
Specific Gravity (25°C)	1.03	ASTM D70	N/A	N/A
Ductility (25°C, 5 cm/min)	120 cm	ASTM D113	>100 cm	>100 cm
Brookfield Viscosity (135°C)	0.7 Pa·s	ASTM D4402	N/A	N/A

C. Recycled Polyethylene Terephthalate

Waste PET bottles, collected from local sources, were used as the modifier in this study. The bottles were washed, dried, and stripped of labels before being shredded into granules. To ensure uniformity, the processed PET was sieved through a No. 4 (4.75 mm) sieve before incorporation. This preparation ensured consistent dispersion during mixing and minimized impurities that could affect the mix's performance.

III. MIX DESIGN AND SAMPLE PREPARATION

The asphalt mixtures were prepared following the Marshall mix design method ASTM D6926 [22]. PET was added at 1%, 5%, 10%, and 20% by weight of the bitumen, with a control mix (0% PET) for comparison. These dosages were selected based on prior studies, covering both the optimal and upper-limit PET contents [7–9, 13, 14]. The dry process was adopted, where PET granules were blended with heated aggregates before bitumen was added. The specimens were compacted using 75 blows per side to ensure uniform density and air voids. Cylindrical samples were prepared with dimensions of 101.6 mm diameter and 63.5 mm height. For each PET level, fifteen specimens were produced to determine the Optimum Asphalt Content (OAC), using five bitumen contents (4.0%, 4.5%, 5.0%, 5.5%, and 6.0%) with three replicates each.

IV. CURING AND TESTING CONDITIONS

To simulate the field aging in high-temperature environments, the specimens were subjected to controlled curing before testing. Two curing temperatures were used: 50°C and 70°C, applied for durations of 7, 14, and 30 days. The selected curing temperatures (50 °C and 70 °C) represent typical Iraqi surface conditions [1], while the durations (7, 14, and 30 days) reflect short- to long-term aging periods based on prior thermal conditioning studies [17–19]. An uncured group was also included as a baseline. The specimens were conditioned in an oven at 50 °C and 70 °C for 8 h per day, which was repeated daily throughout the entire curing period (7, 14, or 30 days). Subsequently, gradual cooling to room temperature was performed by placing the specimens inside an insulated chamber, allowing them to cool slowly under ambient conditions. Each curing condition was applied to mixtures with 0%, 1%, 5%, 10%, and 20% PET content. For consistency and identification, each combination was labeled using a three-part code: T for curing temperature, C for curing duration, and P for PET content. For example, T70-C14-P5 represents a specimen cured at 70°C for 14 days with 5% PET. Three replicates were prepared for each group, resulting in a total of 195 specimens.

V. MARSHALL AND VOLUMETRIC PROPERTY TESTING

Marshall stability and flow test ASTM D6927 was used to examine the mechanical properties of asphalt mixtures [20]. Stability represented the load-carrying capacity of the samples and flow indicated the deformation of the sample while loaded. The volumetric properties were also studied to assess the mix composition and long-term performance. The bulk density was measured according to ASTM D2726, while the V_a were calculated based on ASTM 3203. Other parameters are Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt

(VFA) developed to evaluate the distribution of the binder and quality of the compaction [22].

VI. MARSHALL QUOTIENT ANALYSIS

The MQ was calculated as the ratio of Marshall stability to flow for each specimen group. MQ serves as an indicator of the mixture stiffness and resistance to permanent deformation. Higher MQ values reflect stiffer mixes with better rutting resistance, while lower values suggest increased flexibility, which may be beneficial in certain loading or environmental conditions.

VII. RESULTS AND DISCUSSION

A. Optimum Asphalt Content

The OAC decreased as the PET content increased. While the control and 1% PET mixes required 5.00% binder, the OAC dropped to 4.90%, 4.70%, and 4.55% for 5%, 10%, and 20% PET, respectively, as shown in Figure 2. This reduction is due to PET's low absorption and its tendency to coat aggregate surfaces, which lowers the binder demand. Similar observations were reported in [2, 9, 14]. However, at PET levels $\geq 10\%$, this trend may compromise the binder adhesion and compaction quality. Authors in [10] emphasized that excessive PET increases the V_a and weakens the internal cohesion, reinforcing the need to keep PET within moderate limits.

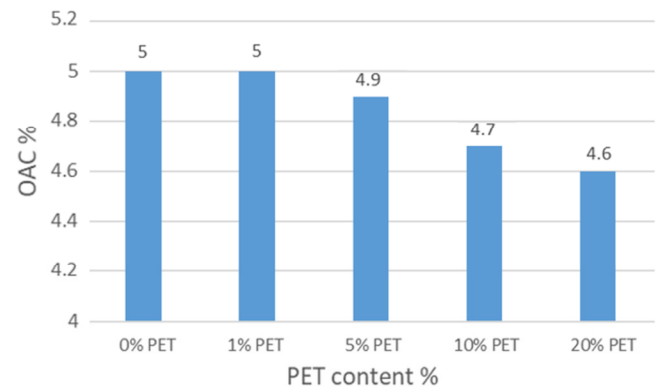


Fig. 2. Variation in OAC with PET dosage

B. Marshall Stability and Flow Analysis

Marshall stability improved notably with the PET incorporation up to 5%, followed by a consistent decline at higher dosages, as illustrated in Figures 3 and 4. At 50 °C, the mix T50-C14-P5 achieved the highest stability at 15,456 N, representing a 15.1% increase over the control mix T50-C14-P0 (13,378 N). At 70 °C, the peak value was recorded at T70-C14-P5 with 17,865 N—a 27.2% gain compared to T70-C14-P0 (14,035 N). These results affirm that 5% PET significantly enhances the load-bearing capacity, particularly under elevated temperatures and moderate curing, complying with the findings in [2, 8], where improved strength was reported at moderate PET dosages. However, stability declined beyond this dosage. For instance, T70-C30-P20 reached only 9,044 N, which is 49.4% lower than the peak T70-C14-P5. This drop reflects a

reduced cohesion and possible thermal softening at higher PET contents during prolonged curing—a trend similarly noted in [12], where decreased stiffness and cohesion were observed at PET contents above 14%. The influence of PET on the aging performance also became evident through curing duration trends. While curing up to 14 days generally improved stability for low PET mixes, extended curing to 30 days had the opposite effect, particularly at higher PET levels. For example, stability dropped by 12.7% from T50-C14-P5 (15,456 N) to T50-C30-P5 (14,698 N), supporting the observations in [3], where it was reported that aging reduces the healing and stiffness performance of the asphalt mixtures over time. This suggests that while PET may initially reinforce the mix, its long-term resistance to aging is limited beyond optimal content. PET appears to partially mitigate the short-term aging, but its effectiveness diminishes with extended thermal exposure, especially when PET content exceeds 5%.

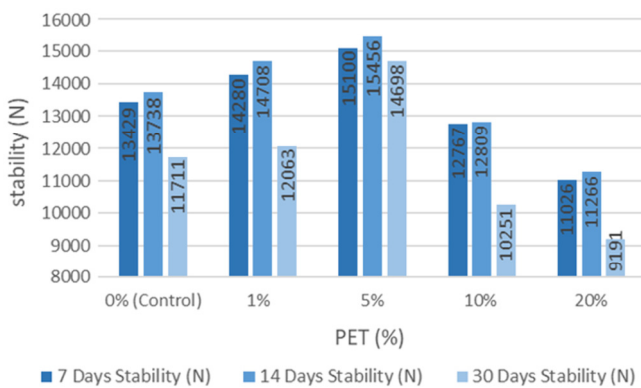


Fig. 3. Marshall stability of PET-modified asphalt mixtures cured at 50°C for 7, 14, and 30 days

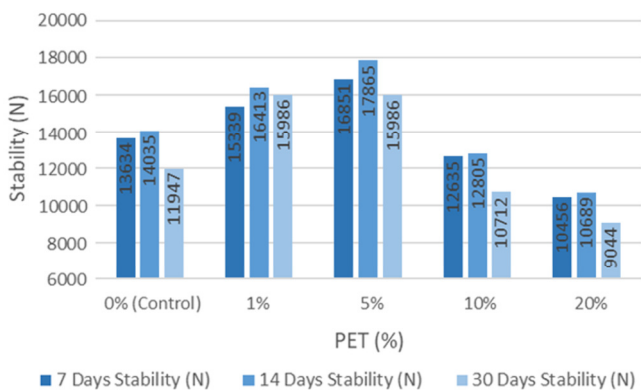


Fig. 4. Marshall stability of PET-modified asphalt mixtures cured at 70°C for 7, 14, and 30 days

Flow behavior remained stable and within the SCRB limits (≤ 4 mm) for PET levels up to 5%, across all curing conditions. The lowest flow was observed in T70-C30-P0 at 3.31 mm, while T70-C14-P5 remained close at 3.516 mm. However, at 10% and 20% PET, flow values increased sharply. The mix T70-C7-P20 reached 6.82 mm—more than 98% higher than the control, exceeding the deformation limits and indicating a

reduced stiffness and poor rutting resistance. These trends are consistent with the findings in [10, 17], where also an increased flow and deformation were reported at higher PET contents due to reduced cohesion and binder interaction. The observed flow variations are visualized in Figures 5 and 6 for 50 °C and 70 °C curing conditions, respectively.

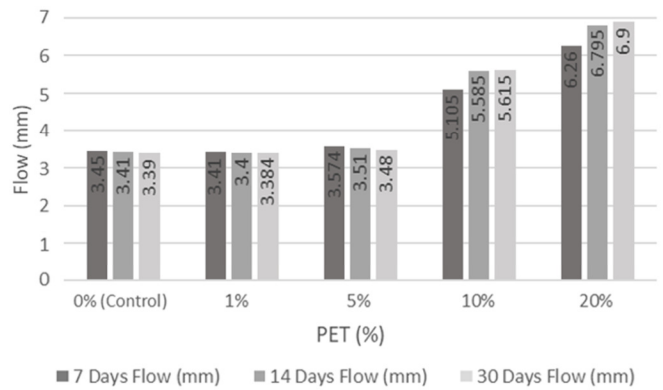


Fig. 5. Marshall flow values of PET-modified asphalt mixtures cured at 50°C for 7, 14, and 30 days

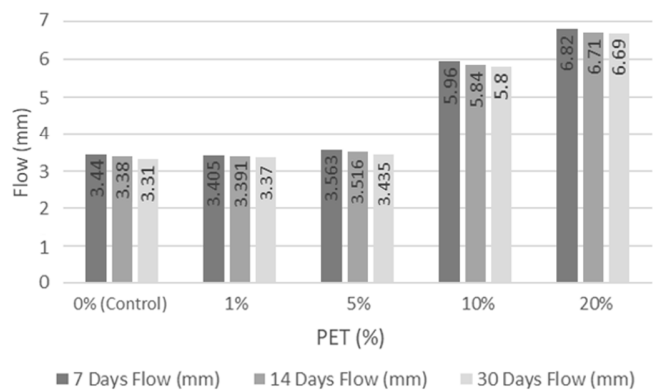


Fig. 6. Marshall flow values of PET-modified asphalt mixtures cured at 70°C for 7, 14, and 30 days

C. Marshall Quotient Analysis

The MQ values increased with a PET content up to 5%, and then declined sharply, as displayed in Figure 7. The peak MQ was observed in T70-C7-P5 and T50-C7-P5, both exceeding 5,000, marking over a 25% improvement compared to their respective control mixes. This confirms that 5% PET enhances the stiffness and rutting resistance, complying with the findings in [2, 7, 14]. At 10% and 20% PET, the MQ dropped significantly—with T70-C30-P20 falling below 1,500, more than 70% lower than the peak. This reduction reflects increased flow and reduced structural cohesion at high PET contents, especially under prolonged curing. A similar trend was observed in [3], where aging exacerbated the mix softening over time. Higher curing temperatures intensified this effect, as seen in the steeper MQ drop at 70 °C compared to 50 °C. These results indicate that PET improves the early stiffness but does not consistently mitigate the long-term aging effects when used beyond optimal levels.

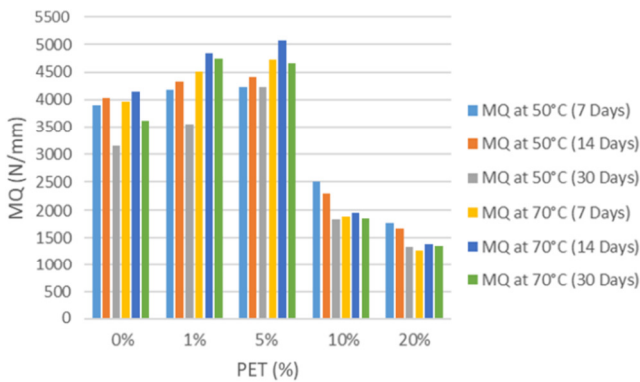


Fig. 7. MQ of PET-modified asphalt mixtures at 50°C and 70°C for 7, 14, and 30 days of curing

D. Volumetric Property Analysis

The unit weight decreased consistently with an increasing PET content, dropping from 2257.7 kg/m³ at 0% PET to 2047.8 kg/m³ at 20%, as presented in Figure 8. This trend reflects PET’s lower specific gravity and its interference with aggregate interlocking, which reduces the mix density—a finding supported in [2, 8, 14, 23]. Va remained within the SCRB limits (3–5%) for PET percentage up to 5% but increased sharply at 10% and 20%, reaching 12.93% at the highest dosage. The reduced compaction efficiency at higher PET levels aligns with the findings in [7], which also reported increased Va and VMA due to poor particle compatibility. VMA increased from 13.25% to 20.29%, indicating a looser internal structure, while VFA fell from ~70% at 5% PET to just 36.26% at 20%. This suggests a critical loss of binder saturation at high PET contents. Similar reductions in binder effectiveness and cohesion were also reported in [10, 12], raising concerns about long-term durability at higher PET dosages. Together, these findings show that PET improves the volumetric balance and binder efficiency up to 5%, but disrupts the structural integrity and compaction at higher contents. Figure 9 illustrates the trends in volumetric properties across different PET levels.

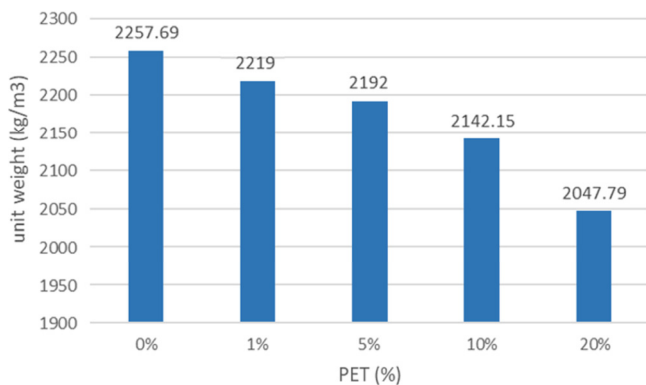


Fig. 8. Unit weight of PET-modified asphalt mixtures at varying PET contents.

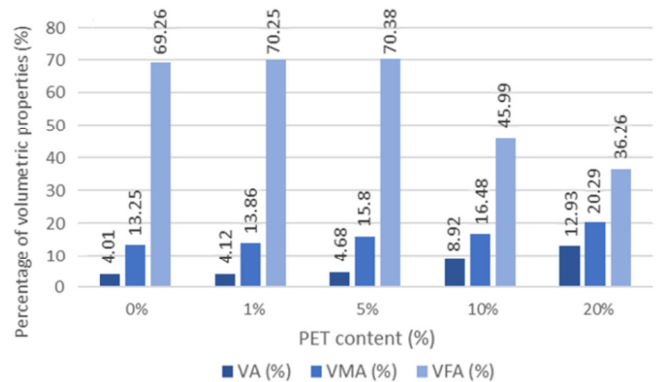


Fig. 9. Volumetric properties (Va, VMA, VFA) of PET-modified asphalt mixtures across PET content levels.

E. Statistical Analysis

Statistical analysis was conducted using two-way ANOVA, regression, and effect size (η^2) to evaluate the influence of the PET content, curing time, and temperature on the asphalt mixture performance. Variations in flow and MQ were observed to remain within a consistent range across repetitions, confirming the reliability of the results. The results confirm that the PET content was the dominant factor, significantly affecting both the mechanical and volumetric properties. For the mechanical properties, the PET content had a statistically significant effect ($p < 0.0001$) on stability, flow, and MQ. Flow was also significantly influenced by the curing temperature ($p < 0.0001$), while the curing time had no meaningful impact ($p > 0.05$). The regression analysis revealed that the PET content explained 91% of the variation in flow ($R^2 = 0.91$), 76% in MQ, and 54% in stability. The effect sizes were all large ($\eta^2 > 0.89$), confirming PET’s strong influence on the mechanical behavior. For the volumetric properties, the PET content also produced important effects ($p < 0.00001$) across Va, VMA, and VFA. Although regression models were not applied to these parameters, ANOVA and η^2 values indicated extremely large effects, particularly on Va ($\eta^2 = 0.97$). This supports earlier findings, according to which higher PET levels reduce the compaction efficiency and binder saturation. A summary of all statistical results is presented in Table III.

VIII. CONCLUSION AND RECOMMENDATIONS

This study explored the mechanical and volumetric performance of Polyethylene Terephthalate (PET)-modified Hot Mix Asphalt (HMA) under varying curing temperatures (50°C, 70°C), durations (7, 14, 30 days), and PET contents (0% to 20%). A total of 195 specimens were produced using the Marshall mix design and tested across key parameters, such as stability, flow, Marshall Quotient (MQ), unit weight, Air Voids (Va), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA).

TABLE III. STATISTICAL SUMMARY OF PET CONTENT, CURING TIME, AND TEMPERATURE EFFECTS ON ASPHALT PROPERTIES

Property	p-value (PET)	p-value (Curing Time)	p-value (Temp)	F-value (PET)	η^2 (PET)	R ² (PET)
Stability	< 0.0001	0.82	0.22	34.03	0.89	0.54
Flow	< 0.0001	0.33	< 0.0001	328.17	0.99	0.91
MQ	< 0.0001	0.07	0.19	92.87	0.97	0.76
Va	< 0.00001	—	—	335.97	0.97	—
VMA	< 0.00001	—	—	118.99	0.94	—
VFA	< 0.00001	—	—	164.57	0.95	—

* η^2 (Eta squared): Proportion of variance explained by the factor (effect size).*R² (Coefficient of determination): Indicates how well the model fits the data.

The findings demonstrate that recycled PET, when used at 5% by weight of bitumen, significantly enhances the performance of the asphalt mixtures. Improvements in stability, reduced flow values, and elevated MQ scores were consistent across both curing temperatures, particularly at early and mid-term durations. The volumetric analysis further confirmed that PET improves the binder distribution and compaction quality at moderate dosages, while higher contents led to structural inefficiencies, such as excessive voids and reduced density. Although the statistical analysis indicated that the PET content was the most dominant factor, and that curing time and temperature did not significantly affect most parameters, the engineering interpretation provides a wider perspective. The enhancement provided by PET—even without statistical interaction with curing time—means that the PET-modified mixtures start with stronger structural properties. As a result, their resistance to aging, deformation, and fatigue over time is inherently improved compared to the unmodified mixes. That is, a stronger, stiffer, and better-compacted mix is naturally more durable, even if the deterioration curve flattens over a longer curing window. This outcome is particularly relevant for regions like Iraq, where extreme surface temperatures accelerate the binder aging. The data suggest that 5% PET can offer not just performance gains, but lifecycle benefits in terms of reduced maintenance needs and better long-term serviceability. It is proposed to incorporate PET at 5% by weight of bitumen using the dry mixing method, as this dosage achieved the best mechanical and volumetric performance under the conditions tested. Although PET particles passing the No.4 sieve were used in this study, finer particle sizes should be explored, as they may enhance the dispersion, binder compatibility, and long-term durability. While the curing time and temperature showed limited statistical influence, moderate thermal conditioning remains advisable to simulate the field aging. The mechanical improvements achieved through the PET modification suggest a possible extension of the pavement service life, highlighting the need for further research on optimizing PET particle size and surface treatment for enhanced aging resistance in hot climates.

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