EVALUATION OF PET WASTE-MODIFIED ASPHALT PERFORMANCE UNDER ENVIRONMENTAL STRESS: A MULTI-SCALE ANALYSIS OF RHEOLOGICAL AND DURABILITY PROPERTIES

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Abstract: Diesel fuel spills can significantly accelerate asphalt binder softening and mixture deterioration, leading to reduced pavement durability. This study applies a multi-scale evaluation framework to quantify the effectiveness of polyethylene terephthalate (PET) waste in mitigating diesel-induced degradation of asphalt by comparing conventional asphalt (0% PET, control) with PET-modified binders and mixtures containing 6% and 8% PET. The primary objective is to determine whether PET modification can enhance asphalt resistance to diesel contamination by examining the relationship between molecular-level stability, rheological response, and mixture-level performance, using standardized procedures in accordance with the Indonesian Bina Marga 2018 specification and relevant SNI and ASTM standards. The results indicate that diesel exposure causes severe degradation in the control binder, with non-recoverable creep compliance (J_{nr}) increasing by up to 62% after six hours, reflecting a substantial loss of resistance to permanent deformation. In contrast, PET-modified binders show markedly improved stability, with the 8% PET binder limiting the Jnr increase to approximately 51% under the same exposure, indicating the highest resistance to diesel-induced rheological deterioration. This improvement is consistently reflected at the mixture scale, where the control asphalt mixture experiences a 47% reduction in Marshall stability, while the mixture containing 8% PET shows only an 11% reduction after diesel conditioning. Overall, the findings demonstrate that PET waste—particularly at an 8% dosage—significantly enhances asphalt resistance to diesel-related chemical and mechanical damage. This study provides clear mechanistic and performance-based evidence that PET upcycling is an effective and sustainable strategy for producing more fuel-resistant asphalt pavements.

Keywords: asphalt; diesel spill; molecular size distribution; pet-modified asphalt; rheological properties

Abstrak: Tumpahan bahan bakar diesel dapat secara signifikan mempercepat pelunakan aspal dan degradasi campuran aspal, sehingga menurunkan daya tahan perkerasan jalan. Penelitian ini menerapkan kerangka evaluasi multi-skala untuk mengkuantifikasi efektivitas limbah polyethylene terephthalate (PET) dalam mengurangi degradasi aspal akibat paparan diesel dengan membandingkan aspal konvensional tanpa PET (0% sebagai kontrol) dan aspal termodifikasi PET dengan kadar 6% dan 8%. Tujuan utama

penelitian ini adalah untuk menilai kemampuan modifikasi PET dalam meningkatkan ketahanan aspal terhadap kontaminasi diesel melalui keterkaitan antara stabilitas molekuler, respons reologi, dan kinerja mekanis campuran, dengan menggunakan prosedur pengujian yang mengacu pada spesifikasi Bina Marga 2018 serta standar SNI dan ASTM yang relevan. Hasil penelitian menunjukkan bahwa paparan diesel menyebabkan degradasi yang signifikan pada pengikat kontrol, yang ditunjukkan oleh peningkatan nilai kepatuhan rangkak tidak pulih (J_{nr}) hingga 62% setelah 6 jam, menandakan penurunan ketahanan terhadap deformasi permanen. Sebaliknya, pengikat aspal termodifikasi PET menunjukkan stabilitas yang jauh lebih baik, di mana pengikat dengan 8% PET membatasi peningkatan Jnr hingga sekitar 51% pada kondisi paparan yang sama, sehingga memberikan ketahanan reologi tertinggi terhadap diesel. Peningkatan kinerja ini tercermin secara konsisten pada skala campuran, di mana campuran aspal konvensional mengalami penurunan stabilitas Marshall sebesar 47%, sementara campuran dengan 8% PET hanya mengalami penurunan sebesar 11% setelah pengkondisian diesel. Secara keseluruhan, hasil penelitian ini membuktikan bahwa pemanfaatan limbah PET—terutama pada kadar 8%—secara signifikan meningkatkan ketahanan aspal terhadap kerusakan kimia dan mekanis akibat paparan diesel. Temuan ini memberikan bukti mekanistik dan berbasis kinerja bahwa daur ulang PET merupakan strategi berkelanjutan yang efektif untuk menghasilkan perkerasan jalan yang lebih tahan terhadap kontaminasi bahan bakar.

Kata kunci: aspal; paparan diesel; distribusi ukuran molekul; aspal modifikasi PET; sifat reologi

Introduction

Road pavements' durability is critical in maintaining efficient transportation systems and ensuring seamless community connectivity. Many regions, including Indonesia, face challenges from traffic loads, climate change, and environmental stressors such as oil spills. These issues contribute to significant surface damage and ecological consequences, necessitating the development of more resilient road materials. Sustainable solutions that can enhance the resilience of asphalt road pavements are urgently needed (Rachman, Syammaun, et al., 2024; Syahbana et al., 2024; Syammaun et al., 2025).

One such solution is the incorporation of polyethylene terephthalate (PET) waste into asphalt mixtures. PET, a standard plastic material, presents a growing environmental challenge due to its widespread use and slow decomposition. As countries like Indonesia face an escalating volume of plastic waste, recycling and repurposing PET in construction materials, such as asphalt, cement, and concrete, has gained increasing attention. Recent studies indicate that Indonesia faces a significant and growing challenge related to plastic waste, of which polyethylene terephthalate (PET) constitutes a substantial fraction. Indonesia generates tens of

millions of tonnes of municipal solid waste annually, with plastics accounting for a large share. Recent assessments estimate that the country produces more than 7.8 million tonnes of waste per year, of which approximately 7.8 million tonnes is plastic, and this volume continues to increase with population growth and rising consumption patterns. Plastics, including PET packaging, remain challenging to manage due to limited recycling capacity and low formal waste collection rates. PET consumption in Indonesia has been increasing in recent years, with industry reports estimating annual PET use at around 1 million tonnes, driven primarily by the beverage and packaged goods sectors. Although initiatives to improve recycling exist, only a fraction of PET waste is currently recycled, resulting in an increasing accumulation of PET in the waste stream and environmental leakage. This upward trend in PET waste generation highlights the need for developing sustainable management solutions for PET waste, including reuse in infrastructure applications such as asphalt modification (Kelly et al., 2025). Prior research has demonstrated that the integration of PET into asphalt can improve various properties, including resistance to fatigue cracking, stability, and flow, particularly when using the dry mixing technique. However, the wet mixing technique has offered better moisture resistance in some instances (Agha et al., 2023).

PET-modified bitumen paving blocks exhibit enhanced compressive strength, skid resistance, and reduced water absorption, with optimal performance at a 10% PET replacement level (Awolusi et al., 2023; Nouali et al., 2020). The use of polymer waste, including PET, in road construction has been optimized using response surface methodology, which demonstrates improved Marshall characteristics and supports sustainable infrastructure development (Mushtaq et al., 2022). Recycled PET as synthetic aggregates in asphalt mixes has demonstrated benefits in terms of cracking and rutting resistance, depending on the plastic content and size (Xuan Lu & Giustozzi, 2023). A life-cycle analysis of concrete with recycled plastic aggregates reveals a reduction in global warming potential while maintaining mechanical properties suitable for municipal infrastructure (Gravina et al., 2021). Additionally, PET resin modified with methyl methacrylate (MMA) and used in polymer mortar has improved mechanical properties and reduced porosity (Sarde et al., 2021). Finally, functionalizing PET with waste cooking oil enhances its compatibility with bitumen, significantly improving resistance to aging and extending the service life of roadways (Aldagari et al., 2021). These findings underscore the efficacy and sustainability of PET waste in construction materials.

While previous studies have demonstrated that PET waste can enhance conventional asphalt performance indicators and improve mechanical properties in related construction materials, the research gap remains insufficiently defined with respect to petroleum-contamination exposure, which is a highly relevant field stressor in Indonesia. In practice, the probability of road surface contamination by diesel and lubricating oils is amplified by two contextual factors. First, the effectiveness of vehicle inspection and compliance mechanisms remains uneven;

for example, evaluations of inspection programs have reported implementation obstacles, and independent assessments of vehicle testing enforcement have noted delayed or incomplete implementation and participation challenges (Kania, 2021) These conditions increase the likelihood that vehicles with inadequate maintenance remain in operation, thereby increasing the potential for fuel and oil leakage onto pavements.

Second, heavy-duty transport intensity is particularly pronounced along commodity logistics corridors, including regions associated with the oil-palm supply chain, where freight movement and industrial activity are substantial. Infrastructure studies in palm-industry contexts report negative impacts on road conditions and drainage, indicating elevated stress and vulnerability of road assets in such areas. Importantly, diesel contamination is not a minor surface nuisance: prior experimental evidence shows that hydrocarbon spills can rapidly reduce asphalt mechanical integrity because diesel can dissolve and mobilize binder fractions, leading to accelerated deterioration (Sindua & Kaihatu, 2023). Despite this practical relevance, most PET-modified asphalt studies do not explicitly evaluate diesel conditioning as the primary degradation mechanism, nor do they connect molecular-level changes to rheological responses and mixture-level durability under fuel contamination. Consequently, it remains unclear whether PET modification improves asphalt performance specifically against diesel-induced damage pathways.

This study addresses that gap by evaluating how PET waste affects the performance characteristics of asphalt mixtures when exposed to environmental stressors, specifically oil spills. The primary objectives are: (i) to examine the impact of PET waste on the molecular interactions within modified bitumen at the nanoscale using Gel Permeation Chromatography (GPC); (ii) to evaluate the rheological properties of PET-modified bitumen at the microscale using a Dynamic Shear Rheometer (DSR) and assess performance under various traffic conditions; and (iii) to assess the durability and deformation resistance of PET-modified asphalt mixtures at the mesoscale using Marshall mixture designs, particularly in the presence of petroleum-based contaminants.

Methodology

Materials

The criteria applied in this examination adhere to the standards of the Indonesian National Standard (SNI) and the American Society for Testing and Materials (ASTM), as specified in Bina Marga 2018. Specific details of the inspection findings for each parameter are available in Table 1.

Table 1. Coarse aggregate properties

Properties	Units	Standard	Results	Limit
Specific gravity	gr/cm^3	SNI 03-1969-1990	2,800	Min. 2,5

Properties	Units	Standard	Results	Limit
Absorption	%	SNI 03-1969-1990	1,739	Max. 3
Weight volume	Kg/cm^3	SNI 03-1969-1990	1,610	Min. 1
Impact	%	SNI 4426-1997	6,49	Max. 30
Wear	%	SNI 2417-2008	16,44	Max. 40
Flakiness index	%	ASTM D-4791	9,83	Max. 10
Elongation index	%	ASTM D-4791	9,63	Max. 10

The aggregate gradation test results (Figure 1) revealed that adjustments are needed in the gradation of aggregates found in the field to meet the requirements specified in the General Specification Bina Marga 2018 Revision 1 of 2019 (Division 6), especially for AC-WC (asphalt concrete wearing course) mixtures. The gradation considered in this research follows a continuous approach, aiming to achieve an optimal gradation based on the midpoint between the upper and lower limits of the specified criteria.
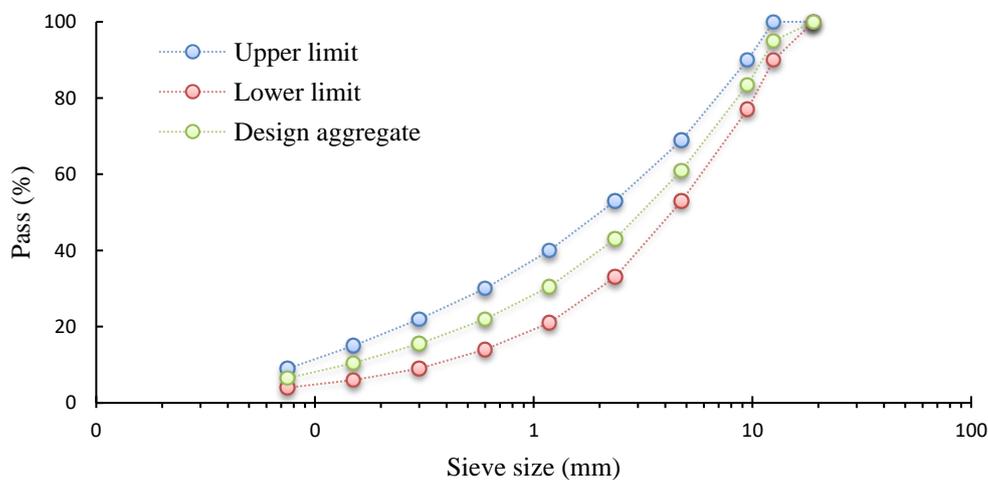

Figure 1. Aggregate gradation

Table 2 presents the physical properties of the asphalt binder without PET (0% PET) and the PET-modified binders containing 6% and 8% PET, together with the corresponding requirements specified by the Standar Nasional Indonesia (SNI). In this study, the 0% PET binder is explicitly designated as the control (baseline) sample, representing conventional 60/70 penetration grade asphalt. The effectiveness of PET modification is therefore evaluated by comparing the 6% and 8% PET binders directly against this control binder.

As shown in Table 2, the specific gravity of the binder increases from 1.031 for the control binder to 1.046 and 1.053 for the 6% and 8% PET binders, respectively, indicating that the incorporation of PET results in a denser binder structure relative to the baseline condition. The penetration value decreases from 64 (0% PET) to 56 (6% PET) and 52 (8% PET), demonstrating an increase in binder

stiffness compared with the control sample, which is consistent with the reinforcing effect of polymer addition.

The ductility of the binder decreases with increasing PET content, from 140 cm in the control binder to 83 cm and 62 cm for the 6% and 8% PET binders, respectively. Although reduced relative to the control, all PET-modified binders remain above the minimum ductility requirement of SNI 2432-2011, indicating that sufficient flexibility is maintained. Conversely, the softening point increases from 51 °C for the control binder to 54 °C and 55 °C for the PET-modified binders, reflecting enhanced resistance to high-temperature deformation. Notably, while the control binder is slightly below the specified minimum softening point, both PET-modified binders satisfy the requirement of SNI 2434-2011.

Table 2. Neat and modified asphalt binder properties

Properties	Units	Standards	PET			Limit
			0%	6%	8%	
Specific gravity	gr/cm^3	SNI 2441-2011	1,031	1,046	1,053	Min. 1
Penetration	(0,1 mm)	SNI 2456-2011	64	56	52	Min. 40
Ductility	Cm	SNI 2432-2011	140	83	62	Min. 50
Softening point	°C	SNI 2434-2011	51	54	55	Min. 54

Overall, the results in Table 2 demonstrate that, when evaluated relative to the 0% PET control binder, the addition of 6% and 8% PET systematically increases stiffness and high-temperature resistance while maintaining acceptable ductility. This confirms that the observed changes in binder properties are attributable to the modification of PET rather than the inherent variability of the base asphalt.

Methods

Materials Preparation and PET Incorporation

The asphalt binder used in this study was a 60/70 penetration grade bitumen, with PET contents of 0%, 6%, and 8% by weight of binder. The binder without PET (0% PET) was designated as the control sample. As depicted in Figure 2, post-consumer polyethylene terephthalate (PET) waste in the form of beverage bottles was collected from local recycling facilities, cleaned to remove impurities, and mechanically shredded into sizes ranging from approximately 3 to 5 mm.

PET incorporation into the asphalt mixtures was carried out using the wet mixing process. Aggregates were heated to the mixing temperature prior to the addition of PET to promote adequate softening and distribution of the plastic particles. The shredded PET was introduced either by pre-mixing with the heated aggregates or by blending with the hot binder before aggregate addition, depending on the wet-mixing procedure employed. All mixtures were prepared in accordance with the gradation and volumetric requirements specified in Bina Marga 2018, using aggregates with sizes ranging from 0.075 mm to 19 mm.

Diesel Exposure Procedure

To evaluate resistance to petroleum contamination, both binder and mixture specimens were subjected to controlled exposure to diesel fuel. Commercial diesel fuel was used as the contaminant. Specimens were fully submerged in diesel at ambient laboratory temperature (25 ± 2 °C) for predetermined durations of 1 h, 3 h, and 6 h, simulating short-term accidental spill conditions commonly encountered in service environments.

After the designated exposure period, the specimens were removed from the diesel bath and allowed to drain naturally for a fixed period to remove excess surface fuel. No additional washing or solvent treatment was applied prior to testing to preserve the effect of diesel absorption on the material properties.
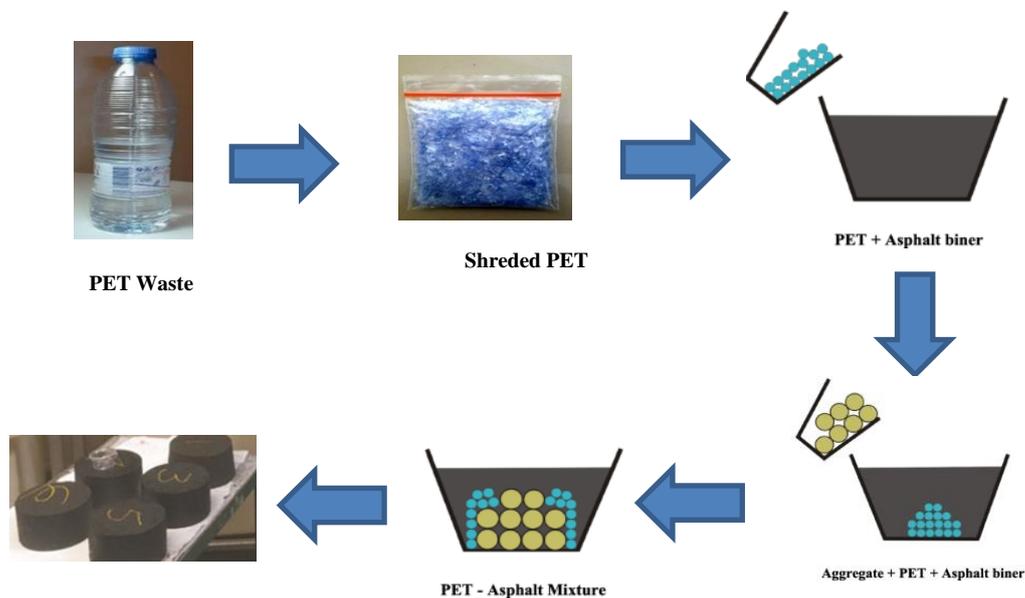

Figure 2. Preparation of PET-modified asphalt mixtures using the wet mixing process.
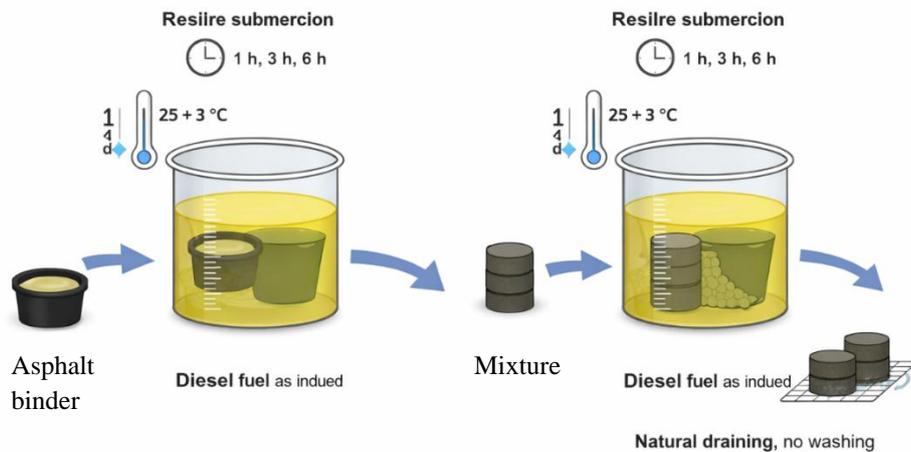

Figure 3. Preparation Schematic of diesel exposure procedure for asphalt binder and mixture specimens.

Nanoscale characterization using GPC.

The nanoscale characterization of PET-modified bitumen was conducted using Gel Permeation Chromatography (GPC) to investigate the molecular interactions within the modified binder. Both neat bitumen and bitumen modified with 6% and 8% PET by weight were prepared by dissolving approximately 0.5 grams of each binder sample in 10 mL of tetrahydrofuran (THF), ensuring complete dissolution, as recommended in previous studies (Ma et al., 2021). The solutions were filtered through a 0.45 μm PTFE filter to remove particulate matter, following standard preparation protocols for bitumen samples used in GPC analysis (Dally et al., 2023). The chromatograms obtained were baseline-corrected to eliminate noise and drift. The refractive index curves were deconvoluted using a Gaussian fitting algorithm to separate the contributions of small molecular size (SMS), medium molecular size (MMS), and large molecular size (LMS) fractions, a method widely employed for analyzing polymer-modified bitumen (Polacco et al., 2022).

Micro-scale characterization using MSCR.

The rheological properties of the PET-modified bitumen were analyzed at the microscale using the Multiple Stress Creep Recovery (MSCR) test, a method widely employed to assess the rutting resistance of asphalt binders under stress conditions relevant to traffic loads (Rachman, Yang, et al., 2023, 2024). This test was conducted using a Dynamic Shear Rheometer (DSR) to evaluate the performance of the modified bitumen under varying traffic conditions. The bitumen samples were subjected to stress levels of 3.2 kPa at a testing temperature of 64°C, which aligns with standard procedures for evaluating the high-temperature performance of binders (H. Liu et al., 2021). The MSCR test involved applying repeated cycles of stress and recovery to the samples and measuring the non-recoverable creep compliance (J_{nr}), a critical parameter indicating the binder's susceptibility to permanent deformation under high traffic stress. The changes in J_{nr} values were analyzed for samples exposed to diesel fuel for 0 hours, 1 hour, 3 hours, and 6 hours, allowing for the assessment of the binder's performance under environmental stressors such as petroleum contamination.

Meso-scale characterization using Marshall stability and flow.

At the mesoscale, the performance of the PET-modified asphalt mixtures was evaluated using Marshall Stability and Marshall Flow tests. These tests were conducted to assess the durability and deformation resistance of the mixtures, particularly when exposed to diesel spills. The Marshall Stability test measured the maximum load-bearing capacity of the asphalt samples, while the Marshall Flow test assessed the deformation of the asphalt mixture under load (Rachman, Syammaun, et al., 2023). The tests were performed on hot mix asphalt (HMA) without PET modification and on mixtures containing 6% and 8% PET. The samples were conditioned by submersion in diesel fuel for 0 hours, 1 hour, 3 hours, and 6 hours to simulate the impact of diesel spills.

Results and Discussion

Effect of petroleum spills on PET-modified bitumen

As depicted in Figure 4, the Gel Permeation Chromatography (GPC) results quantitatively confirm that PET modification improves the molecular stability of asphalt binder under diesel exposure, with the most pronounced effect observed at a PET content of 8%. To establish an explicit reference, the asphalt binder without PET (0% PET) is defined as the baseline condition, representing the molecular structure of conventional 60/70 penetration grade bitumen prior to contamination. Before diesel exposure, the control binder exhibits a typical molecular size distribution characterized by a dominant large molecular size (LMS) fraction, accompanied by medium (MMS) and small molecular size (SMS) fractions, reflecting a stable binder network.

After diesel submersion, the control binder undergoes substantial molecular degradation. Specifically, the SMS fraction increases by approximately 4.5%, 14%, and 29% after 1 hour, 3 hours, and 6 hours of diesel exposure, respectively, while the LMS fraction decreases by approximately 4%, 7%, and 29% over the exact exposure durations. These pronounced shifts indicate a progressive breakdown of larger molecular structures into smaller, more fundamental components. This behavior is attributed to the solvent action of diesel fuel, which preferentially dissolves lighter maltene fractions and disrupts the association of asphaltene-rich structures, thereby accelerating molecular disaggregation and binder softening.

In comparison, PET-modified binders exhibit significantly reduced molecular degradation under identical exposure conditions. For the binder containing 6% PET, the SMS fraction increases by approximately 7%, 18%, and 22%, while the LMS fraction decreases by 4%, 20%, and 20% after 1 hour, 3 hours, and 6 hours of diesel exposure, respectively. Although molecular degradation is still evident, the magnitude of change is consistently lower than that observed in the control binder at prolonged exposure durations. The binder containing 8% PET demonstrates the highest molecular stability, with SMS increases limited to approximately 6%, 16%, and 18%, and LMS reductions constrained to 3%, 11%, and 20% after 1 hour, 3 hours, and 6 hours of exposure, respectively.

The consistency of these trends across all exposure durations reinforces the robustness of the GPC results. In all cases, longer diesel immersion times lead to greater molecular degradation; however, the relative performance ranking remains unchanged (0% PET > 6% PET > 8% PET in terms of degradation severity). This consistent hierarchy confirms that the observed improvements are attributable to PET modification rather than experimental variability.

From a mechanistic perspective, the reduced SMS increase and LMS loss in PET-modified binders suggest that PET particles restrict diesel penetration and reduce the mobility of maltene fractions, thereby preserving the integrity of larger molecular structures. This enhanced molecular stability has direct practical implications, as it underpins the improved rheological resistance to permanent

deformation and the enhanced mixture durability observed in subsequent MSCR and Marshall tests. The reduced percentage decreases in LMS for PET-modified binders indicate better structural integrity and enhanced resistance to diesel-induced degradation (Ben Zair et al., 2021). This enhanced performance is attributed to PET's ability to increase the binder's stiffness, elasticity, and tensile strength, while also improving the mixture's resistance to moisture susceptibility, rutting deformation, and fracture resistance (Mulpuru Madhuri et al., 2024).
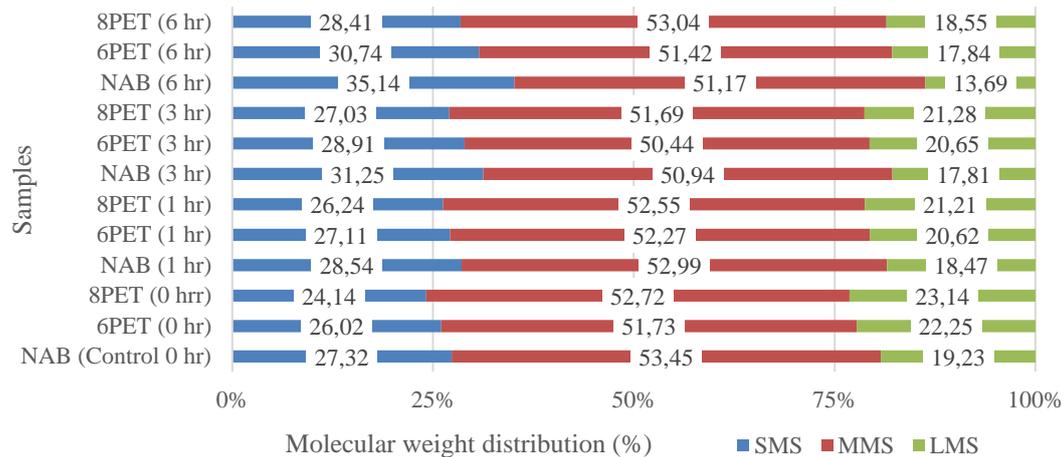

Figure 4. GPC results analysis based on the deconvolution method

Effect of petroleum spills on PET-modified bitumen

The MSCR test results for the neat asphalt binder (NAB) and PET-modified binders (6% PET and 8% PET), conducted at a stress level of 3.2 kPa and a temperature of 64 °C, are presented in Figure 5. The non-recoverable creep compliance (J_{nr}), which reflects the binder's susceptibility to permanent deformation, was evaluated as a function of diesel exposure duration. For the NAB, Jnr increased by approximately 12% after 1 hour, 36% after 3 hours, and 62% after 6 hours of diesel immersion, indicating a progressive and substantial loss of resistance to permanent deformation. This behavior confirms that diesel exposure severely degrades the rheological integrity of unmodified asphalt binders.

In contrast, PET-modified binders exhibited significantly smaller increases in Jnr over the same exposure periods. The binder containing 6% PET showed Jnr increases of approximately 18%, 27%, and 54% after 1, 3, and 6 h, respectively, while the 8% PET binder exhibited the lowest increases, limited to approximately 22%, 30%, and 51%. These results demonstrate that PET modification effectively mitigates diesel-induced rheological degradation, with the 8% PET binder providing the highest resistance to permanent deformation.

Importantly, these rheological trends are entirely consistent with the GPC results, thereby reinforcing the proposed multi-scale degradation mechanism. As previously discussed, GPC analysis revealed that diesel exposure resulted in a

pronounced reduction of the large molecular size (LMS) fraction and a corresponding increase in the small molecular size (SMS) fraction in the NAB, indicating severe molecular disaggregation. This molecular breakdown directly explains the sharp increase in Jnr observed for the NAB, as the loss of LMS structures reduces elastic recovery and load-bearing capacity. Conversely, PET-modified binders—particularly at an 8% PET content—exhibited more minor LMS losses and more stable MMS fractions, indicating preservation of the binder's molecular network. The improved LMS/MMS stability observed in GPC translates directly into enhanced elastic response and lower non-recoverable strain under MSCR loading.

From a mechanistic standpoint, the reduced J_{nr} increase in PET-modified binders arises from polymer–asphalt synergy at the molecular and microstructural levels. The lower J_{nr} increase in PET-modified asphalt under diesel is due to polymer–asphalt synergy: (1) PET increases the binder's base stiffness and elastic recovery(W. Liu et al., 2021; Mahdi et al., 2022). (2) PET forms a dispersed network restricting bitumen flow (Abdulhasan et al., 2024; W. Liu et al., 2021). (3) The polar, aromatic PET interacts with resin/asphaltene molecules, improving compatibility and preventing phase separation (Chen et al., 2024). (4) Diesel fuel, while dissolving some oils, can less disrupt this polymer-reinforced matrix. The PET particles do not dissolve and may even absorb light oils, reducing their impact on the binder. Thus, the PET-modified binder retains more of its mass and elasticity after fuel exposure (consistent with reports that polymer-modified binders lose much less mass in diesel than the neat binder (Lv et al., 2024)). (5) The net result is improved high-temperature rheology: lower non-recoverable strain, higher rutting resistance, and smaller J_{nr} compared to unmodified asphalt under the same exposure (W. Liu et al., 2021; Lv et al., 2024). Together, these effects explain why PET-modified binders (6% and 8% PET) exhibit smaller increases in J_{nr} and better permanent deformation resistance than neat asphalt when soaked in diesel. The PET's structural reinforcement and molecular interactions counteract the softening and component loss caused by the fuel, stabilizing the rheological behavior under aggressive conditions (Chen et al., 2024; Lv et al., 2024). These mechanisms are consistent with the GPC-observed preservation of LMS/MMS fractions and with literature reporting reduced mass loss and improved rheological stability in polymer-modified binders exposed to fuel contamination.

The implications of these binder-level improvements are directly reflected in the performance of asphalt mixtures. Lower J_{nr} values under diesel exposure indicate reduced accumulation of permanent strain, which corresponds to improved rutting resistance at the mixture scale. This relationship is confirmed by the Marshall test results, which show that PET-modified mixtures exhibit substantially smaller reductions in stability and lower increases in flow after diesel conditioning. Therefore, the combined GPC and MSCR results provide a clear mechanistic

explanation for the enhanced mixture durability observed in PET-modified asphalt under petroleum contamination.

From a field perspective, these findings are particularly relevant for pavements located near fuel stations, freight corridors, industrial zones, and logistics routes, where accidental diesel spills and chronic fuel leakage are more likely to occur (Sindua & Kaihatu, 2023).
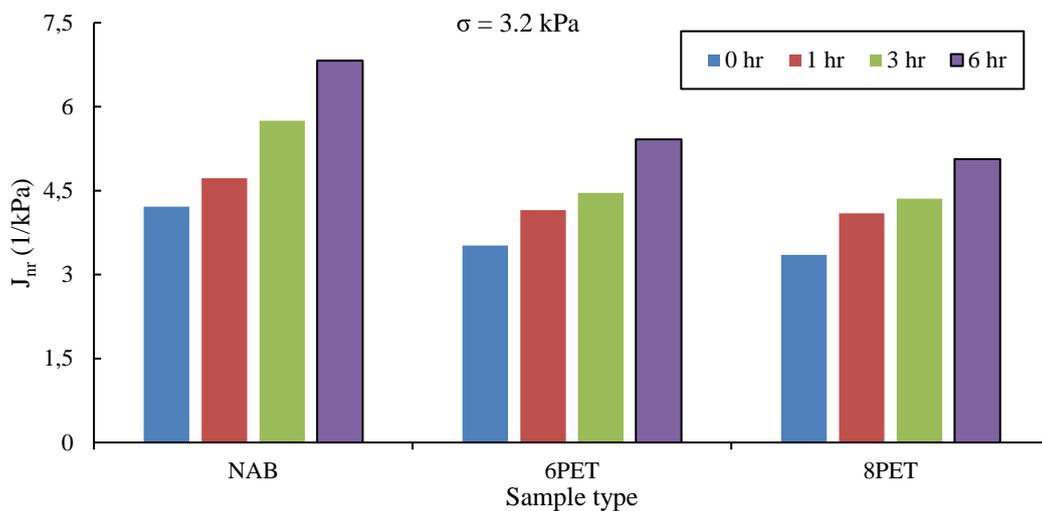

Figure 5. Non-recoverable creep compliance (J_{nr}) tested at high-stress level (3.2 kPa)

Effect of petroleum spills on PET-modified asphalt mixture

The Marshall Stability test results for the hot mix asphalt (HMA) and PET-modified asphalt mixtures (6% PET and 8% PET) under various diesel fuel conditioning durations are summarized in Figure 6. The stability values, which indicate the mixture's ability to resist deformation, were analyzed for changes resulting from diesel fuel exposure. The Marshall Stability of HMA decreased by approximately 10% after 1 hour, 28% after 3 hours, and 47% after 6 hours of exposure to diesel fuel. This significant decrease highlights the adverse effect of diesel fuel on the structural integrity of the asphalt mix. In contrast, the stability of the 6% PET binder decreased by approximately 6% after 1 hour, 16% after 3 hours, and 30% after 6 hours of diesel exposure. Although less severe than HMA, these reductions indicate an enhanced ability to withstand the effects of diesel-induced degradation.

The 8% PET binder experienced the smallest decrease in stability, with reductions of about 3% after 1 hour, 7% after 3 hours, and 11% after 6 hours of diesel exposure. The slight decline in stability values suggests that the 8% PET binder demonstrates the highest resilience to diesel fuel among all samples tested. The HMA without PET modification substantially decreased in Marshall Stability with prolonged diesel exposure. The 47% reduction in stability after 6 hours indicates a significant deterioration in the asphalt mixture's ability to withstand

deformation, suggesting a high susceptibility to rutting and structural failure in the presence of diesel spills.
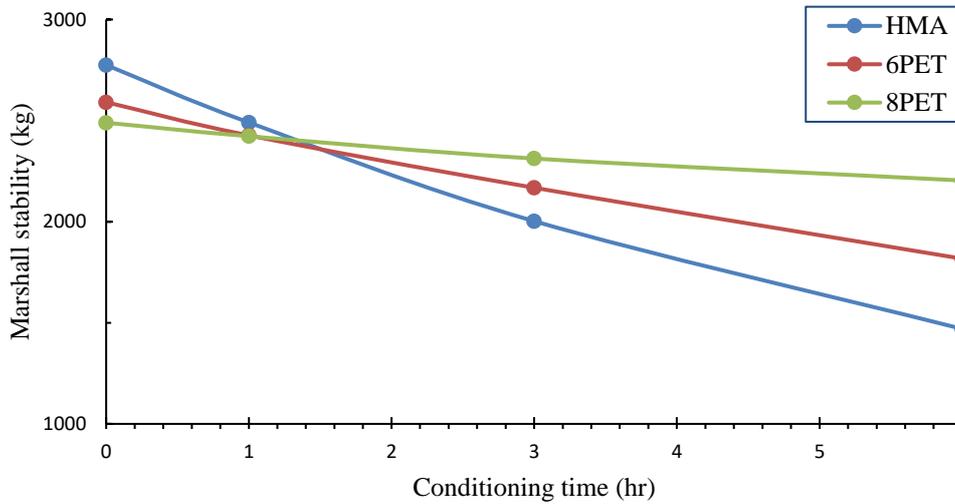

Figure 6. Results of the Marshall Stability Test

The comparison between the 6% PET and 8% PET binders reveals that increasing the PET content from 6% to 8% further enhances the binder's resistance to diesel-induced degradation. The consistently lower percentage decreases in stability for the 8% PET binder highlight the effectiveness of higher PET content in improving the structural integrity and durability of asphalt mixtures. This finding supports the use of higher PET incorporation to achieve superior pavement performance in environments susceptible to petroleum spills.

The Marshall Flow test results for the hot mix asphalt (HMA) and PET-modified asphalt mixtures (6% PET and 8% PET) under various diesel fuel conditioning durations are summarized in Figure 7. The flow values, which indicate the deformation of the asphalt mixture under load, were analyzed for changes over time due to exposure to diesel fuel. There was an approximate 24% increase in Marshall Flow for HMA after 1 hour, 49% after 3 hours, and 97% after 6 hours of exposure to diesel fuel. This significant rise indicates a notable decrease in deformation resistance caused by diesel fuel exposure. In contrast, Marshall Flow values for the 6% PET binder rose by about 14% after 1 hour, 27% after 3 hours, and 35% after 6 hours of diesel exposure. Though lower than HMA's, these increments suggest an enhanced ability to withstand diesel-induced deformation.

The 8% PET binder exhibited the smallest increase in flow values, rising by approximately 14% after 1 hour, 23% after 3 hours, and 26% after 6 hours of exposure to diesel. The slight elevation in flow values implies that the 8% PET binder offers the highest resistance to deformation. The HMA without PET modification substantially increased the Marshall Flow with prolonged diesel exposure. The 97% increase after 6 hours indicates a significant decrease in the asphalt mixture's ability to resist deformation under load, suggesting a high susceptibility to rutting and structural failure in the presence of diesel spills.
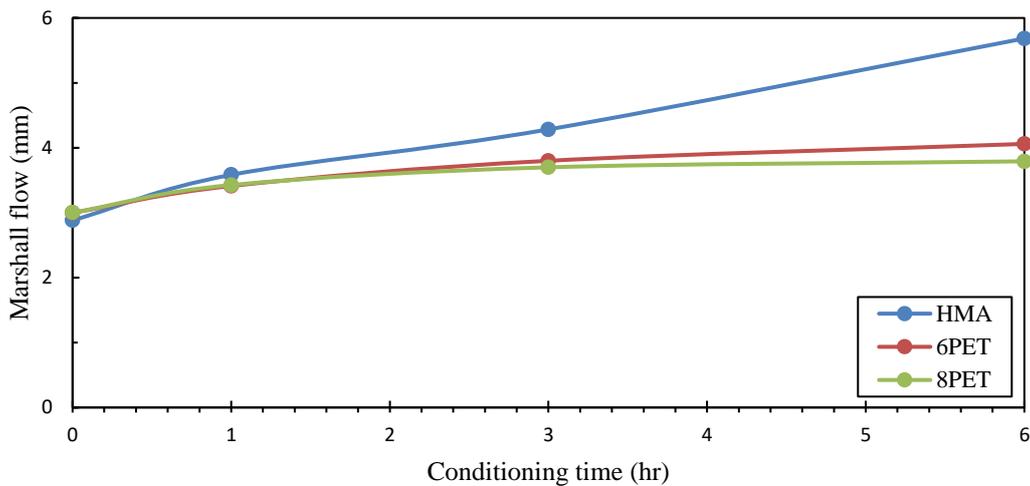
Figure 7. Marshall flow value for all samples

The comparison between the 6% PET and 8% PET binders reveals that increasing the PET content from 6% to 8% further enhances the binder's resistance to diesel-induced deformation. The consistently lower percentage increases in flow values for the 8% PET binder highlight the effectiveness of higher PET content in improving the structural integrity and durability of asphalt mixtures.

A higher PET dose means a larger fraction of the binder is polymer (fuel-resistant) rather than bituminous (fuel-soluble), so the mixture better resists diesel softening. In the 8% PET mixture, increased polymer chains further stiffen and strengthen the binder network, whereas the 6% mix still has a comparatively higher proportion of free bitumen. Under diesel exposure, the 6% mix will lose a larger fraction of its binder and thus show a greater drop in cohesion. The 8% mix, by contrast, keeps more of its structure: even if some binder is washed out, the residual PET scaffold keeps aggregates bonded. Consequently, Marshall stability is retained better, and permanent deformation (flow) is kept lower in the 8% mix. This dose effect is consistent with rheological data: as the PET content increases from 6% to 8%, viscosity and stiffness rise dramatically (Mahdi et al., 2022); therefore, the 8% binder holds up to stress (and diesel) more robustly. In summary, a higher percentage of PET results in a tougher, more viscous binder with fewer vulnerable oils, allowing the mixture to maintain higher strength and resist rutting more effectively than the 6% PET case (Ahmad & Ahmad, 2022; Mahdi et al., 2022).

Conclusion

This study demonstrates that incorporating polyethylene terephthalate (PET) waste into asphalt binders and mixtures significantly enhances their durability and resistance to diesel-induced damage compared to conventional hot-mix asphalt. PET modification enhances molecular stability under diesel exposure, limits binder degradation, and improves rheological performance, as indicated by lower increases

in non-recoverable creep compliance. At the mixture level, PET-modified asphalt exhibits higher stability and improved resistance to deformation, with the 8% PET content consistently providing the best overall performance. These findings indicate that PET-modified asphalt is a promising and sustainable solution for road pavements, particularly in areas prone to petroleum contamination. Further field-based studies are recommended to validate long-term performance and support practical implementation.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. The research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest. Conceptualization, methodology, investigation, data analysis, and original draft preparation were carried out by the first author. Supervision, validation of results, and critical review and editing of the manuscript were performed by the co-author(s). All authors have read and approved the final version of the manuscript. Limited assistance from Artificial Intelligence (AI) tools was utilized during the preparation of this manuscript to support language refinement and enhance the clarity and readability of the text. The AI tools were not used for data generation, data analysis, result interpretation, or the formulation of scientific conclusions. All technical content, analysis, and interpretations presented in this manuscript remain the sole responsibility of the authors.

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