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A Comprehensive Review on the Use of Polyethylene Waste in Hot Mix Asphalt: Material Properties, Performance Enhancement, and Sustainability Perspectives

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ABSTRACT

Polyethylene (PE) waste is both an environmental threat and a chance for innovation in pavement engineering. This review examines low-density (LDPE) and high-density (HDPE) PE as asphalt modifiers, outlining their influence on binder performance, mixture properties, environmental gains, and economic viability. Drawing on laboratory studies and field trials, it compares PE types, dosages, and mixing methods. PE raises the binder's softening point, viscosity, and elasticity, while reducing penetration and ductility. In mixtures, it can lift Marshall stability by up to 167%, cut rut depth by about 70%, and raise tensile strength by 30%. HDPE usually delivers the bigger mechanical boost thanks to its higher crystallinity, whereas LDPE offers better workability and cold-weather flexibility. Environmentally, PE-modified asphalt can divert up to 2 t of plastic per kilometer, save up to 8% bitumen, and trim greenhouse-gas emissions by 4–7%. Life-cycle analyses indicate 5–15% cost savings through longer service life and lower maintenance. However, key research gaps remain in long-term performance, storage stability, low-temperature cracking, and microplastic risk. Addressing these challenges requires standardized testing and field validation. PE-modified asphalt thus emerges as a practical, scalable, and sustainable option—turning plastic waste into a resilient and cost-effective infrastructure solution.

Keywords: Polyethylene waste, Hot mix asphalt, Asphalt binder modification, Mechanical performance, Sustainable pavement, Recycled plastics.

1. INTRODUCTION

Asphalt pavements, despite their widespread use in road infrastructure, continue to face persistent performance challenges under increasing traffic demands, temperature extremes, and long-term oxidative aging. Numerous studies have shown that conventional hot mix asphalt (HMA) is prone to rutting and fatigue cracking under heavy loading and elevated

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temperatures **(MacArthur et al., 2016; Ghabchi et al., 2015; Moghadas Nejad and Azarhoosh, 2014)**. Other research highlights the susceptibility of HMA to moisture damage and durability issues in regions exposed to seasonal stress cycles and harsh climatic variations **(Lee et al., 2011; Bohm, 2016)**. More recent investigations have further confirmed that these deficiencies remain critical under modern traffic and climate conditions, emphasizing the need for advanced modification strategies **(Zhuang et al., 2023; Shamami and Effati, 2025)**. In response, polymer modification has emerged as a strategy not only to enhance asphalt performance but also to promote sustainable materials management, especially through the reuse of waste plastics such as polyethylene (PE). Among the PE variants, Low-Density Polyethylene (LDPE) has received the most attention due to its flexibility, widespread availability in post-consumer waste streams, and thermoplastic behavior. using high-shear wet blending above 160 °C, LDPE stiffens the binder (higher softening point, lower penetration) and improves rutting resistance **(Yu et al., 2024; Ho et al., 2006; Dalhat and Al-Abdul Wahhab, 2015)**. **(Bagampadde et al., 2013)** demonstrated that LDPE addition significantly improved the complex modulus of asphalt binders, enhancing their high-temperature viscoelastic behavior and reducing moisture susceptibility across a range of aggregate types. Similar observations were made by **(Dalhat et al., 2020)**, who found that even modest LDPE dosages could upgrade the binder's performance grade from PG 64 to PG 76, especially when hybridized with reinforcing fibers. But LDPE's performance comes with some limitations. Several studies have found storage stability problems involving phase separation during long hot storage. **(Liang et al., 2019)** explained these results by noting the low crystallinity and high melt flow index of the LDPE, which allows for quick swelling but induces gravitational segregation in the binder matrix upon standing for more than 90 min over time. To counter this, alternative approaches to PE and alterations in mixing procedures have been used, such as powder-grade LDPE, semi-wet mixing techniques, and hybrid compositions with additives such as PAN fiber to enhance elastic recovery and long-term homogeneity. Research in this area is far from unanimous. Although LDPE is frequently highlighted for its ease of blending and the improvements it can deliver in performance grades, other reports have raised red flags around storage stability, pointing to real concerns about its long-term applicability unless compatibilizers are introduced **(Liang et al., 2019; Nizamuddin et al., 2024; Revelli et al., 2023; Brasileiro et al., 2019)**. Importantly, the behavior of polyethylene in asphalt systems is not uniform across types. Comparative investigations make it clear that HDPE, LLDPE, and LDPE interact with the binder in distinct ways, a difference largely attributed to variations in molecular weight, crystalline arrangement, and melt flow properties **(Ghani et al., 2022; Nisar et al., 2024; Li et al., 2023)**. HDPE, for example, typically increases stiffness and improves resistance to surface wear, while LLDPE provides a middle ground between flexibility and thermal resistance **(Suleiman et al., 2024; Nguyen et al., 2025)**. Also, **(Liang et al., 2019)** reported that HDPE has better storage stability than LDPE, while LLDPE has better phase dispersion and moderate thermal stability. However, **(Basheet and Latief, 2024)** reported on HDPE being superior to LDPE in both mechanical stability and moisture resistance, particularly at higher dosages. There is no consensus in the literature on a "best" polyethylene type.

Some studies report HDPE as more mechanically reliable **(Basheet and Latief, 2024)**, but others highlight challenges with its workability and high melting point, which may reduce its field applicability without advanced mixing equipment **(Ho et al., 2006)**. Dosage and method of incorporation are also important from an implementation perspective. But too much polymer, especially over the 6–8% range, can make binder viscosity too high to be workable and hinder elastic recovery without elastomeric co-modifiers. The choice of mixing technique dry, wet, or the more recently explored semi-wet plays a decisive role in shaping blend homogeneity as well as influencing both cost and energy requirements. Semi-wet methods, in particular, have attracted attention as a pragmatic middle ground, balancing improvements in performance with operational feasibility **(Prahara et al., 2020; Basheet and Latief, 2024; Bueno and Teixeira, 2024; Spadoni et al., 2022)**. What is equally striking is that the discussion around polyethylene (PE) in asphalt has moved well beyond laboratory performance metrics. A growing body of literature highlights its economic and environmental significance: one kilometer of pavement can incorporate on the order of a ton of plastic waste, effectively diverting post-consumer material from landfill streams. In practice, this recycling pathway not only mitigates disposal pressures but also extends pavement life cycles, reducing maintenance demands and thereby recovering costs over the service period **(Singh and Gupta, 2024; Abernathy et al., 2025)**. In locales grappling with both waste management and high infrastructure needs, this is what we call the sweet spot between engineering need and environmental stewardship.

This review discusses the current state of research on PE-modified asphalt binders and mixtures and highlights their comparative performance concerning LDPE, HDPE, and LLDPE. Unlike prior reviews that focused on a single PE grade or binder-level tests, this article cross-examines LDPE, HDPE and LLDPE from binder through field performance and links those findings to life-cycle impacts. Their implications on rheological behavior, mixture performance, moisture susceptibility, thermal stability, storage issues, and practical applications are discussed. Despite abundant lab evidence, guidance on storage stability, micro-plastic release, and field validation remains fragmented, constituting the research gap this review addresses.

2. POLYETHYLENE MATERIAL PROPERTIES AND CLASSIFICATION

Polyethylene is comprised of repeating units of ethylene, but due to differences in molecular architecture, its behavior in asphalt modification is not binary, but rather on a spectrum **(Polacco et al., 2005)**. The three primary forms of polyolefin, that is, Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Linear Low-Density Polyethylene (LLDPE), were investigated for their contribution as modifiers on the binder rheology and mixture performance **(Bagampadde et al., 2013)**. It is worth noting that post-consumer PE is first sorted and washed, granulated into =15 mm flakes, dried to below 0.5% moisture, then melted in a single-screw extruder at 180–210 °C; the molten strands are water-cooled and pelletized into 3–5 mm pellets, yielding a clean, free-flowing feedstock that disperses uniformly during wet or semi-wet asphalt blending **(Wang et al., 2023; Junaid et al., 2024).** LDPE is the most commonly used variant, favored for its availability and workability **(Khurshid et al., 2019; Almeida et al., 2020; Bueno and Teixeira, 2024; Kovács et al., 2024).** Its highly branched molecular structure results in low crystallinity (≈35%), low density (≈0.914 g/cm^3), and a melting point around 108°C, which promotes ease of mixing but can introduce problems with phase stability **(Roja et al., 2021; Filonzi et al., 2023; Arshadi and Taherkhani, 2024; Cuadri et al., 2016)**. **(Liang et al., 2019)** reported that LDPE-modified asphalt binders exhibited large polymer phase domains exceeding 200 μm and a viscosity ratio of 4.25 (top vs. bottom sections) after 48 hours at 163°C, indicating significant segregation during storage. The tendency can be traced back to LDPE's relatively high melt flow index (MFI = 32 g/10 min), which accelerates swelling but undermines thermal stability by making the material more prone to gravitational segregation under heat **(Saroufim et al., 2018)**. What complicates the picture is that, in spite of these well-documented stability issues, LDPE still delivers measurable performance benefits, a paradox that continues to fuel debate in the literature. For example, **(Bagampadde et al., 2013)** reported that incorporating LDPE at levels of 2.5–3.0% by binder weight produced reductions in shear susceptibility in the range of 16–34%, alongside gains in complex modulus and pseudo-plastic behavior at elevated temperatures. These improvements are not trivial, as they directly support rutting resistance in hot-climate pavements, where thermal loads are often the dominant distress mechanism.

In contrast, HDPE exhibits a linear chain structure with minimal branching, which yields a high density (=0.954 g/cm^3), high crystallinity (≈86%), and a melting point of 131°C, making it structurally stiffer and more thermally stable **(Fang et al., 2013; Ma et al., 2016)**. These properties were quantified by **(Liang et al., 2019)** using differential scanning calorimetry and microscopy. However, this also means HDPE is more challenging to blend uniformly, often requiring mixing at temperatures above 165°C with high-shear mixing at 3000–5000 rpm **(Ho et al., 2006)** . The payoff, though, can be substantial, although some studies caution that HDPE's blending challenges may offset these gains in field conditions, creating disagreement in practical feasibility assessments. **(Basheet and Latief, 2024)** recorded a 167.6% increase in Marshall stability and a 16% improvement in moisture resistance (as measured by Tensile Strength Ratio) at 6% HDPE content, compared to unmodified mixes. LLDPE, which remains less frequently studied, features short, uniform branches that confer a balance between flexibility and structural cohesion. Its density (0.924 g/cm^3) and melting point (124°C) place it between LDPE and HDPE **(Nizamuddin et al., 2020; Zhang et al., 2013)**. In phase separation studies **(Liang et al., 2019)** observed that LLDPE-modified binders had a viscosity ratio of just 1.25, significantly better than LDPE or HDPE, suggesting superior stability during hot storage. In general, LDPE offers processing ease and moderate gains, HDPE delivers superior strength but demands careful processing, and LLDPE looks promising for storage stability, albeit with less mechanical validation to date. For example, if blended correctly, HDPE will perform better in high-load or high-temperature applications, whereas LDPE may be preferred where equipment limits or cost constraints make low-viscosity blends advantageous. A summary comparison of LDPE, HDPE, and LLDPE is presented in **Table 1.**

Table 1. Summary of Polyethylene Types in Asphalt Modification.

Polymer Type	Key Strengths	Known Limitations	Performance Notes
LDPE	Easy mixing; good low-temp flexibility	Phase separation, poor storage stability	Best for low-temp areas, easy to process
HDPE	High stiffness and rut resistance	Difficult to blend, high melting temp	Best for high-load roads in hot climates
LLDPE	Balanced traits, stable during storage	Limited mechanical data	Promising but under-studied

3. MIXING METHODS AND PROCESSING TECHNIQUES

How PE is integrated into asphalt strongly shapes binder and mixture performance. Three incorporation routes dominate current studies: wet, dry, and the newer semi-wet method. Each route affects material behaviour, energy demand, and field fit **(Naskar et al., 2012; Jan et al., 2018; Liang et al., 2019; Kakar et al., 2021).**

In wet mixing, PE is sheared into hot bitumen **(Masad et al., 2020)**. The goal is a homogeneous polymer dispersion in the binder. This method is broadly exploited in laboratories because of its control over polymer distribution and its facility for rheological characterization **(Dalhat et al., 2020; Yan et al., 2015; Vargas et al., 2013).** This technique to blend LDPE and PAN fibers into 60/70 penetration-grade bitumen, observing substantial improvements in rutting resistance and stiffness modulus at dosages as low as 4% LDPE. However, the wet route has well-known limits. (**Liang et al., 2019)** found that high-MFI LDPE separates during long-term tank storage. On the other hand, the dry mixing method involves the direct addition of shredded or powdered PE to hot aggregates before bitumen is introduced **(Yeh et al., 2010)**. This approach, favored in field applications, eliminates the need for polymer–bitumen pre-blending and can be integrated into existing batch plant operations with minimal modification. **(Basheet and Latief, 2024)** demonstrated that dry mixing HDPE at 5% improved Marshall stability by 167.6% and also yielded improved moisture resistance without any major modification to the plant equipment. However, dry mixing often results in less uniform dispersion of the polymer and has shown weaker enhancements in low-temperature performance compared to wet blending. Emerging between these two extremes is the semi-wet method, wherein PE is first partially melted or softened in a bitumen-like matrix (or in a premix system), then blended with heated aggregates. This method aims to combine the processability of dry mixing with the uniformity of wet mixing. According to **(Basheet and Latief, 2025),** the semi-wet technique led to improved homogeneity and reduced air voids in the mix, while also showing less phase separation than traditional wet mixing. One recurring theme across all methods is the sensitivity to polymer particle size and form. Powders tend to melt and disperse more effectively than pellets, and pre-treated or chemically modified PE tends to offer better interfacial bonding with the binder. **(Al-Hadidy and Tan, 2009)** Noted that pulverized PE improved binder elasticity and reduced penetration index more consistently than pelletized forms, which tended to remain undissolved at standard blending temperatures.

Beyond temperature and shear, factors such as pre-blend time, hold duration, and addition order also shape final rheology. **(Liang et al., 2019)** highlighted that increasing the mixing time from 30 to 60 minutes under constant shear led to a 14% increase in complex modulus, but also slightly reduced phase stability at rest. Overall, the literature presents conflicting preferences among researchers, with no universal agreement on the most effective mixing method, each having trade-offs in homogeneity, energy input, and field viability. A concise comparison of the three primary mixing methods, including differences in polymer state, mixing requirements, PE dosage, and practical feasibility, is provided in **Table 2**.

Table 2. Comparative Overview of PE Incorporation Methods in Asphalt Modification.

Method	Ref.	PE state during addition	PE dosage (%)	Mixing temperature (°C)	Mixing speed (rpm)	Mixing duration (min)	Field feasibility*
Wet	**(Dalhat and Al-Abdul Wahhab, 2015)**	Melted pellets	4–6	170 ± 5	2000	45	Moderate
Wet	**(Basheet and Latief, 2024)**	Fine powder	5	165	2500	30	Moderate

Dry	**(Ho et al., 2006)**	Shredded film	4 – 8	150 (aggregate)	Drum mixer, 60	25	High
Dry	**(Singh and Gupta, 2024)**	Granules	6	145 (aggregate)	Batch pug-mill, 70	20	High
Semi-wet	**(Latief, 2025)**	Softened chips	3 – 5	160	1200 , ribbon impeller	25 (pre-soften) + 15 (wet)	Moderate
Semi-wet	**(Kakisina et al., 2020)**	Fine powder	4	155	1500, high-torque mixer	35	Moderate
Hybrid	**(Dalhat et al., 2020)**	Melted LDPE + PAN fiber	5, LDPE + 0.3% fiber	170	2000	40	Moderate

*Qualitative ratings compiled from each cited paper's microscopy or tube-test results.

4. EFFECT OF POLYETHYLENE ON BINDER RHEOLOGY AND PHYSICAL PROPERTIES

The inclusion of polyethylene (PE) in asphalt binders leads to immediate, measurable changes in fundamental physical properties, most notably penetration, softening point, and ductility, which remain central to binder classification and quality control. While modern rheological tools like the Dynamic Shear Rheometer (DSR) offer deeper insight into viscoelastic behavior, these classic empirical tests continue to serve as reliable indicators of binder performance shifts induced by polymer modification.

One of the most consistent outcomes observed across studies is a decrease in penetration value with increasing PE content(**Singh et al., 2013; Li et al., 2022)**. This reduction signals a stiffening of the binder and a corresponding improvement in resistance to deformation under load. For instance**, (Al-Hadidy and Tan, 2009)** documented that the penetration of 60/70 bitumen dropped from 67 dmm to 44 dmm after the addition of just 4% LDPE, confirming a notable increase in hardness. Comparable findings were reported by **(Bagampadde et al., 2013)**, who noted penetration reductions of up to 38% at LDPE contents of 3–4%. In parallel, the softening point of LDPE-modified binders generally rises by about 7–10 °C **(Dalhat et al., 2020)**. HDPE tends to push this effect further, a consequence of its higher crystallinity and melting point **(Suksiripattanapong et al., 2022; Abdulfatai et al., 2023)**. **(Basheet and Latief, 2024)**, for instance, documented that adding 6% HDPE raised the softening point from 46.8 °C to 60.1 °C, underscoring its value in hot-climate applications. Yet these improvements come with a caveat. Both LDPE and HDPE blends often show reduced ductility at higher dosages, and the problem is exacerbated when dispersion is inadequate. This loss of ductility complicates field performance predictions, since binders that resist rutting may still become vulnerable to low-temperature cracking.

This is where literature diverges: **(Nizamuddin et al., 2020)** reported ductility falling below 30 cm at LDPE levels above 5%, while **(Bagampadde et al., 2013)** maintained values above 50 cm under similar conditions, highlighting conflicting results based on polymer size and mixing control. This suggests that particle size, mixing conditions, and polymer type play a critical role in controlling ductility outcomes. **(Dalhat et al., 2020)** recorded a 43% rise in G* and an 11% drop in δ at 64 °C with 6% LDPE. By contrast, **(Al-Hadidy and Tan, 2009)** noted a 60% increase in G/sin δ at 76 °C when using HDPE, upgrading the binder's PG grade by two classes. Even so, performance at lower temperatures can be tricky. Although the addition of stiffness is beneficial to resist rutting, it can also lead to brittle behavior in cold climates, especially when ductility is lacking **(Pérez-Lepe et al., 2006; Assolie et al., 2025)**. **Figs. 1 and 2** illustrate the effect of PE content on key binder properties such as penetration, softening point, and ductility for LDPE and HDPE, respectively. The figures were prepared by the authors using numerical data compiled from several experimental studies**.**

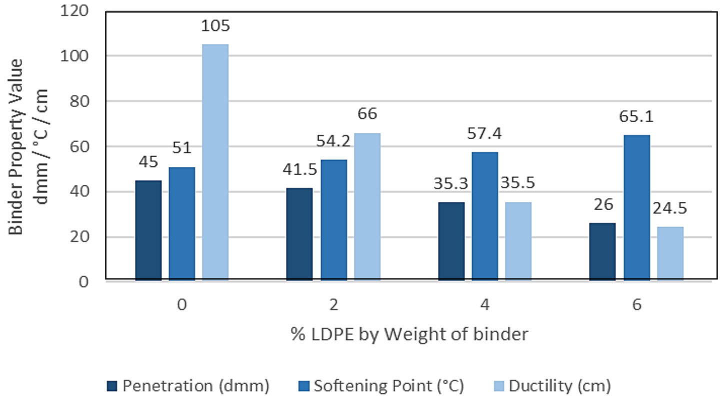

Figure 1. Effect of LDPE content on penetration, softening point, and ductility of asphalt binder. Figure prepared by the authors using numerical data compiled from previous studies **(Al-Hadidy and Tan, 2009; Bagampadde et al., 2013; Eme and Nwaobakata, 2019; Lubis et al., 2020).**

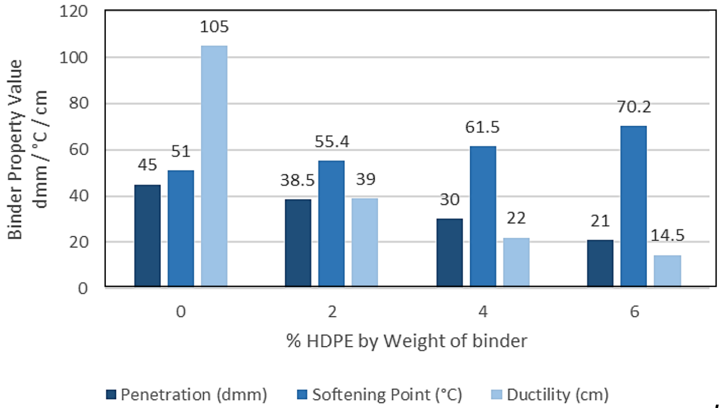

Figure 2. Effect of HDPE content on penetration, softening point, and ductility of asphalt binder. Figure prepared by the authors using numerical data compiled from previous studies **(Bagampadde et al., 2013, Al-Hadidy and Tan, 2009; Basheet and Latief, 2024; Dalhat et al., 2024).**

This trade-off emphasizes the necessity of optimizing dosing and processing conditions rather than relying solely on the addition of PE. In summary, PE-modified binders demonstrate a consistent pattern: higher stiffness, better high-temp performance, and reduced flow, but with the potential drawback of reduced flexibility. These changes, reflected in simple empirical tests, remain critical for practitioners seeking balance between durability and constructability.

5. PERFORMANCE OF PE-MODIFIED ASPHALT MIXTURES

The mechanical improvements of polyethylene (PE)-modified asphalt mixtures are not limited to the binder level. Several studies have been performed to measure the impact of PE addition, specifically LDPE and HDPE, to asphalt concrete by identifying performance characteristics such as Marshall stability, indirect tensile strength (ITS), and moisture susceptibility, as well as rutting resistance. Generally, it can be seen that all the polymers improved the performance, but the extent and nature of performance improvements are highly dependent on the type of PE used, dosage employed, and the fine dispersion of the same **(Sojobi et al., 2016; Kakar et al., 2021; Li et al., 2024)**, However, reported gains vary widely and are not always proportional to dosage. Two factors repeatedly emerge as decisive: (i) particle dispersion quality and (ii) the trade-off between stiffness and crack tolerance at low temperature.

In Marshall stability, the HDPE-modified mixtures are observed to perform outstanding than both unmodified and LDPE-modified mixes. **(Polacco et al., 2005; Abduljabbar et al., 2022; Issa et al., 2022;Basheet and Latief, 2024)** found that an increase HDPE content from 0% to 6% increased stability from 9.2 kN to 24.6 kN, while LDPE increased to a maximum of 18.1 kN under the same conditions. **(Ullah et al., 2021)** found comparable behavior, where both HDPE and LDPE significantly enhanced Marshall stability, with the HDPE-modified mixes improving stability by 167% and LDPE by 150%, respectively, when both these polymers were finely ensured homogeneous interaction in the matrix. However, this finding is not universal; some studies report only marginal differences between LDPE and HDPE when both are well-dispersed, suggesting that performance gains may depend more on processing quality than polymer type **(Ullah et al., 2021; Jan et al., 2022)**. Taken together, these studies show HDPE consistently tops LDPE on stiffness-related metrics, yet LDPE retains a safety margin against cracking—especially critical on lightly trafficked or cold-region pavements.

However, flow values paint a more nuanced picture. HDPE has drastically reduced the flow value of the mix from 3.85 mm to 2.58 mm, whereas with LDPE the flow value was reduced to 2.28 mm, showing that LDPE retains a better balance between strength and flexibility LDPE is especially beneficial in environments susceptible to cracking, such as colder climates or pavements prone to aging **(Ali et al., 2024)**.

Also notable are the improvements to indirect tensile strength (ITS). With 6% HDPE content, ITS increased from 0.63 MPa to 0.91 MPa as reported by **(Basheet and Latief, 2024)**, while LDPE-modified mixes reached an ITS of 0.78 MPa at the same percentage of LDPE. **(Bagampadde et al., 2013; Jan et al., 2022)** found comparable results for LDPE, with ITS increases ranging from 15–20%, depending on particle size and mixing technique.

Moisture susceptibility, measured through TSR, also improved across both polymers. **(Basheet and Latief, 2024)** recorded an increase in TSR from 73.4% (unmodified) to 89.6% (HDPE, 6%), while LDPE reached 81.3%, exceeding the minimum Superpave requirement of 80%. These findings as also reported by **(Bagampadde, 2013; Liang et al., 2019),** who noted that HDPE-blended asphalt showed improved water resistance, particularly when processed via high-shear wet blending.

The rutting resistance benefits of PE are among the most clearly documented. **(Othman, 2010; Dalhat et al., 2020)** reported that LDPE-modified mixes exhibited up to 45% lower rut depth in wheel tracking tests compared to control specimens. **(Nizamuddin et al., 2020)** found that HDPE reduced rutting by over 60%, supported by higher dynamic stability indices and lower permanent strain accumulation under repeated load tests. **(Liang et al., 2019; Dalhat et al., 2020)** further confirmed these trends across various climate simulations.

Nonetheless, performance does not infinitely increase with higher PE content. At levels higher than 6–8%, mixed, poorly dispersed or pelletized polymers in mixes may be extremely stiff, not easily compacted and subject to cracking. Especially apparent in the fatigue and cracking studies of **(Yousuf et al., 2020; Jan et al., 2022),** fracture energy decreased when the amount of LDPE was > 4%. The author found that HDPE dosage greater than 7% increased the air voids and the flow decreased below the optimal values, thus it is necessary to optimize it in an appropriate manner.

On the whole, HDPE tends to deliver greater improvements in stiffness, rutting resistance, and overall structural strength, which explains its frequent use in heavily trafficked pavements exposed to warm climates. LDPE, while less effective in raising strength parameters, contributes valuable ductility and thermal flexibility traits that become particularly important where fatigue cracking or low temperature stresses are the primary concern. In practice, the choice between the two polymers, as well as the dosage applied, should be guided not only by target performance indices but also by climate exposure and constructability in the field. Ultimately, the decision is less about achieving the highest stiffness values and more about striking an appropriate balance: resisting rutting without compromising flexibility in service. The evolution of asphalt mixture performance with increasing polyethylene content is illustrated in **Fig. 3**, which presents LDPE-based results obtained from **(Basheet and Latief, 2024)**, and in **Fig. 4**, which shows HDPE-related data drawn from *both* **(Nizamuddin et al., 2020; Assefa, 2021; Basheet and Latief, 2025).** To synthesize the mechanical performance outcomes of LDPE and HDPE across multiple studies, **Table 3** presents a structured comparison of key properties, including their reported benefits, limitations, and corresponding literature sources**.**

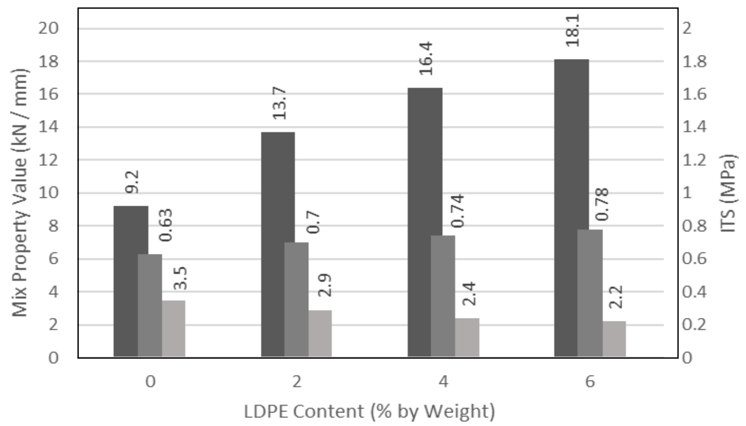

Figure 3. Effect of LDPE content on asphalt mixture properties: Marshall stability, indirect tensile strength (ITS), and flow. Figure prepared by the authors using numerical data adapted from **(Basheet and Latief, 2024)**.

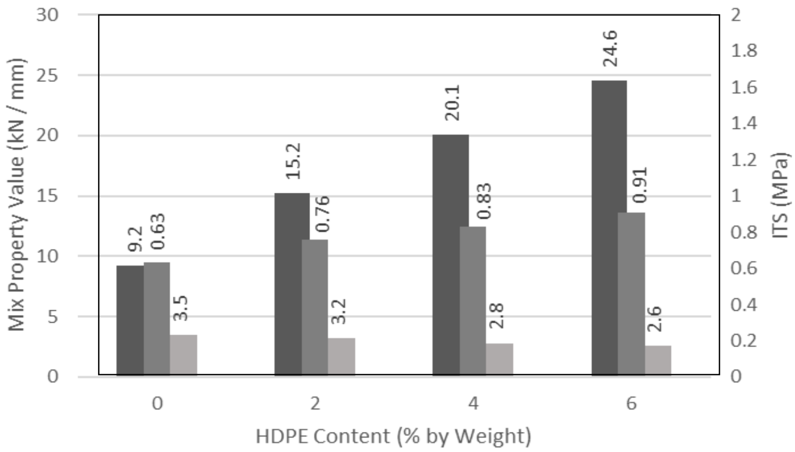

Figure 4. Effect of HDPE content on asphalt mixture properties: Marshall stability, indirect tensile strength (ITS), and flow. Figure prepared by the authors using numerical data compiled from **(Nizamuddin et al., 2020; Assefa, 2021; Basheet and Latief, 2025).**

Table 3. Summary of mechanical performance properties of LDPE and HDPE in asphalt mixtures, including reported strengths, limitations, and representative supporting studies.

Mechanical Property	Reported Strengths	Cited Studies
Marshall Stability	HDPE generally delivers the largest stability gain; LDPE also strengthens the mix but to a slightly lower level. Very high HDPE doses can create extra voids.	**(Basheet and Latief, 2024; Ullah et al., 2021; Issa et al., 2022)**
Indirect Tensile Strength (ITS)	Both polymers raise ITS; LDPE improvements depend on particle size and mixing quality.	**(Bagampadde et al., 2013; Jan et al., 2022)**
Flow Value	LDPE lowers flow a little more than HDPE, helping the mix stay flexible. Excessively low values, however, may hurt fatigue resistance.	**(Ali et al., 2024; Basheet and Latief, 2024)**
Moisture Resistance (TSR)	HDPE mixtures reach the highest TSR values; LDPE also improves moisture resistance but is more sensitive to dispersion quality.	**(Nizamuddin et al., 2020; Liang et al., 2019)**
Rutting Resistance	HDPE offers the greatest reduction in rut depth; LDPE gives moderate improvement. Very high polymer contents can make the mix too stiff.	**(Dalhat et al., 2020; Nizamuddin et al., 2020)**
Cracking / Fatigue Resistance	LDPE tends to resist thermal and fatigue cracking better than HDPE because it keeps more flexibility; HDPE may need a co-modifier in cold regions.	**(Yousuf et al., 2020; Jan et al., 2022)**

6. STORAGE STABILITY AND COMPATIBILITY ISSUES

Storage stability remains one of the persistent obstacles in using polyethylene (PE) with asphalt, largely because the polymer tends to separate from bitumen during long, high-temperature storage. The root of this instability lies in the molecular mismatch, differences in density, polarity, and melt flow index between the polymer chains and the bitumen matrix **(Becker et al., 2001; Ghuzlan et al., 2013; White and Reid, 2018)**. LDPE is particularly vulnerable. With its low density and high MFI (32 g/10 min), it swells quickly under heat but loses vertical uniformity. After only 120 minutes at 163 °C, binders modified with LDPE

develop phase domains exceeding 200 μm, with polymer-rich zones accumulating near the surface of storage containers. Tube tests confirm this behavior, producing top-to-bottom viscosity ratios above four, which is far from acceptable **(Liang et al., 2019)**. Numerical modeling echoes these results: LDPE scores a simulated stability index of 48.1, compared with only 1.25 for LLDPE and 3.56 for HDPE **(Fang et al., 2012; Liang et al., 2019; Assolie et al., 2025)**. Microscopy offers further evidence, fluorescence images of LDPE blends show highly coarsened domains, while LLDPE maintains a more uniform dispersion with slower phase growth **(Liang et al., 2019)**. The underlying reason again comes back to polymer structure. Crystallinity, branching, and molecular distribution all dictate how each PE interacts with the asphalt, and in LDPE's case, early swelling gives way to segregation as thermal exposure lengthens **(Dalhat et al., 2020)**.
Mixing approach can intensify or mitigate these issues. Wet mixing, where PE is introduced under high shear, produces good initial dispersion but often separates during storage unless agitation is maintained **(Gawel et al., 2006)**. Dry mixing, while convenient in field conditions, yields less uniformity but sometimes better long-term stability because molten pools do not accumulate **(Latief, 2025)**. More recently, semi-wet routines have been trialed, in which the polymer is pre-softened with a compatibilizing agent before being introduced. Early results suggest this method reduces separation and improves energy efficiency **(Latief, 2025)**. Particle size also matters. Powders and finely shredded chips disperse faster than pellets, thanks to greater surface area, but field reports remain divided on which form is superior. Some evidence shows pelletized HDPE can still perform adequately if mixing is vigorous enough **(Latief, 2025)**. High-shear mixers are particularly effective at incorporating small particles into the binder film, provided they remain below a threshold size **(Kakisina et al., 2020)**.
Despite careful process control, some degree of phase separation seems unavoidable during long storage unless the material is stirred periodically. Gravity, viscosity mismatches, and swelling dynamics all act in concert to destabilize the system. For this reason, most recommendations converge on a set of practical rules: favor LLDPE over LDPE for better homogeneity; keep polymer content in the 3–5% range to balance performance with stability; and use blending routines, such as semi-wet methods, that encourage dispersion without excessive energy costs. Particle form also deserves attention, with powders generally dispersing more reliably than pellets in plant conditions **(Becker et al., 2001; Kakisina et al., 2020; Latief, 2025)**. Finally, when storage times extend beyond two hours at 160 °C or higher, gentle agitation remains necessary. Even well-formulated binders will stratify under static conditions. In practice, tailoring polymer grade, particle form, dosage, and mixing protocol to the plant's capabilities provides the most dependable pathway to a homogeneous, field-ready binder.

7. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

The integration of polyethylene (PE) waste into asphalt systems does more than just improve mechanical properties, it addresses pressing global challenges of sustainability and cost-efficiency. This section brings together environmental and economic dimensions, grounded in real examples from your research set.
Recycling polyethylene into asphalt contributes significantly to mitigating the environmental burden of plastic waste, particularly in regions where landfill overflow and marine plastic accumulation are severe. For every kilometer of roadway paved with 4–6% PE-modified binder, approximately 1.5 to 2 tons of post-consumer plastic can be diverted

from the waste stream. Life Cycle Assessment (LCA) studies consistently show reduced greenhouse gas (GHG) emissions and lower energy consumption in PE-modified asphalt compared to conventional mixes. A cradle-to-grave LCA by **(Kim and Kim, 2025)** demonstrated that substituting even 5–6% bitumen with LDPE or HDPE can lead to a 6–12% reduction in CO_2 equivalents over a pavement's life cycle. These benefits stem from reduced virgin bitumen demand and longer service intervals due to improved durability. Case studies in India and Southeast Asia document further environmental savings — including reduced construction emissions, enhanced surface life, and fewer raw materials used per lane-kilometer. However, these advantages are tempered by emerging concerns. Recent studies show that microplastic particles can be generated as the pavement surface wears under traffic and weathering, with the risk being somewhat higher for HDPE-modified surfaces due to their greater hardness and brittleness **(Junaid et al., 2024)**. These microplastics may enter nearby soil and water, though current field data suggest their contribution is lower than that from tire wear or road paint.

In addition, processing PE-modified asphalt at high temperatures (especially ≥160 °C) can emit volatile organic compounds (VOCs), including aliphatic hydrocarbons and aldehydes, particularly when using HDPE or if the polymer is not fully incorporated **(Liang et al., 2019; Junaid et al., 2024).** While VOC emissions are generally lower than those from some other polymer-modified binders, proper ventilation and temperature control remain important during mixing and paving. To minimize these risks, it is recommended to use lower PE dosages, optimize processing temperatures, and consider surface treatments or co-modification with degradable polymers **(Junaid et al., 2024).** From an economic perspective, the use of recycled PE offers a mix of direct and indirect savings. While initial processing may require specialized heating or shearing systems, long-term lifecycle analyses reveal substantial reductions in total cost. According to **(Singh and Gupta, 2024),** LDPE-modified pavements showed comparable or better fatigue and rutting resistance than VG-30, VG-40, and PMB mixes, while being 4.3% to 10% more cost-effective overall. **(Awwad and Shbeeb, 2007)** performed a 20-year life cycle cost analysis of HDPE pavements and found that maintenance and overlay intervals were extended by up to 35%, contributing to cumulative savings in both material and labor. Vasudevan's field trials with LDPE in rural road sections confirmed that PE-based roads required no major rehabilitation even after five years of service under mixed traffic loads. Moreover, PE is widely available as industrial and municipal waste, reducing sourcing costs compared to imported polymer additives. Local waste utilization not only lowers economic input but also supports regional circular economy initiatives. **Table 4.** shows the comparative summarization of environmental and economic benefits PE modifications, prepared by the authors using data compiled from previous studies **(Masad et al., 2020; Nizamuddin et al., 2020; Suleiman et al., 2024; Basheet and Latief, 2024)**. The table below compares conventional asphalt with PE-modified mixtures and their key differences, including plastic waste saving, reduced bitumen consumption, reduced green gas emissions, savings in life cycle cost and longer maintenance intervals. LDPE allows for less processing time and more familiarity in the field; however, HDPE typically provides better performance characteristics and better savings.

Table 4. Comparison of Environmental and Economic Indicators for Conventional and PE-Modified Asphalt Mixtures

Indicator	Conventional Asphalt	PE-Modified Asphalt (LDPE)	PE-Modified Asphalt (HDPE)
Plastic Waste Utilized (tons/km)	0	1.5	2.0
Bitumen Savings (%)	0	5	8
GHG Emissions Reduction (%)	0	4	7
Life Cycle Cost Reduction (%)	0	5–10	10–15
Maintenance Frequency (years)	5–7	7–9	8–10
Potential Microplastic Risk	None	Low	Moderate

8. RESEARCH GAPS AND FUTURE PERSPECTIVES

However, despite the promising results of modifying asphalt mixtures with PE, there are several research gaps that need to be addressed to further advance the field and facilitate widespread use in actual pavement applications.

One of the primary concerns is the limited understanding of long-term field performance. Most studies to date have focused on laboratory-scale testing, often evaluating short-term mechanical and rheological properties. However, the behavior of PE-modified asphalt under actual traffic loading, environmental exposure, and seasonal temperature changes remain underexplored. While accelerated aging tests provide some insight, there is a need for full-scale field trials and long-term monitoring to validate the durability, aging resistance, and maintenance behavior of these modified pavements **(Masad et al., 2020; Junaid et al., 2024).** A second major limitation concerns the storage stability of PE-enhanced binders, especially those based on high-density polyethylene (HDPE). Because of the thermodynamic incompatibility between PE and the bitumen matrix, during the hot storage phase, separation may take place, in particular at high polymer dosages and poor mixing control. While compatibilizers, including maleic anhydride, and high-shear mixing have demonstrated promise in enhancing compatibility, there continues to be a knowledge gap, which leads to the requirement for further studies to enhance these solutions for the applications at large scale **(Liang et al., 2019; Assolie et al., 2025).** Low-temperature cracking susceptibility is another unresolved issue. The stiffening effect of PE, particularly HDPE, may reduce ductility and increase the risk of cracking in cold regions. Only a limited number of studies have investigated this aspect in depth, and there is little consensus on how to effectively mitigate this issue without compromising high-temperature performance. Co-modification strategies using elastic polymers like SBS, crumb rubber, or bio-based rejuvenators offer potential, but require more systematic investigation **(Basheet and Latief, 2024; Kim and Kim, 2025).** Furthermore, the lack of standardization in testing protocols, PE preparation methods, and performance criteria presents a significant barrier to comparison and scalability. Across the literature, studies vary in terms of PE form (powder, granules, shredded), source (post-consumer vs. industrial), dosage range, and mixing conditions. Establishing standard test methods and performance benchmarks, particularly for moisture susceptibility, rutting, and fatigue, will support broader industry acceptance and consistent implementation **(Nizamuddin et al., 2020; Suleiman et al., 2024).** From an environmental standpoint, while PE offers benefits in terms of waste diversion and emissions reduction, emerging concerns around microplastics and emissions during mixing remain largely unaddressed. Only a few studies have modelled or monitored the potential for microplastic release due to surface wear over time **(Masad et al., 2020).** Moreover, emissions from high-temperature processing, particularly when PE is used at high contents, may introduce additional environmental risks if not properly controlled. Lastly, to further improve conditions, future research can study advanced enhancement technologies like chemical grafting, nano-scale additive PE, or hybrid composite modifier development. They can enhance compatibility, decrease necessary dosages, and customize the efficacy for specific climatic conditions and functions of pavement.

In summary, although the available literature demonstrates that PE has the potential to be a sustainable and efficient asphalt modifier, further research is needed for long-term performance and environmental safety, as well as industrial scalability of PE to form an asphalt modification system. To fully capitalize on the potential of PE-modified asphalt within modern pavement engineering, the discipline will need to engage in further multi-disciplinary research drawn from field validation and supplementary test method protocols.

In summary, although the available literature demonstrates that PE has the potential to be a sustainable and efficient asphalt modifier, further research is needed:

- Long-term field performance studies: There is a critical need for multi-year, real-world monitoring of PE-modified pavements to confirm durability, aging, and maintenance trends observed in laboratory settings **(Masad et al., 2020).**
- Standardization of testing and mixture design: Developing unified protocols for PE preparation, dosage, and performance testing will enable better comparison across studies and support broader industry adoption **(Nizamuddin et al., 2020; Suleiman et al., 2024).**
- Quantification and mitigation of microplastic and emission risks: Research should prioritize measuring microplastic release and VOC emissions in the field, and testing mitigation strategies such as surface treatments or co-modification with degradable polymers **(Liang et al., 2019).**
- Optimization of storage stability and compatibility: Further work is needed to refine compatibilizer use, polymer content, and blending techniques to ensure stable, homogeneous binders suitable for large-scale application **(Latief, 2025).**
- Balancing high- and low-temperature performance: Investigating co-modification with elastic polymers and tailored formulations for different climates will help address the risk of low-temperature cracking without compromising rutting resistance **(Basheet and Latief, 2024; Kim and Kim, 2025).**

9. CONCLUSIONS

This review evaluated the use of polyethylene (PE) waste—LDPE and HDPE—in hot mix asphalt (HMA) as a sustainable modifier. PE enhances mechanical properties and offers environmental benefits by diverting plastic from landfills. LDPE improves flexibility and mixing ease, HDPE increases strength and rutting resistance but is harder to blend, and LLDPE may provide a balanced alternative. LDPE dominates asphalt applications due to its availability and easier blending.

Among the mixing methods, wet processes generally ensure better dispersion but are challenged by phase separation and equipment requirements, while dry and semi-wet approaches offer field practicality but risk uneven polymer distribution. Mechanical performance outcomes are highly sensitive to polymer form (powder vs pellet), mixing energy, and dosage — with overdosage (>6–8%) often leading to brittleness or compaction issues. Critically, the literature remains conflicted on several fronts: optimal polymer type, long-term field performance, environmental risks (e.g., microplastics), and the economic

viability under different regional constraints. While most studies affirm performance benefits, contradictions persist due to methodological differences, testing conditions, and context-specific interpretations. This review synthesizes these diverse findings and argues that application-specific strategies, matching polymer type and mixing method to climate, traffic loading, and equipment availability, are key to successful implementation.
This review is limited by the dominance of laboratory-scale, short-term studies, with scarce field data and context-dependent findings influenced by climate, traffic, and local materials. Differences in test protocols, polymer preparation, and reporting standards also affect result comparability. Therefore, the trends and recommendations offered should be adapted to specific regional and operational contexts.

Credit Authorship Contribution Statement

Anwer M. Ali: Conceptualization, Writing – original draft, Writing – review & editing, Supervision. Ahmed D. Abdulateef: Writing – review & editing, Methodology, Validation. Mustafa Q. Khalid: Writing – review & editing, Resources, Data curation. Rasha K. Mahmoud: Writing – review & editing, Visualization, Validation.

Declaration of Competing Interest

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

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مراجعة شاملة لاستخدام نفايات البولي ايثيلين في الخلطة الاسفلتية الساخنة: خصائص المواد وتحسين الأداء وافاق الاستدامة

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الخلاصة

يُعَدّ التراكمُ المتزايدُ لنفاياتِ البولي إيثيلين (PE) تحدّيًا بيئيًا وفرصةً للابتكار في هندسة الطرق. يستعرض هذا المقالُ أهمَّ فوائدِ استخدامِ البولي إيثيلين منخفض الكثافة (LDPE) والبولي إيثيلين عالي الكثافة (HDPE) في الخلطات الأسفلتيّة، مع التركيز على تأثيرهما في أداء المادّة الرابطة، وخصائص الخليط، والمزايا البيئية، والجدوى الاقتصادية. وتقدّم المراجعة تقييمًا مقارنًا لأنواع البولي إيثيلين، ونِسَب الإضافة، وطُرُق الخلط .أظهر تعديلُ الأسفلت بالبولي إيثيلين تحسّنًا في الخصائص الرئيسة للمادة الرابطة؛ إذ يرفع نقطة التليين، واللزوجة، والمرونة، ويُخفِّض قيمة الاختراق. وعلى مستوى الخليط، يُعزِّز البولي إيثيلين استقرارَ مارشال بنسبةٍ تصل إلى167 ٪، ويُقلِّل عمقَ التخدُّد بنسبةٍ تصل إلى70 ٪، ويرفع مقاومةَ الشدّ بنحو30 ٪ .يُوفِّر HDPE مكاسبَ ميكانيكيّةً أكبر بفضل بلوريته العالية وصلابته، بينما يمنح LDPE قابليةَ تشغيلٍ أفضل ومرونةً أعلى في درجات الحرارة المنخفضة .بيئيًا، يستطيع الإسفلتُ المعدَّل بالبولي إيثيلين إعادةَ تدويرِ ما يصل إلى طُنَّيْن من البلاستيك لكل كيلومتر، وتقليلَ استهلاكِ البيتومين بنسبةٍ تصل إلى 8٪، وخفضَ انبعاثاتِ غازات الاحتباس الحراري بنسبة 4–7٪. وتُظهر تحليلاتُ دورة الحياة وفوراتٍ اقتصاديةً تتراوح بين 5٪ و15٪ بفضل إطالة عمر الرصف وتقليل أعمال الصيانة. رغم هذه المزايا، تبقى فجواتٌ بحثيّةٌ في الأداء الميداني طويل الأمد، واستقرار التخزين، والتشقق في درجات الحرارة المنخفضة، وخطر الجسيمات البلاستيكية الدقيقة. يتطلّب سدّ هذه الفجوات بروتوكولاتِ اختبارٍ موحَّدة وتوسيعَ نطاق التحقّق الميداني. بناءً على ذلك، يبرز الإسفلتُ المعدَّل بالبولي إيثيلين خيارًا عمليًا ومستدامًا لتصميم الأرصفة الحديثة، بتحويل النفايات البلاستيكية إلى موردٍ متينٍ وفعّالٍ من حيث التكلفة وصديقٍ للبيئة.

الكلمات المفتاحية: نفايات البولي اثلين، خلطة الاسفلت الساخن، الربط الاسفلتي المعدل، الاداء الميكانيكي، الرصف المستدام، البلاستك المعاد تدويره،