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# Utilizing waste polyethylene for improved properties of asphalt binders and mixtures: A review

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## ABSTRACT

This review highlighted the effects of adding to asphalt binder and asphalt mixtures, emphasizing its growing adoption globally due to environmental and economic advantages. The analysis evaluated the performance of asphalt binders and concrete mixtures modified with different forms of polyethylene (PE), including low-density polyethylene (LDPE) and high-density polyethylene (HDPE). The review revealed that incorporating waste polyethylene significantly enhanced key properties of asphalt mixtures. Specifically, PE addition increased the softening point, viscosity, and specific gravity while reducing penetration. Furthermore, it improved the complex shear modulus, thermal stability, moisture resistance, and resistance to permanent deformation, although it might have led to a decrease in bulk density and creep rate of modified mixtures. The optimal PE content was recommended to be in the range of 4–12% by weight of binder, yielding substantial improvements in Marshall stability, flow, voids in mineral aggregates (VMA), air voids, dynamic modulus, and overall strength.

**Keywords:** asphalt cement; asphalt concrete mixtures; polyethylene; rheological properties; waste polyethylene; Marshall test; pavement performance.

## INTRODUCTION

In large countries with substantial populations, challenges such as high fuel consumption, traffic congestion, delays, and accidents are significant. This creates a pressing need to optimize resource use [1]. Since road networks often reflect a country's economic status, repurposing pre-produced waste materials can enhance road pavement characteristics, boost economic efficiency, and contribute to environmental preservation [2]. Resource utilization of waste materials varies widely; some countries recycle up to 100% of their waste, while others use far less. Effective recycling and the incorporation of waste materials into new products are crucial for optimizing resources.

Roads are a vital infrastructure component, demanding considerable resources and costs. Over the past decade, asphalt production has reached 270 million tons, with 14 million tons used specifically for asphalt binder and additives [3]. In developed countries, economic productivity and competitiveness now emphasize not only increasing production but also improving efficiency and safety. With growing populations and rising demand for goods and transportation, there is an increased need to accommodate higher axle loads and tire pressures. This necessitates advancements in road design to address these changes effectively.

Hot mix asphalt (HMA) is primarily composed of asphalt cement binder, a black to dark brown material derived mainly from petroleum refining. This binder is utilized in road construction due to its waterproofing properties and exceptional binding capabilities. However, asphalt is a complex material with some limitations, as it consists of a mix of aromatic and aliphatic compounds with high carbon numbers [4, 5]. It is predominantly made up of carbon (approximately 80%) and hydrogen (about 10%), along with smaller amounts of sulfur, asphaltenes, nitrogen, and oxygen [6].

Environmental and thermal conditions, coupled with traffic loading, are primary causes of pavement distress. Extreme temperatures can lead to severe pavement cracks and rutting. Significant efforts have been made to address these issues, with the use of additives like polyethylene (PE) showing promise in mitigating these problems [7]. Incorporating waste plastics, particularly waste polyethylene (WPE), into asphalt mixtures can provide great benefits, both economic and environmental, by extending the service life of the pavement and improving its performance [8]. Adding polymers to asphalt binders enhances the bond between binder and aggregate, thereby strengthening the pavement and improving its properties [9]. These additives or modifiers not only enhance performance, but also help reduce cost [10]. This study aimed to provide a robust foundation for advancing modern pavement construction practices and making them more environmentally friendly.

Accordingly, the utilization of WPE in asphalt mixtures has garnered increasing attention as an innovative and eco-friendly approach to enhance the properties of asphalt binders and mixtures, while simultaneously addressing the growing issue of plastic waste. This method not only improves the durability, flexibility, and resistance of asphalt but also promotes environmental sustainability by recycling non-biodegradable plastic materials that would otherwise accumulate in landfills or oceans. The practice of incorporating waste plastic into asphalt dates back to the early 1990s [11], reflecting a growing interest in sustainable construction methods. Plastics, such as PE, are characterized by their non-biodegradable nature and strong molecular bonds, making them highly resistant to natural degradation processes. This durability, while useful in product applications, poses a severe environmental challenge, as plastic waste remains in ecosystems for centuries, contributing to pollution, greenhouse gas emissions, and health risks, including cancer [12]. In particular, the large-scale accumulation of plastic waste in oceans and terrestrial environments has led to widespread environmental damage. Billions of tons of discarded plastic have entered ecosystems since the mid-20th century, often mixing with water bodies, where they cannot decompose and thus endanger aquatic life. Marine animals frequently ingest or become entangled in plastic debris, leading to disruptions in food chains and biodiversity loss. The persistence of microplastics also presents a growing concern, as they infiltrate water supplies and agricultural soils, further exacerbating ecological imbalances. One practical and effective solution to mitigate these environmental impacts is to repurpose waste plastic into useful materials, for instance via incorporating it into asphalt mixtures for road construction [2]. This approach not only prevents plastic waste from being discarded in landfills and oceans but also improves the mechanical properties of asphalt, such as its resistance to deformation, cracking, and moisture-related damage. Moreover, the addition of plastic to asphalt can improve the material's temperature tolerance, leading to longer-lasting roads that can withstand both high temperatures and heavy traffic loads. This innovative practice supports the circular economy by transforming plastic waste into a valuable resource, reducing reliance on raw materials, and promoting more sustainable infrastructure development [13].

Plastic waste encompasses various shapes originating from materials such as PE, polypropylene (PP), polyurethane (PU), ethylene-vinyl acetate (EVA), and other fibers that can be combined with asphalt binder to enhance its properties. PE, as a polymer, has been widely tested for its effectiveness in asphalt mixtures. Modified asphalt concrete containing WPE has been shown to reduce thermal cracking and extend pavement fatigue life. The impact of PE addition on asphalt mixtures, including properties such as stability, unit weight, flow, and air voids, has been extensively studied to assess its effectiveness [14, 15].

Wang et al. (2022) identified PE as one of the most significant sources of plastic waste. The study demonstrated that incorporating PE into asphalt by replacing a portion of the conventional binder not only reduces the cost of pavement construction and repairs, but also addresses common pavement problems, such as rutting and potholes, leading to more durable roads. Heydari et al. (2024) [16] demonstrated that WPE can serve as a binder modifier, enhancing the stiffness and deformation resistance of asphalt binders. The dry process, in which plastics are mixed with hot aggregates, has proven effective in improving the dispersion and swelling of polymers within the binder matrix, especially when amorphous plastics are used. Li et al. (2024) [17] found that adding recycled PE to asphalt increases binder stiffness, thereby improving its resistance to deformation. However, there are still challenges in enhancing low-temperature flexibility and fatigue performance, both of which are essential for the long-term durability of asphalt pavements. According to Mainieri et al. (2024) [18], incorporating high-density polyethylene (HDPE) as a binder modifier in airfield pavements has shown enhanced stiffness and superior moisture resistance. However, it exhibits lower ductility in comparison to conventional polymer modifiers. While WPE significantly contributes to environmental pollution, incorporating it into asphalt mixtures can reduce the binder content, a major cost factor, and enhance overall binder performance [19]. This utilization of secondary materials is substantial, offering a solution for environmental conservation and improved pavement characteristics [7].

When incorporating plastic waste material into asphalt pavement, it can be utilized through two distinct processes: wet and dry. In the wet process, plastic waste is integrated into the asphalt mixture by melting the plastic to serve as a binder polymer additive. The wet process involves incorporating plastic waste into bitumen, which acts as a binder polymer additive. This method has been shown to improve the mechanical properties of bituminous pavements. For instance, plastic-modified bitumen exhibits higher complex modulus and lower phase angle, indicating enhanced load and temperature resistance [20]. Fitri et al. [21] showed that incorporating approximately 8% plastic by weight into bitumen significantly enhances pavement strength and durability, resulting in higher Marshall Stability and improved flow values. On the other hand, the dry process involves directly adding plastic waste to the asphalt mixture either as aggregate or modifier material, where the plastic waste functions as a portion of the aggregate particles in the asphalt mix. It is essential to ensure that the plastic particles are compatible with the aggregate particles when incorporating waste plastic as part of the aggregate. During the mixing process, waste plastic softens at elevated temperatures, as indicated by Almeida et al. [22]. Bueno and Teixeira [23] found that incorporating plastics such as low-density polyethylene (LDPE) and HDPE using the dry process enhances resistance to rutting, cracking, and moisture damage. Lee et al. [24] noted that the dry process is particularly effective with smaller plastic particle sizes, which integrate more seamlessly into the asphalt mixture. However, the role of plastic in the dry process remains a topic of debate, with some research suggesting that replacing both bitumen and filler with plastic could improve cost efficiency and reduce the carbon footprint [16].

Asphalt concrete, also known as bituminous concrete, is commonly used in construction projects such as paving roads, parking lots, and airports. It involves the mixing of asphalt binder (bitumen) with aggregates, followed by layering and compaction [25]. The escalating traffic volume and rapid environmental changes necessitate exploring suitable alternatives to enhance pavement characteristics and extend its service life by implementing the modifications that ensure robust pavement performance and improve cost-effectiveness. Ramshankar et al. (2023) [26] investigated the use of construction demolition waste aggregates (CDWA) and plastic waste in bituminous mixes to develop a more sustainable pavement solution. The study found that incorporating an optimal mix of 10% plastic waste and 15% CDWA significantly enhances pavement strength, as demonstrated by improved Marshall Stability test results. This approach not only reduces the reliance on new aggregate materials but also addresses the challenges related to waste management.

Pavements are generally classified into two categories: flexible and rigid. Flexible pavements, which use bituminous concrete as the surface layer, can deflect or bend under traffic loads [27]. Bituminous concrete is composed of aggregates and bitumen, with the potential addition of various modifiers or additives to enhance its properties [28]. Flexible pavements consist of a binder material, typically bitumen or asphalt, mixed with mineral aggregates. This mixture is layered and compacted to form the pavement structure. As traffic volumes, load intensities, and seasonal temperature variations have increased, there has been a growing need to improve the performance of bituminous pavements to accommodate these changes effectively. Many studies have been focused on developing and applying different modifiers and additives to bituminous mixtures to enhance their durability and performance under varying conditions [29, 30]. However, integrating additives poses challenges, such as ensuring compatibility with the base bitumen and achieving uniform dispersion. Identifying the optimal concentration of additives is crucial for balancing performance improvements with cost-effectiveness. For example, Arif et al. [31] demonstrated that a 4% concentration of certain polymers yields optimal mechanical properties and durability. Additionally, the properties of bitumen can vary significantly based on its source, affecting the performance of modified mixtures and complicating the generalization of additive effects.

While the use of modifiers and additives in bituminous mixtures has shown promise, further research is needed. For instance, the long-term resistance to aging and economic feasibility of these modifications require comprehensive evaluation [32]. Additionally, developing new additives that enhance performance while being environmentally friendly remains a critical area for future research [33].

This review aimed to consolidate and summarize existing studies on the impact of incorporating PE into asphalt binder and mixtures. The gap in the literature that this review bridges is the need for a comprehensive analysis of the effects of PE addition on asphalt properties, considering its increasing popularity globally due to environmental and economic benefits. While previous research has touched on this topic, there is a lack of a consolidated review that systematically evaluates the performance enhancements resulting from PE utilization in asphalt applications. Accordingly, the main objectives for this review article can be summarized as follows:

- To provide a comprehensive overview of current studies on the use of WPE in asphalt binders and mixtures, summarizing findings on its effects on asphalt properties and performance.
- To determine the most effective ratios of waste PE for enhancing asphalt properties, based on a review of existing research and testing outcomes.
- To assess the long-term durability and aging resistance of asphalt mixtures modified with waste PE, including any potential impacts on performance over time.
- To conduct a detailed analysis of the performance of asphalt binder and asphalt concrete mixtures after the addition of PE. This includes assessing changes in properties such as softening point, viscosity, specific gravity, penetration, complex shear modulus, phase angle, thermal stability, deformation resistance, moisture resistance, and creep modules.

The goal of this review was identifying improvements in asphalt binder properties such as penetration values, ductility, rheological properties, softening point temperatures, rutting resistance, crack propagation control, safety levels, and blending criteria effects on asphalt binder properties.

## WASTE POLYETHYLENE (WPE) MATERIAL CHARACTERIZATION

PE is classified as an elastomer, which softens and flows when exposed to high temperatures and becomes rigid as the temperature decreases. The melting point of PE ranges between 110°C and 120°C for LDPE [34], and between 130°C and 149°C for HDPE [35, 36]. These melting points are below the typical temperature ranges used in the production of hot asphalt mixtures, making PE suitable for incorporation into asphalt concrete mixtures.

PE, represented as $(CH_2\text{-}CH_2)_n$, is a long-chain polymer of ethylene produced in various forms, including HDPE, LDPE, and linear LDPE (LLDPE). It is chemically synthesized through the polymerization of ethane, with variations in its side chains, which can be altered during manufacturing. The backbone of PE consists of single (C-C) bonds that are resistant to hydrolysis. PE exhibits relatively weak mechanical properties, with poor creep resistance and low tensile strength, though it has good impact resistance. The impact resistance increases in the following order: HDPE < LLDPE < LDPE. As the molecular weight and crystallinity increase, the mechanical properties of PE improve [37].

Various methods can be used to incorporate WPE into binders. The particle size added to the binder typically ranges from 0.3 to 0.5 mm [38]. Generally, WPE is washed, dried, and then extruded if it is not clean [11, 39]. However, if the waste is already clean, it is directly trimmed or ground. According to the reviewed studies, the percentage of PE added to the binder varies from 1% to 10% by binder weight, with a common range between 3% and 5%. The method of incorporating the polymer into the binder also varies, with mixing temperatures ranging from 150°C to 180°C, digestion times from 3 minutes to 4 hours, and mixing speeds between 120 rpm and 7200 rpm [40].

Brasileiro et al. [10] found that PE fibers or particles act as a bridge that prevents the cracks propagation. The low-temperature properties of the asphalt with PE modified binder are dependent mainly on the ordinary asphalt binder properties and PE properties in addition to the interaction between the two material particles.

PE is primarily classified based on its density and the degree of molecular branching. Several types of PE polymers can be used as additives. LDPE is a flexible and tough polymer characterized by its long, branched chains, which do not pack tightly into crystallites. As the polymer chains become more linear, the material becomes denser, as seen in HDPE, where the molecules pack more closely, resulting in increased strength. Ultra-high molecular weight polyethylene (UHMWPE) consists of linear, long chains that distribute the load along the polymer backbone, enhancing its strength. Cross-linked polyethylene (PEX) features cross-linked bonds that improve chemical resistance and high-temperature durability [41].

When ethylene is polymerized under varying pressure and temperature conditions, it can produce a wide range of polymers, including greases, oils, hard and soft waxes, as well as plastics. This variability arises from changes in molecular weight. Even at the same molecular weight, differences in the polymer's molecular structure can lead to further variation. The properties of solid polymers are influenced by their degree of crystallinity, which is affected by both the average and distribution of molecular weight, but is primarily dependent on the degree of chain branching [42].

PE has long been one of the most widely used plastics, recognized as a semi-crystalline polymer with excellent fatigue resistance, wear resistance, and chemical resistance, along with a wide range of properties. It is available in various forms [43,44]. Table 1 presents key properties of PE, as outlined by Biron (2020) [45]. The brittle point of -40°C indicates the temperature below which PE becomes brittle and prone to cracking. The water absorption rate ranges between 0.1% and 0.2%, highlighting its minimal water uptake, which contributes to its durability in various environments. PE has a thermal conductivity of 0.29 W/m·K, making it a moderately insulating material. The chemical formula of PE is $C_{10}H_8O_4$, and its specific gravity is 1.459, indicating it is relatively lightweight compared to other materials. The melting point of 255 °C reflects its high thermal stability. Figure 1 presents a scanning electron microscope (SEM) image of PE, illustrating the detailed surface morphology of this commonly used plastic. The image reveals its semi-crystalline structure, highlighting the distribution of crystalline and

**Table 1.** Polyethylene properties [45]

| Property | Value |
|---|---|
| Brittle point | -40 ºC |
| Water absorption | 0.1% - 0.2% |
| Thermal conductivity | 0.29 W/mk |
| Chemical formula | $C_{10}H_8O_4$ |
| Specific gravity | 1.459 |
| Melting point | 255 ºC |

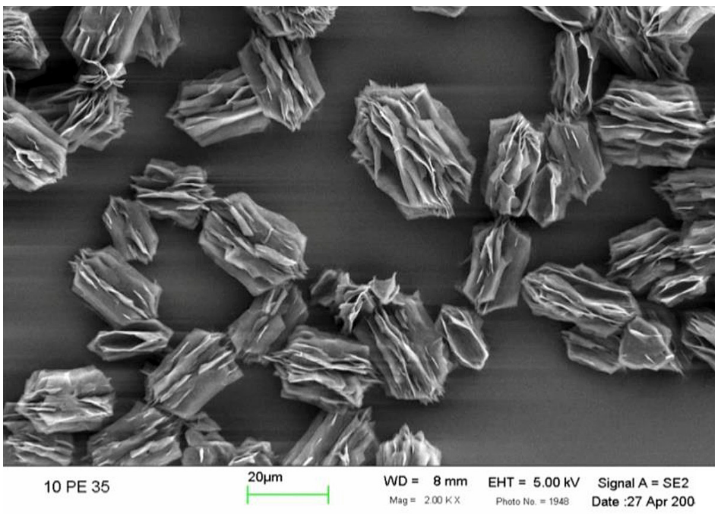


**Figure 1.** Scanning electron microscope image of polyethylene

amorphous regions within the polymer. These structural features play a significant role in determining the mechanical properties of PE, such as flexibility, toughness, and resistance to wear and fatigue. The texture visible in the SEM image reflects the arrangement of polymer chains, which directly impacts the material's strength and durability. This micrograph provides key insights into the characteristics that make PE versatile and suitable for a wide range of applications.

## UTILIZING WASTE POLYETHYLENE IN ROAD CONSTRUCTION

The use of WPE has been increasing rapidly, with the material becoming a common part of daily life. In India alone, the demand for WPE is predicted to rise by up to 129% by 2023 [46]. This increase in PE usage will inevitably result in higher levels of pollution, affecting all environments, including aquatic and terrestrial ecosystems. One of the most effective ways to reduce PE waste is through biological degradation [47]. Microorganisms colonize the surface of the plastic, forming biofilms, which contribute to the gradual breakdown of the polymer structure. The effectiveness of biological degradation depends on environmental conditions and the types of microorganisms involved [54]. Combining both methods can accelerate the overall degradation process and reduce the environmental impact of PE.

The degradation of environmentally degradable commercial PE material was investigated on two levels. First, abiotic oxidation was simulated through exposure to air, simulating the effects of compost-like environmental conditions. Second, the presence of microorganisms was introduced to observe biodegradation. Initial biofilm formation was monitored using fluorescence microscopy, followed by bacterial growth on the surface of the plastic, which was observed through scanning electron microscopy (SEM). Results indicated that microbial growth generally occurred in the presence of PE. Molecular magnification and a broadening of the molecular weight distribution were observed after preheating the material in air at 60 °C [55].

Accordingly, the utilization of WPE in road construction presents a promising solution to both environmental and economic challenges. This innovative approach addresses the escalating issue of plastic waste while enhancing the quality and durability of road infrastructure. By integrating WPE into road construction, significant environmental benefits can be achieved, including a reduction in plastic waste that would otherwise contribute to landfills or incineration. This practice supports the principles of a circular economy by repurposing waste as a valuable resource, thereby minimizing environmental impact. Incorporating PE waste into bituminous mixes improves the engineering properties of roads, leading to increased Marshall stability, tensile strength, and resistance to water and temperature variations [56]. As a result, roads become more durable and require less frequent maintenance, which in turn reduces the environmental footprint associated with road repairs [57].

Substituting traditional construction materials with recycled plastics not only conserves natural resources but also lessens the environmental degradation linked to their extraction. Furthermore, the use of WPE in road construction can lead to substantial cost savings. By decreasing the reliance on conventional materials like bitumen and aggregates, overall project costs are lowered. The enhanced durability of plastic-modified roads results in reduced maintenance expenses over time [58]. Additionally, the demand for WPE in road construction creates economic incentives for waste collection and recycling industries, stimulating job creation and economic activity in waste management and recycling sectors [60]. Overall, this approach not only addresses the plastic waste crisis, but also fosters a more sustainable and economically beneficial construction practice.

## EFFECT OF WASTE POLYETHYLENE CONCENTRATION ON THE PROPERTIES OF ASPHALT CEMENT

Integrating WPE into asphalt cement has been proven to greatly improve its properties, making it more effective for road construction. This modification enhances the mechanical characteristics of asphalt while providing an eco-friendly method for addressing plastic waste. The influence of different concentrations of WPE on asphalt properties is complex, affecting thermal stability, mechanical strength, and environmental sustainability.

## Effect on penetration

Several studies have explored the effects of incorporating varying ratios of PE into asphalt binder. Wang et al. [3] indicated a significant decrease in penetration values with the addition of PE. Melting PE to create a homogeneous mixture and adding it in suitable proportions improved the properties of the modified bitumen, although excessive amounts of PE led to segregation in the resulting mix. Specifically, adding 10% PE to an 80/100 penetration grade asphalt produced a harder binder with significantly increased penetration values. According to Rahman et al. [44], this optimum PE content of 10% yielded better results than other concentrations.

To address the storage stability issues associated with PE-modified asphalt, novel low molecular weight $NH_2$-terminated PE (NPE) was introduced. Li et al. [61] found that incorporating NPE resulted in decreased penetration values; specifically, a 3% addition led to a 28.2% reduction, while 5% resulted in a 34.1% decrease. These findings highlighted significant improvements in the NPE-modified mixtures. Kumar et al. [62] concluded that adding LDPE to bitumen decreased penetration values by 13.6%. Similarly, Sultana and Prasad [63] and Abduljabbar et al. [2] reported that using LDPE to coat aggregate particles in 80/100 grade asphalt binder also reduced needle penetration values.

In the case of high-density PE, penetration values generally decreased after its addition. Attaelmanan et al. [64] observed a 35% reduction in penetration values when 5% HDPE was added by weight, indicating significant improvements in deformation resistance. This trend was similarly reported by Sultana and Prasad [63] and Abduljabbar et al. [2]. Gupta and Singh [65] also noted that incorporating grained HDPE into asphalt mixtures, particularly at 12% by weight, significantly reduced penetration values. Punith and Veeraragavan [66] found that using reclaimed PE as a modifier decreased penetration values, with 5% PE by weight providing the best results. Vargas et al. [67] noted that the needle penetration values decreased in the modified asphalt binders that included grafted PE, a finding consistent with García-Travé et al. [68], who observed that increasing PE amounts correlated with decreasing penetration values. Furthermore, Kezhen et al. [69] modified asphalt binder using reclaimed LDPE and waste tire rubber (WTR), revealing significant decreases in penetration values after testing rheological properties with a binding beam rheometer (BBR) and dynamic shear rheometer (DSR). Additionally, Miłkowski [19] suggested that using a small percentage of PE with a catalyst could reduce the penetration values for modified asphalt by 50.7 pen at 25°C. Fang et al. [70] also indicated that higher preparation temperatures for waste PE-modified asphalt led to decreased penetration values.

## Effect on softening point

The influence of WPE concentration on the softening point of asphalt cement is a crucial factor in enhancing asphalt properties for improved performance. Incorporating WPE, including HDPE and XLPE, significantly impacts the softening point of asphalt, which indicates its temperature susceptibility and stability. Notably, the addition of HDPE – particularly when contaminated with oil – has been shown to enhance the heat resistance of asphalt mixtures. This enhancement is attributed to the formation of new physical and chemical bonds between the HDPE and bitumen, leading to an increased softening point [71]. Additionally, when HDPE plastic waste is used in concentrations of up to 5% by aggregate weight, it improves the performance of asphalt concrete, further raising the softening point and contributing to better temperature resistance [72]. Suleiman et al. [73] demonstrated that XLPE serves as an effective modifier for bitumen, significantly increasing the softening point of asphalt. The physical alterations induced by XLPE improve both the temperature susceptibility and stability of the bitumen, with notable enhancements occurring even at lower concentrations of 2% and 4% by weight of pure bitumen.

Liquefied PE oil has been used as a modifier, softening bitumen without substantially affecting its viscoelastic properties. However, its impact on the softening point is less pronounced compared to solid PE forms, indicating that while PE oil can modify bitumen, its effect on the softening point may be limited [74]. Adding PE to 80/100 penetration grade asphalt up to 10% resulted in increased softening point values due to the high softening temperature associated with the PE modifier [44]. Wang et al. [11] also observed increased softening points in asphalt binder with PE addition, which had a significant impact on the binder's performance. Bhale [75] found that adding WPE at heating temperatures of 100–160 °C improved the binding properties when softened in bitumen, resulting in a more adaptable mixture for asphalt pavement layers. This modification contributes to more durable, robust, and environmentally friendly roadways [2]. Furthermore, Mishra and Khan [76] reported a 14.28% increase in softening point with LDPE, aligning with the findings that highlight the need for enhanced performance due to increasing traffic volumes and extreme weather [2]. Both LDPE and HDPE added to 80/100 grade asphalt binder have been shown to increase softening point values when used to coat aggregate particles [2].

Hadidy and Yi-Qiu [34] concluded that modified binders exhibited higher softening points than conventional ones. Specifically, a significant increase in softening point was noted when 5% of PE was used as a modifier by weight [66]. Vargas et al. [77] reported similar findings, demonstrating a substantial increase in the softening point of asphalt binder with grafted PE as a modifier. Al-Dubabe et al. [78] observed that adding LDPE raised the softening point by approximately 3% compared to increments of 2% to 5% when 3% of PE was added. The lowest increment was recorded for an ordinary binder with a softening point of 51 °C [79], while the highest value was for a binder with a softening point of 42 °C [80]. Yan et al. [81] found that adding reclaimed LDPE and waste tire rubber to asphalt resulted in increased softening point values. Additionally, García-Travé et al. [68] noted that as the amount of added PE increases, the softening point of the asphalt binder also rises, while penetration decreases. This results in more rigid characteristics with greater resistance to permanent deformation, especially under high temperatures. To achieve higher stability in asphalt concrete and reduce thermal susceptibility, a combination of 5% PE and 2% catalyst was added to asphalt concrete. This approach yielded a softening point increase of 27.2 °C [19].

The incorporation of HDPE in asphalt binders has strengthened the rheological properties of the asphalt cement, resulting in a 69% increase in softening point when 5% HDPE was added by weight [80] (Attaelmanan et al., 2011). Similarly, the softening point of virgin asphalt was raised by 69% at a 5% weight of HDPE [80] (Attaelmanan et al., 2011). Moreover, the preparation temperature of the materials used for modifying asphalt with WPE significantly affects the outcome; higher preparation temperatures result in increased softening points, with the optimal temperature identified as 190 °C [82].

## Effect on ductility

Ductility, a measure of a material's ability to deform under tensile stress, is crucial for asphalt pavements to withstand temperature variations and traffic loads without cracking. The effect of WPE concentration on the ductility of asphalt cement is influenced by several factors, including the type of PE used, the concentration, and the method of incorporation. The type of PE, such as HDPE or XLPE, and its concentration significantly affect the ductility of asphalt. Studies have shown that while HDPE can slightly improve ductility, it is less effective than traditional polymer modifiers, like styrene–butadiene-styrene (SBS) [18]. Conversely, XLPE tends to decrease ductility, although it improves other properties like softening point and stability [73]. The optimal concentration of PE for enhancing asphalt properties, including ductility, varies. For instance, an 8% concentration of WPE has been identified as optimal for improving the overall performance of bitumen, although specific tests on ductility were not conducted [83]. Another study found that a 6% concentration of PE in an open graded friction course mix provided satisfactory performance, suggesting a balance between improved mechanical properties and ductility [84]. The use of composite modifiers, such as combining WPE with waste cooking oil (WCO), has been shown to improve the low-temperature flexibility of asphalt, which is related to ductility. The addition of WCO helps counteract the adverse effects of PE on low-temperature performance, enhancing ductility [85].

Li et al. [86] demonstrated that adding nonpolar ethylene significantly increases ductility, especially at lower temperatures. Kakar et al. [7] also found that WPE enhances the stiffness of asphalt binder at high temperatures. Mishra and Khan (2022) reported an 18.86% increase in ductility when LDPE was added. However, incorporating both low-density and HDPE into 80/100 grade asphalt binder to coat aggregate particles led to reduced ductility values [2]. While ductility remained within the minimum specification ranges, Al-Hadidy and Yi-qiu [34] observed a significant reduction in weight loss percentage, indicating improved durability compared to original asphalt.

PE mixed with asphalt binder creates a multiphase system that contains substantial amounts of unabsorbed asphaltene, significantly enhancing the viscosity of the mixture [65]. According to Tušar et al. (2022) [87], adding 5% WPE to 95% bitumen resulted in a more elastic combination at low temperatures, while higher temperatures produced a more viscoelastic binder.

Using reclaimed PE (RPE) as a modifier typically reduces ductility values, with an optimal concentration of 5% by weight yielding the best increase in ductility [66]. However, ductility decreases as the preparation temperature of WPE-modified asphalt increases, particularly when materials are prepared at 190°C [82]. Yan et al. [81] found that adding reclaimed LDPE and waste tire rubber to asphalt binder improved rheological properties by increasing complex modulus and rotational viscosity at both high and intermediate temperatures. However, no clear conclusions were reached regarding low temperatures, as the m-values and stiffness decreased with the addition of RPE and waste tire rubber (WTR). Costa et al. [88] reported a significant reduction in ductility, indicating a more brittle behavior for the modified binder at low temperatures. Specifically, a 35% reduction in ductility was observed after adding 5% PE to the binder at 25 °C, compared to a 97% reduction at 15 °C [81]. Conversely, García-Travé et al. [68] noted that stiffness and elasticity increased when reclaimed geomembrane scraps composed of LDPE and polyester fibers were utilized, suggesting that this is a preferable modifier.

### Effect on specific gravity

Lower specific gravity values for bulk density are observed as the PE content increases, primarily due to the addition of a low-density material, as reported by Sharma and Dubey [89]. However, specific gravity values can increase when PE is used as a modifier, with a significant rise occurring when 5% PE by asphalt weight is added, according to Punith and Veeraragavan [66]. Research shows that adding PE to asphalt mixtures generally increases the mix density, attributed to the "filling effect" of PE, which occupies the voids in the asphalt matrix, thus raising the overall mass per unit volume. For instance, Eme & Nwaobakata [90] found that the density of asphalt increased with higher PE content, indicating a direct relationship between PE concentration and specific gravity. Shah et al. [91] indicated that using 2% to 8% PE by binder weight enhances specific gravity and other mechanical properties of asphalt mixtures. The type and form of PE used, such as HDPE or LDPE, also significantly affect the specific gravity of modified asphalt. Different types of PE have distinct densities, which influence the overall density of the asphalt mix. Desidery & Lanotte [92] demonstrated that both HDPE and LDPE can be effectively used to modify asphalt, with each type contributing differently to specific gravity based on its inherent properties.

### Effect on complex modulus and phase angle (rheological properties)

The addition of waste PE to asphalt mixtures generally enhances the complex modulus, indicating increased stiffness and resistance to deformation. Zhang et al. [93] reported that asphalt mixtures with 2% waste PE exhibited the highest dynamic modulus, suggesting improved performance under intermediate and high temperatures. Dynamic modulus tests conducted at various temperatures and frequencies revealed that the PE-modified asphalt mixtures typically have higher modulus values than unmodified mixtures, especially at elevated temperatures. Similarly, Wang et al. [11] found that the PE-modified asphalt binders showed a comparable complex shear modulus to ordinary binders at low temperatures, but higher modulus values at high temperatures. Kakar et al. [94] evaluated the effects of blending two different types of PE with asphalt binder on thermal and mechanical behavior, resulting in significant improvements in rutting resistance. The findings showed that adding waste PE into asphalt binders considerably increased the complex modulus across all frequency and temperature ranges, indicating enhanced rutting resistance. Padhan et al. [95] reported that incorporating waste PE improves rheological properties, such as phase separation and storage stability, effectively mitigating stability issues and enhancing overall rheological performance.

Du et al. [96] examined the impact of recycled PE on future fatigue and rutting resistance for modified asphalt pavement sections designed using the Mechanistic-Empirical Method. Using a 30-year design period, their results showed a positive impact of PE in controlling predicted rutting and fatigue cracking with both dry and wet mixing processes.

Tušar et al. [97] found that adding 5% PE waste to 95% bitumen reduced the susceptibility of the binder to permanent deformation, with PE blends exhibiting better fatigue performance in terms of fatigue and stress life. Ma [98] highlighted that the storage stability of modified PE asphalt is limited; however, adding rubber plastic effectively improved compatibility and enhanced physical characteristics. Brasileiro et al. [10] reported that base asphalt binder properties at low temperatures were superior to the PE-modified binder properties, which was attributed to the use of improper testing methods. Vargas et al. [77] showed that using grafted PE at high temperatures improved the flow activation energy and rutting resistance of the modified binder. Nejres et al. [99] demonstrated that adding LDPE along with eggshell waste to asphalt improved the rheological properties of the ordinary binder. Fernandes et al. [100] reported that incorporating 5% HDPE into bitumen at medium and high temperatures enhanced fatigue and rutting resistance. Different research studies have used various modifiers to improve asphalt pavement durability, yielding distinct performance outcomes. For instance, García-Travé et al. [68] found that reclaimed geomembrane scraps composed of LDPE and polyester fibers enhanced permanent deformation resistance and fatigue life. Al-Dubabe [78] also reported that adding LDPE improved the rheological properties of ordinary asphalt binders.

The phase angle, which indicates the viscoelastic behavior of asphalt, showed no significant trend with varying PE content. However, Zhang et al. [93] observed that the modified asphalt mixture with 2% WPE exhibited the highest phase angle, suggesting more elastic behavior at this concentration. The impact of additives, such as waxes, also influences phase angle; incorporating long-chain waxes alongside PE improved the overall behavior of modified binders and enhanced resistance to permanent deformations [92]. Wang et al. [11] observed higher phase angle values at elevated temperatures. As larger quantities of PE were incorporated, there was a greater increase in the complex modulus of rigidity (G*) of the asphalt binder, along with a significant decrease in the phase angle (δ), leading to improved resistance to permanent deformation (rutting) compared to the unmodified binder [96]. Adding reclaimed LDPE and waste tire rubber into the asphalt binder resulted in a significant reduction in phase angle values of the modified asphalt [81]. Additionally, using recycled PE with 150/200 grade asphalt enhanced the binder's resistance to fatigue cracking and rutting [101].

### Effect on flash and fire point

The research specifically examining the flash and fire points of asphalt modified with polyethylene is limited. However, the studies involving similar polymers, such as polyethylene terephthalate (PET), suggest that adding such materials can influence these properties. For example, the PET-modified bitumen exhibited changes in flash and fire points, implying that similar effects could occur with polyethylene modification [102]. An optimal concentration of polyethylene can improve the thermal performance of asphalt mixtures [84]. However, excessive amounts may have negative consequences, such as surface ruptures, potentially reducing the flash and fire points [72]. Due to the low melting point of waste polyethylene, the flash and fire points of the polyethylene-modified binder decreased as the polyethylene content increased to 10% by weight [44].

## IMPACT OF POLYETHYLENE MODIFICATION ON ASPHALT MIXTURES

The use of polyethylene to modify asphalt mixtures has been extensively studied to enhance properties like stability, flow, voids, dynamic modulus, water sensitivity, deformation resistance, strength, and density. Incorporating polyethylene into asphalt mixtures has shown promising results in improving pavement performance and durability.

### Effect on Marshall stability

To improve the properties of asphalt mixtures, several studies have examined the use of PE modifiers. Rahman et al. [44] added polyethylene to 80/100 penetration grade asphalt and determined the optimum asphalt content. Tests on the modified mixtures showed that adding up to 10% PE enhanced Marshall stability, with the best results obtained at 6% PE, resulting in a 31.79% stability increase compared to ordinary asphalt mixtures [89].

Polyethylene modification significantly improved Marshall stability; for example, adding 5 wt% PE increased stability by 2,720 daN compared to non-modified asphalt [19], and other studies reported stability increases of up to 20% [103]. The use of LDPE in thin asphaltic overlays enhanced mixture characteristics and reduced costs and environmental hazards. Abduljabbar et al. [2] found that 6% LDPE provided the best stability, with a 48% increase in Marshall stability. LDPE and HDPE are commonly used as asphalt cement modifiers. Panda et al. [104] reported that adding 2.5% LDPE significantly improved Marshall stability. Issa et al. [105] found that adding 4% HDPE to HMA resulted in optimal performance under medium traffic, with Marshall stability reaching 1630.48. Polacco et al. [106] also showed that LDPE enhanced the storage stability and mechanical properties of modified mixtures. Kaka et al. [107] demonstrated that adding PE restricted particle movement, reducing storage stability issues. Mishra and Khan [76] observed considerable increases in Marshall properties and stability for the mixtures modified with waste plastic. They concluded that using PE waste to coat aggregates was more effective than using it as a bitumen modifier, resulting in improved Marshall stability and reduced maintenance and construction costs [108]. Using polyethylene to coat aggregate particles improved aggregate properties and stability, even allowing for the use of lower-quality aggregates [63]. Gupta et al. [65] found that adding PE increased Marshall stability up to 4%, after which the effect began to decrease. The HDPE content of 12% provided the best stability improvements. Kakar et al. [7] reported that waste PE used in low-noise asphalt mixes did not fully melt, acting as an elastic segment at low temperatures and enhancing deformation resistance at high temperatures. Chaudhary et al. [109] observed that adding polyethylene terephthalate up to 8% increased Marshall stability, with a decrease thereafter. García-Travé et al. [68] found that adding rubber plastic with PE formed a composite modifier that overcame storage stability issues. Punith et al. [66] demonstrated that the RPE from domestic waste enhanced deformation resistance and reduced permanent deformation. Attaelmanan et al. [80] showed that HDPE modification increased stability, with 4% HDPE providing the best results under specific mixing conditions. Awwad and Shbeeb [110] found that 12% ground HDPE provided significant stability improvement. Ma et al. [111] used maleic anhydride-grafted reclaimed PE to enhance asphalt properties, showing stability improvements at high and low temperatures. Fang et al. [82] concluded that blending WPE with asphalt resulted in better stability, particularly at high temperatures.

Although polyethylene modification significantly enhances stability and deformation resistance, potential drawbacks must be considered, including increased costs and the requirement for specialized mixing and application equipment. Moreover, further research is needed to assess the long-term performance of polyethylene-modified mixtures under different environmental conditions to ensure their reliability and effectiveness across various applications.

### Effect on flow

Polyethylene modification enhances the rheological properties of asphalt, reducing its susceptibility to temperature-induced flow. The addition of LDPE increases the flow activation energy, indicating greater resistance to flow at elevated temperatures [112]. This is crucial for maintaining pavement integrity in hot climates. Polyethylene-modified asphalt mixtures also show an increased complex modulus at high temperatures, indicating improved resistance to deformation and flow under load [113]. This pseudo-plastic behavior contributes to maintaining the structural integrity of the pavement. Adding waste LDPE to asphalt cement resulted in a 33% increase in flow [2]. Blending different ratios of LDPE with 80/100 penetration grade asphalt demonstrated superior performance compared to unmodified mixtures, especially in terms of temperature susceptibility and rutting resistance, particularly with 5% PE content [66]. A wide range of tests, including resilient modulus, dynamic creep, indirect tensile, and Hamburg wheel track tests, supported these findings. Similarly, adding HDPE up to 6% by weight resulted in optimal flow values under medium traffic loading [105], while other studies reported a decrease in flow values with the addition of PE [65, 80].

Generally, the polyethylene-modified asphalt mixtures exhibit higher flow values compared to ordinary asphalt mixtures. The use of non-ground HDPE as a modifier provided higher flow values than other forms of polyethylene, and LDPE showed a continuous increase in flow values, unlike other modifiers that started to decline after reaching a peak [110]. Considering factors such as polyethylene homogeneity, availability, and economic criteria. Lastra-González [114] utilized the dry method to blend PE with ordinary asphalt to form modified mixtures, owing to the simplicity of this process. The results indicated that incorporating PE increased the stiffness of the modified asphalt mixtures. When polyethylene was added up to 4% by weight, Marshall properties were significantly enhanced, and Marshall flow values decreased, indicating higher deformation resistance under heavy traffic conditions [115].

## Impact on voids in mineral aggregates and air voids

The addition of HDPE to asphalt mixtures has been shown to improve properties, including voids in mineral aggregates (VMA). Studies indicate that the optimal HDPE content is approximately 4% by weight of bitumen, enhancing stability and other Marshall parameters of the asphalt mixture [105]. To understand the impact of such modifications without extensive testing, theoretical and empirical models have been developed to predict VMA in asphalt mixtures. One such model, the theoretical packing density model (TPDM), provides accurate estimates of VMA, making it useful for assessing the effects of polyethylene modification [116].

The aggregate gradation significantly influences VMA, and modifications, like the inclusion of polyethylene, can alter the aggregate structure, thereby affecting VMA. Using theoretical models can help optimize these parameters for better performance [117, 118]a prediction method of VMA value ranking without testing is established in this paper. Several theoretical-empirical models about VMA corresponding to skeleton porosity, skeleton dense and suspension dense gradations are set up, respectively. According to VMA standard value, measured VCA and the established equation for calculating the passing rate of 2.36 mm or 4.75 mm sieve of skeleton dense gradation, the gradation types of several gradations to be analyzed can be determined, and then the corresponding prediction model maybe selected to predict the VMA value of each gradation. The experimental results based on AC13 (Asphalt concrete with nominal maximum particle size of 13.2 mm. The use of polyethylene in asphalt mixtures also impacts the air void content. The replacement of natural aggregates with artificial ones, including those modified with polyethylene, can help optimize air voids to meet specific requirements [119].

Adding polyethylene, particularly as waste plastic, affects the distribution and connectivity of air voids within asphalt mixtures, leading to improved performance under load. Polyethylene helps maintain the structural integrity of the mixture [120]. Under varying temperatures, polyethylene-modified asphalt mixtures exhibit different behaviors; at low temperatures, both polyethylene and the binder behave elastically, while at high temperatures, the viscoelastic nature of the binder becomes more pronounced. This influences the air void structure and stability under different environmental conditions [7]. Adding polyethylene (PE) to 80/100 penetration-grade asphalt up to 10% enhances the void characteristics of the modified mixture. Dense-graded asphalt mixed with PE has been found to offer superior stiffness, stability, and void properties for pavement construction [44]. Results have shown that adding HDPE in different ratios between 2% to 10% produces the VMA values within specifications, with air voids being optimal at 4% and 8%, respectively [105]. Similarly, adding PE keeps the VFB, VA, and VMA values within required specifications, with a reduction in void spaces observed in the mix [65].

Using HDPE and LDPE results in a slight increase in VMA. When using up to 12% HDPE or LDPE by weight, air voids remained within specifications. Generally, the air voids in modified mixtures decreased as PE content increased initially, but the relationship became directly proportional after reaching a peak [110].

## Effect on water sensitivity

Polyethylene modification of asphalt mixtures enhances water resistance by altering the surface chemistry of the asphalt-aggregate interface. This modification reduces the surface free energy (SFE) of aggregates, making them more hydrophobic and less susceptible to moisture damage. Hamedi [121] demonstrated that polymeric coatings, such as polyvinyl chloride, significantly reduce the polar SFE, thus increasing aggregate hydrophobicity and improving the coating ability of the asphalt binder. The addition of polyethylene also increases the stability and reduces the moisture susceptibility of asphalt mixtures. Bagampadde et al. [113] found that modifying asphalt with LDPE improved moisture resistance, especially when used with limestone aggregates, which showed better resistance to moisture damage compared to other aggregates. The polyethylene-modified asphalt binders exhibit varying adhesive strengths and resistance to water penetration, independent of their cohesive strength. Stuart et al. [122] emphasized that polymer-modified binders, despite having similar cohesive properties, offer different levels of moisture resistance, highlighting the role of polyethylene in enhancing water sensitivity. According to Abduljabbar et al. [2], the best moisture resistance was observed with an LDPE content of up to 6%. Meanwhile, using different ratios of HDPE with 80/100 grade asphalt resulted in lower moisture and temperature susceptibility, particularly when 5% HDPE was added by weight [80]. Overall, adding plastic waste to asphalt improves key engineering characteristics, such as rutting resistance, water damage resistance, flow value, stiffness, and indirect tensile strength. Poulikako et al. [123] reported that adding PE as a modifier to asphalt mixtures at levels below 1.5% reduced moisture sensitivity compared to unmodified mixtures. Panda et al. [104] found that water absorption and moisture susceptibility improved with the addition of 2.5% LDPE. Additionally, Chaudhary et al. [109] demonstrated that moisture sensitivity was enhanced when polyethylene terephthalate was used as an additive, particularly in its dry form.

### Effect on dynamic modulus

The polyethylene-modified asphalt mixtures demonstrate significantly higher resistance to rutting compared to unmodified versions. Laboratory tests indicate that these modified mixtures exhibit increased layer coefficients by 75–85%, reflecting improved structural performance [124]. Incorporation of polyethylene raises the softening temperature and reduces penetration, which enhances the shear strength and stability of the asphaltic concrete. This results in a more resilient pavement structure capable of withstanding greater loads without substantial deformation [19].

Timm [125] demonstrated that incorporation of polyethylene improves the modulus of asphalt mixtures at elevated temperatures, resulting in increased stresses in the underlying aggregate base. This indicates that the polyethylene-modified mixtures maintain their structural integrity more effectively than the unmodified mixtures when exposed to thermal stress. Additionally, in humid climates and under extreme temperature conditions, the use of polyethylene contributes to extending pavement lifespan by alleviating common distresses [65]. According to Poulikakos et al. [123], polyethylene asphalt mixtures exhibit a lower rate of creep and a higher modulus of creep compared to standard mixtures. However, the addition of polyethylene did not significantly enhance fatigue resistance in modified asphalt mixtures (Lastra-González, 2016). Similarly, Ma et al. [111] found that rutting resistance improved in the asphalt mixtures modified with RPE grafted with maleic anhydride (MAH) to form RPE-g-MAH. Ahmadinia et al. [8] reported that incorporating 2.5% LDPE into asphalt cement increased both fatigue life and resilience modulus. Al-Ghannam [126] observed that adding polyethylene to asphalt mixtures resulted in superior rheological properties compared to conventional asphalt. LDPE was shown to enhance the mechanical properties of asphalt, improving its resistance to high-temperature shear [80] (Attaelmanan et al., 2011). Specifically, a 59% increase in the modulus of resilience (MR) was observed with the addition of 5% HDPE, alongside a 55% increase in the modulus of creep (MQ), indicating better resistance to deformation in modified binders.

### Effect on deformation and strength

Polyethylene modification significantly improves the rutting resistance of asphalt mixtures. For example, incorporating LDPE and polystyrene (PS) into asphalt binders has been shown to reduce the potential for rutting in asphalt concrete mixtures, as demonstrated by the Hamburg wheel-tracking test results [127]. The inclusion of waste LDPE in asphalt binders improves deformation resistance against low-temperature cracking and helps control crack progression [2]. At intermediate temperatures, the indirect tensile strength of the mixtures significantly increased with LDPE addition. Moreover, polyethylene contributes to enhanced deformation resistance under heavy loads, as it reduces flow [65]. The use of the Eastman polymer modifier (EE-2) in HMA led to an impressive 87% reduction in permanent deformation, indicating a substantial enhancement in rutting resistance [128]. Furthermore, adding polyethylene waste to asphalt mixtures enhances resistance to permanent deformation. Poulikakos et al. [123] demonstrated that the PE-modified mixtures exhibited improved elastic behavior and lower creep rates compared to the control mixtures, indicating enhanced deformation resistance. The use of polyethylene in asphalt mixtures also aids in managing pavement deformation, boosting fatigue resistance, and improving adhesion between aggregates and asphalt. While the inclusion of PE increases resistance to permanent deformation, it is essential to limit its addition to no more than 5% by weight, as exceeding this threshold may result in increased rutting. Vargas et al. [77] identified that the polyethylene (PE) content significantly affects rutting resistance and low-temperature cracking, with an optimal addition of 8% leading to a considerable improvement in flexural strength. They found that grafted polyethylene enhances the rheological properties of asphalt at elevated temperatures, resulting in better rutting resistance and flow energy. Additionally, Attaelman et al. [80] reported that modified asphalt mixtures containing 5% HDPE exhibited higher tensile strength compared to conventional mixtures. Furthermore, the modulus of rupture and stiffness of these modified asphalt mixtures surpassed those of standard asphalt, attributable to the increased viscosity of the modified asphalt, which also contributed to a reduction in cracking potential at low temperatures.

Polyethylene modification also increases strength and stiffness in asphalt mixtures. Mohammed et al. indicated that LDPE enhances the stiffness, strength, and durability of asphalt, making it a promising material for pavement engineering [129]. Additionally, incorporating polyethylene glycol (PEG) in epoxy asphalt mixtures improves the strength and road performance of porous structures containing reclaimed asphalt pavement (RAP) [130]. The resilience modulus – a measure of stiffness – was observed to increase threefold with the addition of the EE-2 polymer, highlighting a significant enhancement in the structural capacity of the asphalt mixture [128].

### Effect on density

The incorporation of LDPE into asphalt mixtures has been found to decrease the density of the modified asphalt by less than 5%. This reduction is linked to changes in the free volume ratio (FVR) brought about by the polyethylene, which influences the compactness of the mixture. Additionally, the density reduction is affected by the degree of polymerization and the structural configuration of the polyethylene used [131]. In contrast, the asphalt mixtures modified with HDPE typically maintain or experience a slight increase in density compared to the unmodified mixtures. This can be attributed to the superior stiffness and bonding properties of HDPE, which enhance the interaction between aggregates and the binder, potentially resulting in a denser mixture [18, 132].

The method of incorporating polyethylene into the asphalt mixture significantly influences density as well. Wet processing methods, which involve blending polyethylene directly with the asphalt binder, generally produce mixtures with better workability and potentially higher density compared to dry methods, where polyethylene is mixed with aggregates before adding the binder [133].

Overall, the asphalt mixtures containing polyethylene typically exhibit lower bulk density values than the original asphalt concrete mixtures. The highest bulk density for modified mixtures occurs with a 12% addition of polyethylene by weight, with HDPE reaching bulk density values of up to 2.28 g/cm³ [110]. Conversely, increasing the LDPE content in asphalt mixtures leads to lower bulk density values [89].

## CONCLUSIONS

This review demonstrated the significant impact of incorporating WPE into asphalt binders and mixtures, emphasizing its benefits in enhancing pavement performance, durability, and environmental sustainability. The key findings are summarized as follows:

- Waste PE effectively improves the mechanical performance of asphalt binders and mixtures, providing an environmentally friendly solution for countries with high PE production seeking suitable disposal methods.
- The addition of PE enhances Marshall stability by up to 48%, improving the load-bearing capacity of asphalt mixtures while decreasing flow values by 15–20%, leading to better resistance to deformation and increased flexibility.
- PE-modified asphalt showed a reduction in air voids by 5–8%, strengthening compaction and reducing permeability, thereby enhancing the durability of the mixture.
- PE modification resulted in a 10–15% improvement in moisture resistance by enhancing the indirect tensile strength ratio, thereby reducing susceptibility to water damage.
- The addition of PE improved thermal stability by increasing the softening point by 10–15 °C, while decreasing penetration values by 20–25%, resulting in a stiffer binder that is more resistant to deformation.
- PE modification improved the overall rheological properties, including penetration values and ductility, and controlled crack propagation while enhancing rutting resistance.
- Enhanced resistance to permanent deformation and rutting was observed, with a 20–30%

increase in the dynamic modulus and a reduction in creep rate, contributing to a longer pavement lifespan.
- The flash and fire points of the modified binder increased, resulting in higher safety levels during handling and use.
- Blending and mixing criteria of PE significantly affect the resultant asphalt binder properties, emphasizing the need for optimized processing.
- The most suitable PE content for asphalt modification is in the range of 4–12% by weight of the binder, balancing enhanced performance with manageable processing requirements.

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