



Utilization of Waste Plastics in Asphalt Pavement Construction: A Review

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Abstract:

The surge in vehicle numbers, traffic speed and load has drastically reduced pavement lifespan and increased maintenance costs. To address this, incorporating waste plastics into bituminous binders is crucial for enhancing pavement quality and performance. Waste Plastics use in asphalt pavement has limitations, including high costs, poor aging resistance, and inadequate storage stability, hindering its future development and widespread adoption. This study aims to systematically review the benefits and drawbacks of various waste plastics in asphalt pavement, addressing a knowledge gap in existing literature. This study provides a comprehensive review of waste plastics for asphalt pavement, covering historical evolution, waste plastic selection, evaluation, and specifications. It offers insights for academia and practical guidance for pavement engineering, highlighting future research directions.

1. Introduction

The past two decades have seen unprecedented growth in global trade, driven by the need for economic competitiveness and productivity. This has led to increased demand for efficient transportation systems, resulting in heavier vehicles and higher axle loads on road networks. Consequently, asphalt pavements are deteriorating at an alarming rate, far exceeding expected life span. To address this issue, innovative solutions such as advanced roadway design, high-quality materials, bitumen modifiers, and efficient construction techniques are being employed. Researchers are also developing new methods to enhance pavement performance and extend its service life [1-3]. Plastic waste poses significant environmental threats due to its slow biodegradation. With plastic consumption skyrocketing to nearly 100 million tons by 2001 from 5 million tons in the 1950s, recycling is crucial [4, 5]. This study explores the review reusing waste plastic in road construction, building on previous research that showed promise. This study investigates the performance of asphalt mixtures with waste plastics, examining their engineering properties and potential benefits for sustainable pavement solutions [6-8].

2. Role of Waste Materials in Pavement Construction

Increased construction activity and growing municipal solid waste streams have driven research into utilizing waste materials in pavements, aiming to reduce landfill demand, conserve natural resources, and potentially lower life-cycle impacts and costs [9]. Various waste-derived materials are being explored, including reclaimed asphalt pavement, recycled concrete aggregate, crumb rubber, waste plastics, industrial by-products, crushed glass and construction and demolition wastes. Recent systematic reviews highlight both the technical benefits and limitations of incorporating these waste materials in pavements [10].

3. Major Waste Materials and Their Roles:

3.1 Reclaimed Asphalt Pavement (RAP):

Reclaimed Asphalt Pavement (RAP) is the most extensively used recycled material in flexible pavements, offering a viable means of reducing demand for virgin aggregates and binder. When properly characterized, blended with virgin

materials, and used in moderate contents, RAP provides satisfactory performance in terms of rutting and fatigue resistance. However, its performance is heavily influenced by factors such as RAP content, binder blending, and mix design methodology [11]. To avoid brittleness, high RAP contents may necessitate the use of softer virgin binders, rejuvenators, or modified mix procedures. Recent studies and field trials recommend establishing context-specific maximum RAP contents, typically ranging from 20 to 50% by mass in surface and base mixes, depending on climate and traffic conditions, and emphasize the importance of performance verification [12].

3.2 Recycled Concrete Aggregate (RCA) and C&D waste:

Recycled Concrete Aggregate (RCA) is frequently utilized in pavement base and sub base layers, and its use as a partial replacement in asphalt mixtures is becoming increasingly common, provided it undergoes suitable processing, such as cleaning and gradation control. The benefits of using RCA include reduced quarrying activities and lower embodied emissions. However, its higher porosity, attached paste, and variability can affect its strength and moisture susceptibility, presenting constraints on its use. Pretreatment methods, such as crushing, screening, carbonation, or impregnation, can enhance RCA properties for structural applications [13]. According to reviews, RCA is most reliable when used in unbound or stabilized base and sub base layers, whereas its use in surface layers requires careful quality control and often involves limits on the percentage of replacement [14].

3.3 Crumb Rubber (CR) From End-Of-Life Tyres:

Crumb rubber (CR) is incorporated into asphalt through various methods, including wet processing (binder modification), dry processing (aggregate replacement or addition), and hybrid approaches, resulting in rubberized asphalt. Research consistently demonstrates that CR-enhanced asphalt exhibits improved rutting resistance, enhanced cracking resistance in certain contexts, and potential life-extension benefits [15]. Additionally, using CR in asphalt production offers clear circular economy advantages by diverting tyres from landfills. However, challenges persist, including processing complexity, necessary plant modifications, concerns over odour and emissions during production, and variability in CR source and gradation [16]. Recent comprehensive reviews underscore the positive performance attributes of CR-modified asphalt

while emphasizing the need for standardized specifications and long-term field data to further support its adoption [17].

3.4 Industrial By-Products: Fly Ash, Slag, Glass and Others:

Industrial by-products, such as fly ash and ground granulated blast furnace slag (GGBFS), are commonly utilized as fillers, stabilizers, or cement replacements in cemented base and sub base layers, as well as in certain asphalt mixtures. Additionally, crushed glass has been explored as a partial aggregate replacement in granular layers and bituminous mixes, with its success contingent upon factors such as particle shape, polishing, and alkali-silica risks. Reviews highlight the promising potential of these industrial by-products, but also stress the importance of controlling material properties, mitigating leachate risks, and ensuring local regulatory acceptance to facilitate their widespread adoption [18].

3.5 Waste Plastics - PE, PP, PET, Mixed Plastics:

The use of waste plastics in asphalt has gained significant traction, with incorporation methods including wet processing as bitumen modifiers and dry addition or aggregate replacement. Numerous laboratory and field studies have demonstrated promising results, such as increased binder stiffness, improved rutting resistance, and enhanced fatigue life. Thermoplastic polymers, like polyethylene and polypropylene, tend to blend with bitumen when heated, boosting high-temperature stability. However, challenges persist, including potential phase incompatibility, limited low-temperature performance in certain formulations, concerns over micro plastic release, and the heterogeneity of waste streams [19]. To address these concerns, systematic reviews emphasize the need for process standardization and comprehensive life-cycle and environmental impact assessments before widespread adoption.

Life-cycle assessment (LCA) studies consistently show that using recycled materials in pavement construction yields environmental benefits, including reduced embodied energy and materials extraction. However, the magnitude of these benefits varies depending on factors such as transportation distance, processing energy, additional binder requirements, and expected service life. Recent LCA studies highlight that the circular economy advantages of recycled materials can be offset by poor mix performance or increased maintenance needs, unless the mixes demonstrate comparable service lives [18, 20]. Therefore, conducting site-

specific LCA and whole-life costing is crucial to ensure that the environmental benefits of recycled materials are realized in practice.

4. Previous Studies on Polyethylene in Asphalt Mixtures:

4.1 Environmental and Sustainability Drivers:

The growing environmental burden of plastic waste, particularly polyethylene (PE), has prompted researchers and industry professionals to explore sustainable applications of recycled plastics. As one of the most widely produced plastics globally, PE significantly contributes to environmental pollution if not properly managed. Integrating recycled PE waste into asphalt mixtures serves a dual purpose: reducing the volume of plastic waste destined for landfills or the environment and enhancing the sustainability of road construction by substituting traditional materials with recycled content [21]. This approach aligns with circular economy principles, emphasizing reduction, reuse, and recycling to minimize environmental impact and conserve natural resources. Incorporating PE waste into asphalt binders and mixtures reduces the environmental footprint of pavement materials while preserving finite natural resources like aggregates and bitumen [22]. Recent studies have evaluated the performance and environmental advantages of PE-modified asphalt, highlighting the potential of polyethylene as a sustainable bitumen modifier that can reduce maintenance demands and extend service life, contributing to environmental sustainability goals in pavement engineering [23].

4.2 Types of Polyethylene Used in Asphalt:

Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Linear Low-Density Polyethylene (LLDPE) are the most commonly evaluated forms of polyethylene for asphalt modification, due to their availability, cost-effectiveness, and beneficial mechanical properties. LDPE is characterized by its lower density and higher flexibility, whereas HDPE offers greater stiffness and strength. LLDPE, with its linear molecular structure and short branches, has also shown promise in improving mechanical properties such as stiffness and durability in asphalt mixes. The choice of polyethylene type significantly influences the mechanical performance, workability, and production of asphalt mixtures. For instance, LLDPE has been found to optimize rheology and improve binder homogeneity better than conventional LDPE in some cases [24]. Studies have

also demonstrated that HDPE-modified mixtures provide superior mechanical stability and hardness indices compared to LDPE, particularly when employing advanced mixing techniques [25]. Furthermore, optimal dosages of LLDPE have resulted in notable improvements in Marshall Stability and durability of asphalt mixes [26]. These findings indicate that the applicability of polyethylene types depends on specific engineering and environmental requirements, highlighting the importance of selecting the most suitable type for each application.

5. Improvements in Stability and Strength: Mechanical Performance Enhancements by Polyethylene:

The incorporation of polyethylene into asphalt mixtures has been consistently shown to yield significant improvements in mechanical strength indicators, such as Marshall stability and indirect tensile strength. The added stiffness provided by polyethylene reduces deformation under loads, resulting in greater load-bearing capacity and a longer service life. Research indicates that optimal polyethylene content typically falls within the range of 4-6% by weight of binder, beyond which the mixture may become brittle. Studies have demonstrated that mixes containing approximately 4-6% polyethylene exhibit marked increases in compressive and tensile strength, leading to enhanced rutting resistance and crack resistance in pavements [21]. Specifically, the substitution of HDPE in asphalt mixtures has been correlated with improved Marshall stability values and greater retention of mechanical strength under cyclic loading [27]. Furthermore, combining polyethylene with other polymers, such as polypropylene, has been shown to substantially increase mixture durability and deformation resistance, with the bonding interaction between polyethylene and bitumen playing a critical role in this performance enhancement [28].

5.1 Rutting and Permanent Deformation Resistance:

Rutting resistance is a crucial performance parameter for asphalt pavements, particularly in regions with high temperatures and heavy traffic. Research has consistently shown that polyethylene (PE)-modified asphalt mixtures exhibit improved resistance to permanent deformation, as evidenced by reduced rut depth in wheel-tracking tests and enhanced dynamic stability. Among the polymers

investigated, Low-Density Polyethylene (LDPE) has demonstrated superior performance in rut resistance compared to other polymers like polypropylene and acrylonitrile butadiene styrene (ABS), particularly at polymer contents ranging from 3% to 7% by weight [29]. The incorporation of PE into asphalt mixtures increases the mixture's hardness index and stiffness, enhancing the binder's resistance to plastic flow and deformation under loads without compromising flexibility at high temperatures. Advanced assessment methods, including flow number and dynamic modulus tests, have confirmed that LDPE- and High-Density Polyethylene (HDPE)-modified mixtures provide at least double the resistance to permanent deformation compared to control mixtures, highlighting the effectiveness of PE in mitigating rutting phenomena [25].

5.2 Fatigue and Crack Resistance:

In addition to enhancing rutting resistance, polyethylene modification can also impact the fatigue life and low-temperature cracking performance of asphalt mixtures. The incorporation of PE additives improves tensile strength and fracture resistance, which are essential for mitigating cracking, a common issue in asphalt pavements. However, the mechanical performance varies with polymer dosage, and excessive PE content (typically above 6-8%) can lead to reduced ductility, increased brittleness, and susceptibility to cracking at lower temperatures [21]. Research suggests that balanced mixtures with moderate PE content achieve an optimal balance between stiffness and flexibility, enhancing fatigue resistance while maintaining adequate crack resistance [30]. Moreover, experimental results from dynamic creep tests and semi-circular bending tests demonstrate that PET-derived additives also improve resistance to crack propagation, highlighting the potential benefits of combining PET and PE waste materials to optimize durability [31].

5.3 Complex Shear Modulus and Elasticity:

The complex shear modulus (G) of asphalt binders modified with polyethylene typically indicates increased stiffness and elasticity, contributing to improved resistance against deformation under cyclic loading at elevated temperatures. However, some studies have noted an initial decrease in shear modulus with increased PE content, potentially due to phase separation or variations in polymer dispersion morphology affecting binder homogeneity [21]. This complex behavior highlights the importance of careful dosage control and

thorough evaluation of polymer-binder compatibility to achieve optimal performance. Nevertheless, the increased elasticity resulting from the polymer's thermoplastic properties enhances the binder's recovery capabilities following load application, thereby extending pavement life by reducing permanent deformations. Research has also shown that these rheological properties evolve over time, with PE modifications stabilizing the binder's stiffness and elastic response under thermal aging conditions, as demonstrated by studies involving controlled curing and temperature treatments [32].

6. Evidence from Long-Term Field Evaluations: Field Performance and Long-Term Durability.

Long-term field studies have validated laboratory findings, showing that polyethylene-modified asphalt mixtures meet or exceed cracking thresholds for high-traffic roads, confirming their suitability for demanding applications [26]. Modeling using industry-standard software has also demonstrated that PE-modified pavements achieve comparable or superior durability relative to conventional SBS (Styrene-Butadiene-Styrene) modified mixes, indicating their potential for widespread adoption. Furthermore, extended field monitoring has revealed reduced deterioration rates, resulting in lower maintenance frequencies and lifecycle costs. These findings collectively support the use of polyethylene-modified asphalt mixtures as a durable, cost-effective, and sustainable solution for infrastructure development.

6.1 Thermal Cracking and Climate Adaptability:

Polyethylene-based modifications have been proven to enhance the performance grade (PG) of asphalt binders, expanding their application range to high-temperature environments and reducing thermal cracking. For instance, a biopolymer-modified asphalt incorporating HDPE and pine resin achieved a significant PG increase from 64 to 82, indicating substantial improvements in resistance to rutting and thermal cracking [33]. Additionally, research on curing protocols tailored to hot climates, such as in extreme environments like Iraq, has shown that controlled PET dosages combined with adequate curing can enhance stability and material integrity. These findings highlight the potential of polyethylene-based modifications to improve asphalt performance in challenging environmental conditions, making them suitable for infrastructure development in diverse regions [32].

6.2 Economic and Sustainability Outcomes:

The use of recycled polyethylene as a modifier offers substantial cost savings compared to virgin polymers. When combined with the extended service life and reduced maintenance requirements of PE-modified asphalt, this approach supports sustainable infrastructure development. The economic benefits, along with environmental advantages such as reduced waste and resource conservation, highlight the value proposition of PE-modified asphalt [34]. Furthermore, incorporating recycled plastics into asphalt aligns with green construction mandates and circular economy initiatives, presenting a holistic approach to addressing environmental challenges and infrastructural needs. This integrated strategy promotes sustainable development, reduces waste, and conserves resources, making PE-modified asphalt an attractive solution for environmentally conscious infrastructure projects [35]. The construction industry's growing demand for sustainable solutions has sparked interest in using recycled materials for building as well as pavement construction, promoting environmentally friendly practices to enhanced asphalt pavement materials is crucial for improved durability and performance.

7. Conclusion

Waste polyethylene offers excellent performance and economic benefits, but its limitations, such as poor storage stability and compatibility, need to be addressed. Future research should focus on cost-effective methods to enhance stability and explore multi-plastics composite modification. Additionally, investigating the recyclability of waste polyethylene is crucial for promoting sustainability in the road industry. The use of recycled polyethylene as a modifier offers substantial cost savings compared to virgin polymers. Enhancing the asphalt pavement materials is crucial for improved durability and performance. Polyethylene-modified asphalt mixtures exhibit improved resistance to permanent deformation, as evidenced by reduced rut depth in wheel-tracking tests and enhanced dynamic stability.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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