Emerging Downstream Plastic Waste Disposal Solutions in the United States: A Review of Waste Plastic Modified Pavement

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Abstract

Plastic pollution has been a persistent and urgent global crisis that has surpassed the capacities of current waste management systems. With only about 5-6% of global plastics currently being recycled and microplastic identification in human and environmental samples, there is an urgent need for alternative sustainable waste management systems. A recent downstream recycling technology that has gained recognition is waste plastic-modified roads. This review aims to provide a comprehensive evaluation of plastic roads as a transitioning alternative from downstream waste mismanagement to a circular plastic economy. Factors, including mechanical performance, various modifier contents, potential environmental impacts, economic feasibility, and sustainable ethics, are examined and contextualized within U.S. environmental regulations. Main findings revealed that certain material compositions exerted beneficial effects on the pavements durability and rheology; however, severe variability arose in storage stability resulting from poor adhesion between polymer and asphalt components. Longitudinal environmental impacts were uncertain, primarily due to unclear long-term circularity of plastic roads, inconsistent findings across toxicity studies, and the absence of environmental benchmarks. Future areas of research should focus on the mitigation of storage stability issues, chemical toxicity content, reclaimed asphalt pavement (RAP), and the establishment of MP release thresholds and relevant environmental standards.

Keywords: Asphalt Binder Modification, Polymer Modified Bitumen, Waste Plastic Modified Asphalt, Rheological Properties, Microplastics, Ecotoxicity, Sustainable Waste Management.

1 Introduction

The urbanizing and convenience-driven consumer market has necessitated the rapid expansion of the U.S. plastics industry. Since its invention in 1907 as Bakelite, plastic has revolutionized virtually all industries, including medicine, aerospace, automotive, construction, electronics, and beyond.[1] As a synthetic polymer, plastic offers a unique combination of properties such as lightweight, durability, flexibility, and cost-effectiveness for production. The versatile and economical nature has led to plastic becoming the second most produced material aside from paper. In parallel, this proliferation of the plastic economy has escalated adverse environmental destruction into a staggering global issue.[2]

Due to a lack of biodegradability, the safe disposal of plastics remains a challenge. Currently, only around 5-6% are successfully recycled.[2][3] Plastics that are too damaged or have incompatible melting temperatures are typically managed through end-of-pipe methods. According to the National Renewable Energy Laboratory, approximately 85% are landfilled and 10% are incinerated, which doesnt even account for the 22% of global plastics that are mismanaged.[4][5] Plastic pollution poses an immense threat to public and environmental health. Over time, plastics break down into smaller particles, reaching microscopic sizes, known as micro- and nano-plastics.[6] Unlike virgin polymers, plastics contain elevated amounts of chemical additives that are harmful to ecosystems, especially in microplastic form. These chemicals can leach into soil and bodies of water, accelerating ocean acidification, contaminating nutrient cycles, and threatening biodiversity.[7]Studies show that microplastics have already been found in the soil, air, oceans, and human placentas.[8] Microplastics pose extreme toxicity risks when present in the human body, causing increased hormone fluctuation and risk for neurodegenerative diseases and certain cancers.[9][10]

With plastic waste projected to triple current production rates and accumulate 140 million metric tons by 2060, there is a rapidly growing disparity between production and disposal.[11] U.S. landfills are increasingly burdened by non-recyclable and single-use plastics, contributing to capacity strains. In 2023, the Illinois Environmental Protection Agency (EPA) forecasted that state-wide landfill capacity would be reached in approximately 19 years.[12] End-of-pipe landfills are becoming increasingly less feasible options for plastic waste disposal, and alternative incineration methods are highly inefficient and unsafe replacements.[13] This necessitates the development of alternative sustainable waste management systems to replace current end-of-pipe solutions. One promising downstream recycling approach is waste plastic-modified roads. The concept of plastic roads involves repurposing waste plastics by integrating them into road infrastructure using similar methods to traditional paving, but with the key addition of waste plastic. By repurposing plastic waste into pavement, plastic roads introduce a circular plastic economy.

There are two commonly utilized mixing methods in plastic road engineering: the wet process and the dry process. These approaches resemble those used to create widely commercial polymer-modified roads.[**zahoor**] The wet process for plastic roads involves mixing waste plastics into liquid asphalt binder, resulting in a waste-plastic modified asphalt binder, which is then laid over quarry aggregates. The dry process entails the incorporation of waste plastics as plastic-modified dry aggregates. Waste plastic is melted and coated over molten aggregates, and when solidified, forms a dry aggregate road modifier.[14][15] It is also worth noting the mixed process of plastic road paving, which, although it is not a standardized construction method like the dry and wet method, will be examined in this review. The mixed process combines the mixing methods of the dry process and the lower melting temperature used in the wet method. The plastic partially melts to form a coating around the aggregate, similar to the results of the dry method, except with the use of wet process-affiliated plastics. This process tends to experience less severe storage stability issues than the wet process. See Figure 1.

Currently, multiple states in the United States have implemented plastic road pilot programs, including Missouri, Michigan, California, Hawaii, Pennsylvania, Virginia, and, recently, New York.[16, 17, 18, 19] However, these pilot programs are relatively new, and comprehensive life cycle analyses to evaluate their performance and environmental impacts have not been conducted yet. Though some countries in Asia have officially adopted plastic roads as the new pavement standard.[20]

Plastic roads intend to alleviate the burden on current municipalities and enable safer and more sustainable plastic waste management. This review examines the potential of waste plastic-modified roads as an alternative downstream solution in transitioning to a circular plastic economy in the United States. Key areas of focus include pavement performance and materials properties, economic feasibility, potential environmental impacts, ethical implications, and environmental policy. By synthesizing country-specific and multisectoral factors, this review aims to clarify the developmental scope and long-term viability of plastic road implementation in the United States and evaluate whether it constitutes a viable downstream solution. Additionally, it outlines future areas for research and the development of environmental strategies to advance sustainable plastic waste management strategies.

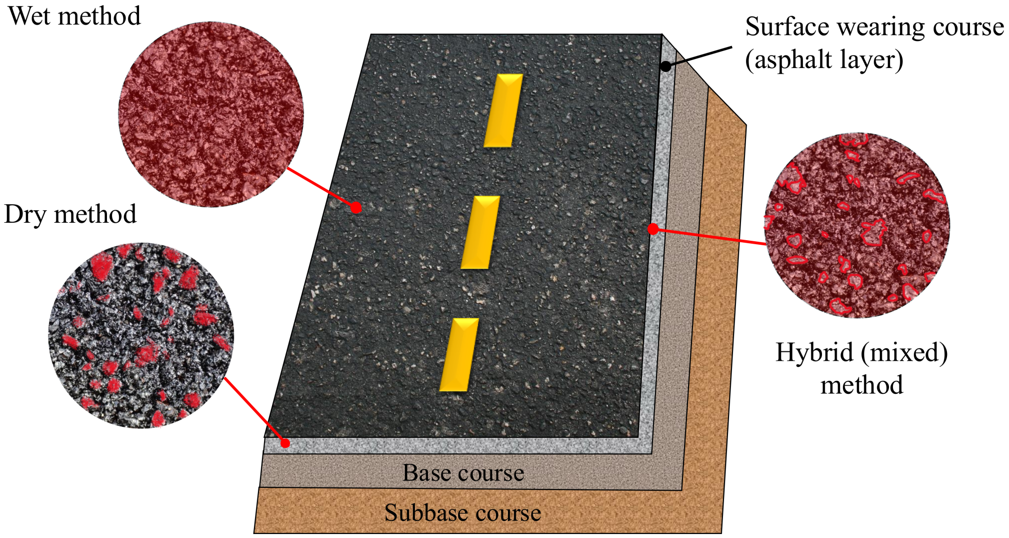

Figure 1: Diagram of pavement course as well as wet, dry, and mixed method asphalt, where red shaded regions represent plastic-modified content. Dry method contains plastic in form of dry aggregates, while wet method contains plastic in its binder and mixed method comprises of partially coated plastic aggregates and plastic-modified binder.

2 Discussion

2.1 Environmental Impact

A potential risk associated with incorporating a persistent environmental pollutant into public infrastructure is the abrasion of microplastics (MPs) off the road over time. Although pilot programs are currently observing for signs of this behavior, field studies have not been implemented long enough to conduct a complete life cycle analysis.[20] The oldest pilot program in the world in Chennai, India, has only been operational for 21 years; by comparison, asphalt has a typical lifespan of 15-25 years, and modified pavements (e.g., polymer-modified bitumen) extend service life for about 6 additional years.[21, 22, 23] In fact, life expectancy projections for plastic-modified roads are three times longer than those for unmodified asphalt roads.[20] Additionally, quantifying microplastic (MP) release from roads in real-world environments remains challenging primarily due to the difficulty in distinguishing road-derived MPs from those originating from tire wear, as well as interference from external environmental factors that may reduce the accuracy of MP collection and measurement.[24, 25, 26, 27] Given the limitations in field study data, this paper alternatively reviews two laboratory methodologies that model potential MP release from plastic road samples. Specific studies on potential MP release of plastic roads remain limited, and only in recent years have methodologies to model this phenomenon started to emerge.

Enfrin et al. conducted a comparative assessment of the wet and dry methods of plastic road construction, where various plastic types and dosages were observed under environmental stress factors such as duration, water pH, and temperature.[28] Recycled low-density polyethylene and linear low-density polyethylene (rLDPE/LLDPE) and commingled recycled polyethylene and polypropylene (crPE/PP) were each incorporated into a bitumen matrix via wet mixing (w) and evaluated at plastic dosages of 1, 2, 4, and 6 weight percent (wt%) of bitumen, respectively. Recycled polyethylene terephthalate (rPET) and recycled acrylonitrile butadiene styrene (rABS) were combined into the asphalt matrix as plastic-coated aggregates via dry mixing (d). They were evaluated at concentrations of 0.5, 1, 2, and 4 wt% of asphalt. Methodology was based on wet track concrete abrasion tests, utilizing a wet track abrasion machine to aid in the quantification of MPs.

Enfrin et al. observed no correlation between MP loss and increasing temperature in rABS (w), where a consistent release rate of 0.43 ś 0.07 g/mš was maintained. On the other hand, lower temperatures facilitated notably high MP release rates in the rLLDPE/LDPE (w) sample. At 5řC, the release rate was nearly triple that observed at 25řC. This trend was attributed to potential brittle tendencies of rLLDPE/LDPE (w) at low temperatures, which increase susceptibility to fatigue and abrasive mechanical stress.[29] This could increase the likelihood of MP shedding, hence the observed result.

MP release from the wLDPE/LLDPE sample exhibited no correlation with water pH values, maintaining an average release of 0.53 ś 0.15 g/mš across a pH range of 4 to 10. The absence of a clear release trend under both acidic and alkaline conditions suggests a high resistance to adhesion weakening. This presents a significant improvement over traditional binders, which are sensitive to moisture susceptibility damage under pH extremes, particularly those caused by acid rain.[30, 31]

Over a duration of 60 minutes, a logarithmic and linear MP release trend was observed for rLDPE/LLDPE (w) and rABS (d), respectively. Enfrin et al. concluded that this distinction was likely due to the different dispersions of waste plastic in the two methods. In the wet method, the polymer-modified binder is poured over the aggregate layer and creates a thin bitumen film layer, which tends to experience frequent direct contact with the abrasion head at the beginning of the simulation. This physical architecture explains the rapid initial release rate of 0.048 g/mš/min at the 5-minute mark, which then slows down over time, and the wheel abrades through the top bitumen layer and into the asphalt core, where rLDPE/LLDPE (w) concentration is lower and more evenly dispersed. In comparison, the plastic content in the dry method is more homogeneously distributed throughout the entire asphalt matrix, resulting in a linear MP release trend.

rLDPE/LLDPE (w) initially exceeded rABS (d) by three times more MPs released, but was then surpassed by rABS (d) at the 30-minute mark. However, beyond the 30-minute mark, the MP release of rABS (d) surpassed that of rLDPE/LLDPE (w). This shift suggests differing long-term release behaviors between rABS (d) and rLDPE/LLDPE (w) modified mix types. Theoretically, dry-mixed pavements may pose a higher potential MP contribution to the environment than wet processes, as they accommodate higher volumes of plastic, approximately 1.5 times more than wet-mixed roads. Nevertheless, MP release trends, such as the crossover points of the logarithmic and linear trends observed in wet- and dry-mixed samples, should be evaluated in the context of road resurfacing frequency. A research study by Li et al. asserted that road resurfacing typically occurs every 11-26 years, depending on road traffic and volume.[32] Following resurfacing, in which the top layer of bitumen is restored, it is reasonable to infer based on simulation results from Enfrin et al. that MP release of wet-mixed roads would initially spike, then decline as the surface layer weathers, and resurge with subsequent resurfacing. Although dry-mixed asphalt introduces more plastic content into the asphalt matrix overall, its higher recycling efficiency and uniform dispersion of its plastic constituents, rather than a surface-concentrated dispersion found in wet-mixed roads, may reduce long-term MP release risk compared to the wet method.[28]

Boom et al. extended the scope established by Enfrin et al. by using a hybrid mixing method of plastic roads.[33] Commercially produced ethylene-vinyl acetate (EVA) and styrene-butadiene-styrene (SBS) polymer-modified roads were utilized as environmental benchmarks to contextualize plastic road MP release, given the absence of such standards in current environmental guidelines. Two asphalt samples were tested, one of which was a combination of rLDPE/LLDPE (68/32 wt%, respectively), and the latter consisted of commingled recycled polyethylene and polypropylene plastic (crPE/PP). Both samples were prepared using the hybrid mixing method (m).

Since Boom et al. employed the MP extraction procedure specified by Enfrin et al. (e.g., testing conditions, variables, and materials), results from both studies could be reliably compared under similar conditions. For comparison and visualization purposes, plastic content data that involved wet process mixing were converted to the same units used for the dry process (wt% of total asphalt mix) and plotted in Figure 2. In wet-mixed asphalt, Enfrin et al. reported that bitumen constituted about 5.1 % of the asphalt mix, so this proportion (0.051) was used as the conversion factor.

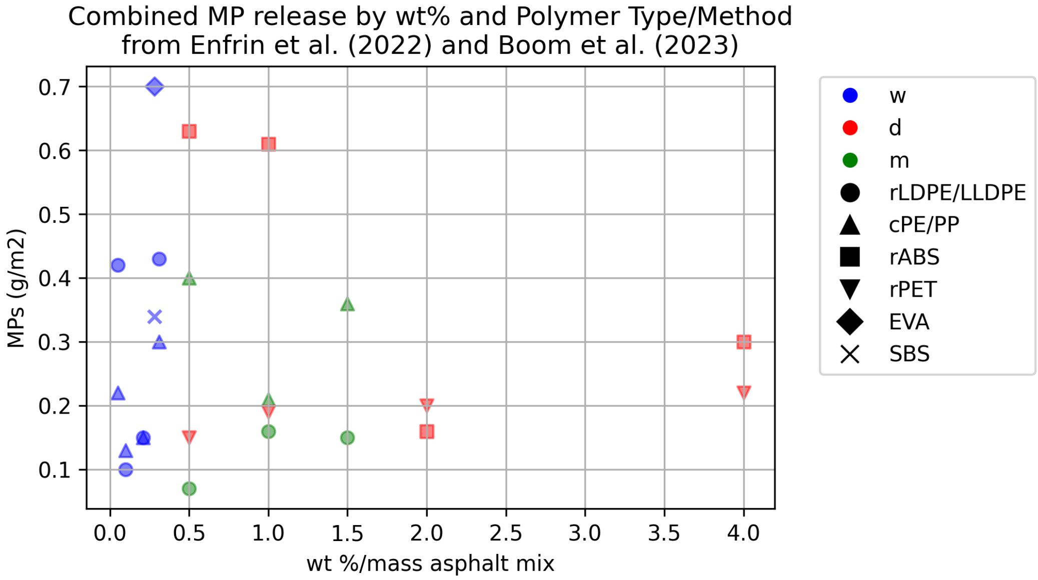

Figure 2: Combined MP release data by plastic content from Enfrin et al. and Boom et al., (excluding error bars). It reveals a logarithmic trend with increasing plastic content in mixed method rLDPE/LLDPE and dry method rPET, while other plastic-modified samples exhibit no correlation.[28, 33]

Over a plastic content range from 0.05–0.31 wt% of asphalt, MP release of rLDPE/LLDPE (w) and rPE/PP (w) exhibited no clear relationship with plastic content and followed similarly high fluctuation patterns, with rLLDPE/LDPE (w) showing the largest fluctuation range and least consistent results. Enfrin *et al.* and Boom *et al.* observed that at dosage ranges from 0.5–1.5 wt% of asphalt, mix-processed rLDPE/LLDPE (m) released the lowest quantities of MPs in the dataset, following a slightly irregular logarithmic trend with MP release rates ranging from 0.07 to 0.16 g/m^2. A similar trend was observed for rPET (d) by Enfrin *et al.*, but with slightly elevated MP release, ranging from 0.15 to 0.22 g/m^2. This logarithmic trend suggests minimal influence on MP release as the plastic content approaches its respective upper dosage thresholds for rPET (d) and rLLDPE/LDPE (m). Across the overall graphical relationship with plastic content, all recycled plastic-modified samples demonstrated lower MP release than the EVA benchmark; however, the samples rLDPE/LLDPE (w), rABS (d), and cPE/PP (m) exceeded the SBS benchmark during certain periods. Overall, the two simulations of MP erosion demonstrated that rLDPE/LLDPE (m) and rPET (d) released the lowest amounts of MPs and exhibited the most evident correlations between MP release trends and plastic content, both following logarithmic curves. Boom *et al.* suggested that this trend occurred due to the larger surface area of rPET (d) and rABS (d) in contact with bitumen when particle size was reduced. This may lead to increased adhesive interactions between the binder and the polymer-modified aggregate interface compared to other mix configurations. This is beneficial, given that interfacial adhesion influences the formation of air voids, which in turn affects properties such as water permeability that govern key mechanical characteristics, including abrasion resistance.[34, 35, 36, 37] This phenomenon was also revealed in the present analysis, where MP release of rPET (d) and rABS (d) was mainly driven by the aggregate surface area in contact with bitumen, suggesting a positive correlation between interfacial interactions among plastic additives, bitumen, and MP abrasion. Given that rPET (d) and rLDPE/LLDPE (m) simultaneously released the lowest amounts of MPs while accommodating moderate and upper plastic content thresholds tested in the study, this indicates that larger quantities of plastic can be recycled into road infrastructure per unit length while minimizing MP pollution relative to other mix designs and plastic incorporation methods.

Duan *et al.* investigated rLLDPE and recycled polyethylene (rPE) pellet-modified binders compared to virgin PE powder in a bitumen binder and quantified MP release under conditions of extreme rutting and moisture.[38] Dosages of 2.5 wt% rLLDPE pellets, 1 wt% rPE pellets, and 1 wt% virgin PE powder (relative to bitumen content) were incorporated via the dry method. To simulate MP abrasion, the Hamburg Wheel Tracking Test (HWTT) was employed for the modified asphalt samples over 40,000 wheel passes, which is approximately twice the amount specified by HWTT testing guidelines. This represents an upper-limit scenario for MP release by up to three orders of magnitude. MP particles were filtered and collected using a series of gravitational, density-based, and chemical separation methods. The results suggested that 1 wt% rPE pellets (d) and 1 wt% virgin PE powder exhibited notably higher MP release rates than 2.5 wt% rLLDPE pellets (d). Estimated release rates were 0.17–0.26%, 0.0674–0.102%, and 0.0355–0.053% of the total embedded plastic content, respectively. These data were extrapolated to infer a maximum lifetime MP generation of approximately 2600 g and a minimum of 355 g, corresponding to 1 wt% rPE pellet (d) and 2.5 wt% rLLDPE pellet (d) asphalt mixtures, respectively.

Based on HWTT results for rLLDPE content at 2.5 wt% of asphalt, Duan *et al.* extrapolated that a theoretical 1000 m plastic road with a 10-year service life would exhibit an annual MP release rate of 0.0053% of the total embedded plastic content. This corresponds to an upper limit of 2209 g MP/km/year for a four-lane interstate road and 920.6 g MP/km/year for a two-lane local road. To contextualize this level of MP release, the authors compared emissions from plastic-modified asphalt to those generated by tire wear. Their findings indicated that the upper limits of road-derived MP emissions were approximately half of those produced by tire abrasion, suggesting that the pollution potential of plastic-modified roads remains substantially lower than that of existing transportation-related sources, particularly given that the simulation overestimated emissions by up to three orders of magnitude relative to projected real-world conditions.

Resistance to abrasion and overall wear-inducing mechanical stress strongly correlates with the potential for MP release. When subjected to environmental wear, including abrasion, rutting, and moisture damage, plastic road samples experienced MP erosion. However, these studies represent accelerated, upper-limit models of potential lifetime MP erosion. Duan *et al.* modeled results that were up to three orders of magnitude higher than expected under field conditions.[38]

These studies provide baseline insights into the MP release potential of plastic roads. MP release appears to depend on the engineering properties of the pavement, particularly bitumen–aggregate adhesion, which governs erosion behavior under abrasive and environmental stress. These properties vary with plastic content, construction method, and plastic type, which are discussed in detail in the performance section of this article. Results and extrapolations from previous studies indicate reduced wear-induced MP emission potential relative to commercially available polymer-modified binder (PMB) roads and virgin polymer-modified pavements. However, not all dynamic environmental scenarios were modeled; therefore, further experimentation is required to assess the effects of aging and other long-term factors that cannot be rapidly simulated. Additionally, the absence of established environmental thresholds for MP release complicates risk interpretation. Standardized criteria should be developed to enable consistent environmental evaluation and support decision-making processes.

Volatile organic compounds (VOCs) are often emitted during the construction and laying of traditional hot-mix asphalt (HMA) pavement, raising concerns about worker exposure to carcinogenic fumes.[39] Non-carcinogenic fumes, including polycyclic aromatic hydrocarbons (PAHs), have also been reported at elevated production temperatures, particularly benzo[a]pyrene.[40, 41] Other VOCs and PAHs observed include benzene, trichloroethylene, tetrachloroethylene, styrene, and dibenz[a,h]anthracene, although these generally pose lower carcinogenic risks.[42] Boom *et al.* reported that VOC and PAH emissions increased with processing temperature but decreased with increasing plastic content. Variation in carcinogenic and lifetime risk profiles was observed between conventional and plastic-modified binders. Specifically, binders extended with waste plastic exhibited benzo[a]pyrene emissions comparable to or lower than those of C170 and C320 binders, but generally higher than those of the A35P binder.

Plastic toxicity may increase with successive recycling cycles due to the accumulation of non-intentionally added substances, such as external chemical contaminants.[43, 44, 45] This is particularly relevant for non-recyclable waste plastics, including copolymers or chemically degraded plastics, which often exhibit heterogeneous polymer compositions and elevated additive or contaminant content.[46] Reclaimed asphalt pavement (RAP) is frequently associated with elevated concentrations of PAHs and toxic metals formed during incomplete combustion processes.[47] Because these compounds are primarily physically dispersed within the asphalt matrix via non-covalent interactions, recent studies have raised concerns regarding their mobilization following the addition of maltene-based rejuvenators, potentially leading to chemical leaching into soil and groundwater.[48, 49] Studies examining chemical leaching from RAP pavements and stockpiles report inconsistent findings. Some investigations suggest no significant groundwater leaching of PAHs from RAP modified with waste plastic or conventional polymers,[50] while others report detectable metal leaching. In many cases, observed concentrations did not exceed U.S. EPA environmental thresholds,[51, 52, 53, 54, 55, 56] though some studies identified elevated leaching of PAHs and metals such as Pb, Zn, Cu, As, Mn, and Sb, indicating potential environmental risks.[47, 57, 58, 59]

There are limited findings regarding RAP performance over multiple rejuvenation cycles. Di Mino *et al.* reported comparable mechanical properties for RAP asphalt modified with recycled hard plastics and graphene nanomaterials over three rejuvenation cycles, with similar rejuvenator dosages required at each stage, suggesting minimal performance degradation.[59] Nonetheless, uncertainties remain, as the literature reports mixed results regarding long-term RAP mechanical performance.[59, 60]

Significant gaps persist concerning the physical and long-term limitations of RAP within circular pavement systems. While multiple life-cycle assessments have been conducted, the feasibility of continuous rejuvenation without extended field validation remains uncertain. If the number of viable rejuvenation cycles is limited, end-of-life disposal becomes problematic. Even assuming minimal chemical leaching, these materials may pose hazardous risks comparable to those of current disposal practices, particularly given the challenges associated with managing large volumes of chemically contaminated waste. Persistent toxic compounds often require active physical intervention and targeted chemical stabilization strategies. Moreover, the environmental toxicity of plastic-modified pavements during service life remains insufficiently understood and necessitates comprehensive, long-term life-cycle assessments encompassing chemical leachates and microplastics.[61, 62]

2.2 Performance

Polymers are widely commercialized modifiers used in pavement engineering. Their use has been noted to improve asphalt durability by enhancing resistance to thermal stress and extending pavement lifetimes, resulting in higher-performing roads.[63, 64] Still, there remains potential for improved mechanical performance, environmental contribution, and greater recycling applications; hence, the exploration of circular plastic modifiers. Commonly tested post-consumer plastics and polymers for road modification include LDPE, high-density polyethylene (HDPE), PP, polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), ABS, and PET. Key performance metrics of asphalt include rheology, moisture susceptibility and aging, viscoelasticity, and morphological and storage stability. There are three different types of polymeric modifiers: plastic, thermoplastic elastomer, and reactive polymer. Inert plastics and thermoplastic elastomers are combined into asphalt via physical mixing.[65] The inert polymers are physically mixed and dispersed into a bitumen matrix to achieve a homogenous state, which is maintained via preferential, Van der Waals interactions and adsorption between bitumen and aggregate components.[15, 66, 67] However, since the polymer-bitumen interface is not chemically bonded, storage stability issues for polymer components dissociating from the mix at elevated temperatures have been frequently reported.[68, 69] Casey et al. observed this phenomenon in PP modified bitumen, where the PP migrated to the surface during high temperature storage, and formed a film layer of pure PP at the bitumen surface that could not be reintegrated into the asphalt. This behavior compromises the durability and service life of the pavement and may inhibit wear-induced MP erosion as previously discussed.[70, 71] Reactive polymers, on the other hand, undergo chemical modification, in which prepolymers are reacted with the asphalt components to form chemical structures composed of polymer and asphalt constituents. This modification method tends to improve high-temperature storage stability due to the chemical bonding between the polymer and asphalt molecules, making them less vulnerable to direct physical changes.[63, 71, 72, 73]

2.2.1 LDPE

LDPE is a frequently assessed waste thermoplastic pavement modifier. It is a high-molecular-weight homopolymer, characterized by its long, linear, and flexible polyethylene chain. Compared to denser forms of polyethylene, it has a lower strength and temperature resistance, which makes it suitable for consumer-based applications in single-use packaging and containers. Commercial LDPE is most often incorporated into pavement via wet-mixing due to its compatible low average melting point of 105120 řC.[15, 74, 75, 76] The most notable and consistently observed improvements associated with rLDPE-modified asphalt are moisture susceptibility and high-temperature deformation resistance.[77, 78, 79] On the other hand, low temperature performance and stiffness remain variable. Studies show increased stiffness at lower temperatures; however, some have revealed those effects to be excessive, noting retained stiffness and flow resistance even at warmer temperatures. This concerns pavement flexibility and susceptibility to brittle fracturing.[26, 78, 80, 81] Several studies attributed an increased viscosity compared to neat binders, and in certain cases, gel-like behavior with the addition of rLDPE.[82, 83, 84] This phenomenon is likely due to increased polymer chain entanglement, resulting from swelling of the plastic components and subsequent formation of a 3D plastic-asphalt network.[15, 85, 86] Elasticity is similarly affected by this molecular-level physical crosslinking, though research results are not entirely aligned. Punith et al. reported a poor elasticity with the sole use of rLDPE; several other studies noted an opposite, beneficial effect.[87] Notably, Zoorob and Suparma and Dalhat et al. consistently reported a 14% increase in elastic recovery, while the latter study also showed a positive correlation between rLDPE content (28 wt% of bitumen) and elastic performance.[78, 88] Ho et al. suggested that the variations among different studies can be primarily caused by varied molecular weight and molecular weight distributions, which influence the degree of entanglement.[89] Other factors related to chemical structure, such as polarity and crystallinity, also have pronounced effects on the compatibility between polymer and asphalt components, which governs related viscoelastic and rheological properties.[15, 85, 90] rLDPE that has a broad molecular weight distribution exhibited higher viscosity with increasing plastic content, while an inverse relationship was observed in PE wax that had a much narrower weight distribution. Compared to base asphalt, rLDPE modified binder exhibited higher viscosity overall with high-molecular-weight rLDPE, in particular, harboring the highest viscosity to its lower-weight counterpart. Due to the nature of the physical modification process, phase separation issues were observed as plastic content dosage increased to 4 wt% asphalt.[91] Similarly, Naskar et al. noted poor stability and phase separation issues at 7 wt% of bitumen.[92] Therefore, additive methods have been explored to enhance the performance of rLDPE-modified asphalt further. Polyphosphoric acid (PPA) (0.8 wt% bitumen) with a dosage of 4 wt% bitumen rLDPE was found to minimize dissociation within the mix.[68] Other stability-enhancing methods include chemical cross-linking with sulfur agents, which have been shown to improve the dispersion of the inert plastic components throughout the asphalt matrix. Despite improvement in the relative stability of waste-modified bitumen, such methods currently do not outperform commercial PMB.[93]

2.2.2 HDPE

HDPE is a rigid and denser form of polyethylene with a typically high molecular weight. HDPE has a higher melting point than LDPE (about 135 řC), which is just below the average mixing temperature of bitumen.[94, 95] Thus, it is generally recommended for wet mixing.[15, 96] Several studies have demonstrated that incorporating recycled HDPE (rHDPE) into asphalt binder can improve the moisture susceptibility of pavement compared to unmodified specimens. Köfteci (2016) reported that a rHDPE additive at concentrations of 1, 2, 3, and 4 wt% of bitumen enhanced resistance to water damage, as evaluated with AASHTO T283 testing specifications, compared to standard pavements.[97] This improvement was attributed to increased storage stability, which is positively correlated with reduced moisture susceptibility. The inclusion of rHDPE has also been associated with increased binder viscosity compared to neat binders, as indicated by elevated softening points and bitumen stiffness.[76, 98] Additionally, molecular weight plays a significant role in a fluid's viscosity, potentially explaining the increased viscous behavior observed with the use of rHDPE due to its high molecular weight.[99] Inconsistency remains for the stability behavior of rHDPE modified bitumen across studies. While some studies have reported enhanced stability in correlation with increased moisture resistance relative to neat binders, others have observed adverse effects.[89, 97, 100, 101] Poor storage stability was noted by Casey et al. and Appiah et al., where the rHDPE modifiers propagated inconsistencies in mechanical properties and durability under thermal stresses in comparison to proprietary polymer-modified bitumen (PMB) and neat bitumen, respectively.[68, 100] Furthermore, Appiah et al. compared rHDPE with recycled polypropylene (rPP) and associated a disproportionate and fluctuating effect on rheological and viscoelastic properties with the incomplete blending of rHDPE, thus concluding that rHDPE is unsuitable for pavement applications. Similarly, Casey et al. found rHDPE to be feasible only at a dosage of 4 wt% of bitumen, where such stability issues were minimized. As a complementary approach, Casey et al. observed that the use of 0.8 wt% of bitumen PPA as a chemical additive minimized dissociation between rHDPE and binder components, as well as increased overall binder viscosity. Deformation resistance at high temperatures also varies across studies. While several reports note enhanced rutting resistance, others have found it to be comparatively lower than that of commercially used polymer-modified binders (PMBs), such as those incorporating EVA and SBS; nevertheless, it still adhered to standard deformation thresholds.[68, 88, 101, 102, 103] There are limited reports regarding elasticity. Similar to findings by Costa et al. and Dalhat et al., who found that rHDPE modifiers alone could not meet the AASHTO TP 70 elastic recovery standard for performance grade asphalt without the addition of an elastomeric polymer additive.[88, 103]

2.2.3 PP

PP is a thermoplastic with a wide-ranging molecular weight and a melting point between 160–170 řC, making it commonly suited towards the wet mixing process.[15, 96, 104, 103, 105, 106]

Regarding pavement rheological performance, studies frequently note increased asphalt stiffness and improvements in fatigue life compared to unmodified bitumen, implied by softening points and decreased penetration value, and enhanced tensile strength with various recycled PP (rPP) modifiers.[68, 106, 107, 108] Similarly, high temperature deformation resistance is also reported to improve. The same studies indicated an improved resistance to permanent deformation (e.g., rutting) and greater stiffness. Additionally, Tapkin noted an extended fatigue life at 1% rPP by 27% compared to the neat binder.[109] However, these findings aren't entirely conclusive regarding overall durability. Some studies report an increase in abrasion loss and variable stiffness characteristics, where stiffness rapidly increases with plastic dosage yet exhibits poorer damping capacity compared to unmodified bitumen.[110] Likewise, studies have also attributed a reduced resilient modulus and ductility, which could result in poorer elastic recovery and low temperature cracking, respectively.[106, 111]

A possible explanation for the observed reductions in fatigue and deformation resistance is reduced impact absorption and excessive brittleness, compounded by poor moisture resistance. This was evident in the experimental findings of Ahmedzade et al., where increased viscosity and stiffness were accompanied by a decrease in ductility.[106, 110] However, other studies report contrasting trends. Dalhat found that micronized rPP could be used to achieve super-hydrophobicity of the pavement.[112] Moisture resistance was primarily influenced by particle size and curing time, with an optimal condition achieved at a particle size of 177 μm and a curing time of 55 minutes. Moisture resistance was significantly enhanced under these conditions, noted by a 41.81% increase in contact angle compared to an unmodified bitumen binder.

The viscoelastic behavior of rPP-modified asphalt mixtures remains insufficiently characterized. Otuoze et al. consistently observed a deterioration in viscoelastic and rheological properties when rPP was incorporated into asphalt binders, while Dalhat et al. reported no clear trend or adherence with recycled PP in relation to elastic recovery adhering to AASHTO TP 70 elastic recovery standards.[88, 111] Without elastomeric polymer additives, recycled PP-modified binders consistently exhibited deteriorated elastic recovery values below 20. The initially poor elasticity associated with solely rPP modifiers was attributed to the incompatibility of PP with the asphalt components and the resulting poor storage stability.[87] The same study found that stability could only be maintained at dosages up to 2 wt% of the bitumen binder. Separately, Chiang et al. and Vamegh et al. supported this conclusion, noting significant improvements in thermal stability when using elastomeric polymer additives.[113, 114]

In contrast, other studies have reported that the sole use of rPP without additives had a profound effect on the bitumen's homogeneity and storage stability at an optimum dosage of 3 wt% of bitumen.[96] Appiah et al. attributed this to the lower molecular weight and polarity of rPP.[89] Furthermore, Appiah et al. found rPP more favorable compared to rHDPE due to its slight, linear improvements to the viscosity and storage stability.[100]

2.2.4 PS

Expanded polystyrene (EPS) foam or Styrofoam is banned in at least twelve states and numerous local jurisdictions due to concerns over its environmental persistence, limited recyclability, and potential health risks.[115, 116, 117, 118, 119] Recycled PS (rPS) has a wide melting range depending on its state, though the melting point of semicrystalline isotactic polystyrene is between 264 and 272 řC.[120]

Generally, rPS has been reported to increase the stiffness and viscosity of asphalt samples compared to unmodified specimens, given its increased softening points and enhanced rotational viscosity.[120, 121, 122, 123, 124, 125] Though thermal deterioration has been documented at both high and low temperature extremes. Hasan et al. noted rPS-modified bitumen to have a faster stiffening rate at low temperatures in comparison to neat binder, which may lead to excessive rigidity and increase susceptibility to brittle fractures; such susceptibility in low temperatures has been noted in other studies.[122, 123]

rPS has also been associated with increased air void content in asphalt mixtures compared to traditional stone aggregate asphalt. Using the dry-mixing method, Vasudevan et al. compared recycled polystyrene, polyethylene, polypropylene, laminated plastics, biaxially oriented polypropylene, and unmodified stone aggregates.[126] They found that the recycled polystyrene sample showed the poorest compactibility, which was attributed to the relatively high air void content due to the weak adhesion between the polymer components and binder. Such characteristics may induce structural issues such as asphalt durability, moisture susceptibility, fatigue, and deformation.

Additionally, wet-mixed applications face similar compatibility issues due to the high melting points of certain polystyrene types, particularly high-impact polystyrene. Hasan et al. reported that the high melting point hindered the formation of a covalently bonded polymer-asphalt network, which may prevent a stable and homogeneous rPS-modified asphalt formulation.[122] On the contrary, studies testing lower melting point PS, namely EPS with acetone and ethyl acetate solvents, found adhesion to be enhanced compared to neat binders.[127]

Vila-Cortavitarte et al. reported increased air voids and higher Cantabro loss at 1 wt% of asphalt rPS content, indicating reduced abrasion resistance compared to the neat binder.[123] Overall, these effects may stem from poor moisture resistance, elevated air void content, or weak aggregate-binder interactions.[128] Despite these limitations, the same study reported unusually improved high-temperature deformation resistance. These discrepancies introduce uncertainties regarding the thermal susceptibility and overall consistency of rPS in pavement applications. Moreover, it is a problematic and ecotoxic material that is banned in several states due to its persistence in the environment and overall health hazards.[129, 130] Integrating rPS into downstream recycling efforts like plastic roads could indirectly enable its continued production and use, which would be counterproductive given the non-biodegradable nature of polystyrene, and could potentially contribute to further environmental damage.

2.2.5 PET

PET is an inert thermoplastic polymer with a very high molecular weight and melting point at around 250–265 řC.[131, 132, 133, 134] This high melting point significantly exceeds the average bitumen mixing temperature and is deemed by some studies as unsuitable for the wet mixing process.[15, 68, 135]

Guru et al. and Ghabchi et al. suggested a strengthening effect on adhesion at the polymer-bitumen interface, which is an overall positive indicator towards fatigue, moisture susceptibility, and deformation resistance.[131, 136] This effect was confirmed in dry method implementation with Quartzite and Granite aggregates by Ghabchi et al., who found improved stripping resistance to neat binder, which is primarily affected by the water resistance abilities of the asphalt. On the other hand, Ahmadinia et al. noted that the crystallization of the rPET, which trapped the sticky binder around the aggregate surface and reduced the surface area in contact with the asphalt film, thereby weakening the aggregate-bitumen adhesion.[132] This raises concerns about air void potential and moisture susceptibility, primarily due to the direct influence of aggregate-binder adhesion.[36, 128] Such vulnerability has been acknowledged by several studies in findings of increased air void content compared to the unmodified control asphalt, though a study in India found that the air voids still adhered to country specifications.[137, 138, 139, 140, 141] Overall, the possibility of weakened adhesion and air voids necessitates further research on the crystallization behavior of rPET in the binder mix, as it can catalyze adverse effects on performance under certain conditions.

Rheology and fatigue remain mostly unaffected by the variable moisture susceptibility behavior derived from aggregate-asphalt adhesive behaviors, and in fact, are noted to improve overall compared to unmodified bitumen.[132, 138, 142, 143] As such, studies have documented improvements in high temperature deformation resistance, stiffness, and viscosity compared to unmodified asphalt mixtures.[86, 131, 142] In particular, Ahmadinia et al. noted a 29% reduction in rut depth and 16% increase in elastic recovery at 4 wt% of bitumen rPET content in comparison to a conventional bitumen mix.[132] These effects are likely attributed to the enhanced stiffness and elasticity of the asphalt, leading to enhanced recovery capacity from deformation than unmodified bitumen binders.[85, 139, 140] Mashaan et al. suggested that the greater elastic recovery rate was possibly due to the compatible swelling of the rPET within the asphalt.[86]

2.2.6 PVC

PVC is a thermoplastic polymer produced from its vinyl chloride monomer, with a high molecular weight and crystallinity.[144] It is the world's third most produced synthetic polymer and versatile in creating both rigid and flexible materials, often as single-use packaging or piping and construction appliances.[145] PVC has a crystalline melting point of 100–260 řC, which falls level with or slightly above average crumb rubber modified HMA (Hot Mix Asphalt) mixing temperature (166–204 řC), thus making it suitable for both the wet and dry methods.[134, 144, 146] Though PVC is often incorporated via wet mixing, some studies found the high melting point to hinder mixing and perform unsuitably when utilizing the wet method.[68]

Recycled PVC (rPVC) modified asphalt is commonly associated with greater stiffness and viscosity, observed with increased softening points and lower penetration values compared to neat specimens.[146, 147] In addition, this modifier enhances resistance to rheological and fatigue stress, such as resistance to permanent rutting deformation.[148, 149, 150, 151, 152] Further evidence of an extended low-temperature fatigue life is suggested by the higher asphalt stiffness relative to neat binders, which is a typical correlation.[147, 153, 154] Since asphalt is expected to perform under a wide range of temperatures, an optimal formulation requires a balance between stiffness and flexibility in order to resist both high temperature deformation and low temperature cracking. In the case of a stiffer asphalt mix, excessive rigidity may increase brittleness and compromise performance at low temperatures.[155] Fakhri et al. observed both resistance to brittle fractures and enhanced stiffness compared to conventional bitumen.[147] This study suggests that it is possible to achieve enhanced asphalt stiffness without risking brittle susceptibility, suggesting that rPVC-modified asphalts can potentially achieve balanced deformation characteristics.

rPVC is also found to improve elastic recovery relative to unmodified asphalt.[147] This is consistent with reports of enhanced rutting resistance, which correlates to the elastic recovery ability of pavement to return to its original form after deformation. Additionally, rPVC has been reported to enhance adhesion between the bitumen-aggregate interface, which minimizes air voids and susceptibility to moisture damage.[147, 156] Rasel et al. and Rahman et al. affirmed that the air void content of the rPVC modified asphalt sample remained within limits specified by The Asphalt Institute.[156, 157] In addition, both studies revealed similar patterns in air void content levels, in which it initially decreased with increasing rPVC dosage but later increased as the dosage reached higher levels. Overall, there appears to be an effective rPVC dosage threshold for optimizing adhesive strength and related properties.

PVC has a high hazardous emission risk when heated to elevated temperatures, specifically, the release of large quantities of HCl gas and potentially other hazardous gases such as benzene and halogenated hydrocarbons.[158, 159, 160] HCl gas is highly toxic to the environment due to its corrosive acidic nature, which is a major contributor to ocean and soil acidification.[161] In the context of pavement applications, which are routinely subjected to variable thermal and environmental stresses, the emission potential of PVC presents a significant challenge to mitigate and control over the pavement's service life.[152, 158] To mitigate the mobilization of such toxic compounds, studies have proposed methods to absorb chlorine content during asphalt preparation using di-2-ethylhexyl phthalate.[162]

2.2.7 ABS

ABS is a heterogeneous, multiphase thermoplastic terpolymer consisting of acrylonitrile, butadiene, and styrene.[163] ABS can be incorporated into asphalt mixtures via both dry and wet mixing methods, owing to its amorphous structure. Although it lacks a definitive melting point, ABS exhibits a glass transition temperature around 100 řC.[42] Notably, ABS is documented to experience chemical degradation at temperatures starting from 120 řC and significant benzene emissions at temperatures exceeding 140 řC. This is attributed to the volatilization of the styrene phase. The heterogeneous composition of ABS introduces variation in the proportions of its constituent polymers, which may confer a broad range of thermal and mechanical properties.[164] Indeed, this variance was reflected in the melting points of ABS, where Casey et al. noticed mixing incompatibility issues between the high melting point of the rABS that hindered conventional wet method mixing.[68] In contrast, other studies expressed no issues. rABS and other waste-derived heterogeneous copolymers have significantly variable material composition, given that consumer waste streams encompass different variants and compositions of ABS plastic and potential chemical contamination. This can lead to different mechanical properties in the resulting pavements, given that mechanical behavior is highly dependent on the chemical compositions and microstructure of the polymer additive.[165]

Rheological and fatigue studies demonstrate a modest degree of variability, with most reporting an increase in stiffness compared to unmodified binders, suggesting higher viscosity and deformation resistance in high temperatures, though not superior to certain commercial PMBs.[104, 122, 124, 166, 167] Aligned with these findings, Singh et al. and Fonseca et al. also noted an increase in elastic properties. In contrast, Morales et al. observed degraded rheology and fatigue performance compared to neat bitumen at rABS concentration of 9 wt% of bitumen. They attributed this to excessive stiffness that may have led to low-temperature brittleness. Additionally, rABS was evidenced to have little to no effect on viscosity. Slight upward increments were attributed to the oxidation of bitumen during processing. It is worth noting that other studies recommended against exceeding rABS dosages of 4–5 wt% of bitumen. The higher dosage of 9 wt% of bitumen employed by Morales et al. may have contributed to the negative performance effects observed.[124, 167, 168] Slight decreases have been observed in the air voids of ABS-modified asphalt compared to unmodified bitumen.[166] Audy et al. reported similar findings in comparison to rPET via dry method modification, as rABS aggregates were observed to have better adhesion with the bitumen compared to PET, which would lead to decreased air void content.[169]

Finally, during its additive manufacturing applications, ABS is known to emit volatile organic compounds (VOCs) harmful to humans when heated to high temperatures ranging from 170 to 240 řC.[170, 171, 172] Tiganis et al. documented the mobilization of benzene byproducts via the volatilization of styrene when ABS was heated to temperatures higher than 140 řC.[164] The asphalt processing temperatures utilized in the study (140–180 řC) approximated industry standard wet mixing thresholds, which indicates credible potential for harmful emissions during the asphalt mixing process.[42, 134]

2.2.8 PU

PU differs from other aforementioned polymers, like polyethylenes or PS, in that it is a chain of alternating copolymers. There are various forms of PU due to its versatile chemical composition, resulting in several different applications such as rigid forms, foams, adhesives, coatings, fibers, etc.[73, 173, 174]

Unlike the inert thermoplastic polymers previously discussed, most PU-modified asphalts utilize active PU, the most common being prepolymers. Prepolymers are reactive polymers incorporated into pavement via chemical modification.[72] Unlike physical modification, in which the polymer is physically dispersed throughout the asphalt mix and maintains stability primarily through Van der Waals interactions, the prepolymer PU is an active component that reacts with asphalt constituents to form new chemical structures and functional groups, achieving a more stable homogeneous state. This results in a higher performing and uniform mixture at high temperatures, since the polymer-asphalt interface is reinforced by chemical bonding.[67, 69]

Overall, PU is generally found to enhance the viscoelastic and rheological properties of asphalt mixtures compared to conventional types.[175] Wei et al. incorporated PU prepolymer at dosages of 3, 5, and 7 wt% of the total asphalt mix. They observed increased complex shear modulus values compared to conventional asphalt mix, indicating greater stiffness and deformation resistance.[176] Although liquid PU at 4.1 wt% of asphalt yielded rutting resistance comparable to SBS-modified mixtures, it still outperformed base asphalt.[177] Similarly, Hao et al. found that recycled PU (rPU) improved rutting resistance compared to an SBS-modified PMB sample and also enhanced low-temperature crack resistance and aging resistance.[178] Chemical analysis revealed that the aging process induced a decomposition reaction of the rPU, resulting in broken-down molecular products that improved the rutting resistance. Overall, the mechanical properties of rPU similarly reflect those enhancements produced by virgin or prepolymer PU in comparison to neat binders. Thermal susceptibility is improved, and mechanical properties are well-balanced so that the pavement is neither overly rigid nor pliable.

The main difference between rPU and reactive PU modified asphalts is storage stability. Unlike reactive PU prepolymers, adding rPU particles typically results in reduced thermal storage stability.[175, 178] This reduction is likely due to differences in material modification methods and the distinct interactions between polymer and asphalt constituents when comparing prepolymers, waste thermoplastics, and thermosetting elastomers. Poor stability may be mitigated through the incorporation of elastomeric additives; for example, Hao et al. demonstrated that storage stability was improved by 42.3% when using styrene-butadiene-styrene (SBS) compared to formulations without elastomer enhancement.[178]

2.3 Economic Feasibility

The long-term economic model of plastic-modified pavements is a critical point of evaluation in the context of public infrastructure renewal and municipal budget constraints. Current pavement networks in the United States contain asphalt composed mostly of neat bitumen or polymer-modified bitumen mixed with quarry aggregates.[179] Partial substitution of these materials with post-consumer plastics introduces elements of a circular economy while reducing raw material costs.[137] Multiple economic analyses demonstrated that waste plastic modified bitumen can match or even reduce the costs of construction and maintenance compared to conventional bitumen. For example, Yao et al. reported a cost reduction of up to 31.8% compared to virgin PMB construction.[180] Singh et al. noted a 4.3 and 9.5% reduction in surfacing costs when comparing rLDPE to crumb rubber PMB. The study observed that laying costs similarly reflected those typically of Viscosity Grade 40 bitumen.[181] The same evaluation by Yao et al. demonstrated extended pavement lifetime with waste plastic integrated asphalt matrices in comparison to unmodified or PMB pavement, thus resulting in lower maintenance frequency and cost.[180] This was noted by a total life cycle cost reduction ranging from 14.5 to 26.2%. Aside from economic benefits, the reconstruction and installation of new roads can also facilitate socioeconomic growth. Studies assert that under the right economic circumstances and spatial factors, the construction of transportation infrastructure often promotes increased economic productivity and competitiveness.[182, 183, 184, 185, 186] According to American socioeconomic studies, there is a causal relationship between income inequality and a lack of domestic transportation.[187] Expanding road infrastructure construction initiatives, particularly sustainable road technologies like plastic roads, could therefore play a critical role in reducing spatial inequality and income disparities in marginalized geographical regions.

Government investment towards road infrastructure restoration has substantially grown in recent years, with recent enactments of road investment policies such as the Infrastructure Investment and Jobs Act passed in 2021.[188, 189] Results of such efforts are illustrated by the 2025 report from the American Society of Civil Engineers, which indicated a record high performance of U.S. roads.[188] Overall, the economic feasibility of plastic roads and current upward road investment trends and attention from stakeholders suggest high potential for the implementation of plastic roads on the national level, that is, until they have undergone comprehensive risk and lifecycle assessments.

2.4 Policy

Changes in the U.S. environmental regulatory landscape are predicted to have considerable impacts on the employment of waste plastic recycled pavement technology. Currently, waste-plastic-modified roads are being constructed by private companies, such as Dow Transportation and the UKs MacRebur, which state departments of transportation and smaller administrative bodies hire.[190, 191] Plastic roads have not been implemented on a larger scale primarily because 1) they are a new technology and still undergoing laboratory tests, and 2) past infrastructural regulations required technology to adhere to a comprehensive environmental review.[192] However, shifting infrastructural policies allude to changes that may enable either a potentially more streamlined or complicated process for the expansion of the plastic road industry. In 2025, several environmental and permitting evaluation processes in the context of transportation infrastructure were rescinded, including greenhouse gas (GHG) regulations and the removal of the authority of the Council on Environmental Quality to oversee the National Environmental Policy Act. The intention was to streamline permitting processes to expedite road infrastructure construction projects, though some experts state that these rescission would in fact have the opposite effect on energy and transportation sectors, claiming that the absence of environmental standards without the oversight of the Council on Environmental Quality would lead to increased process and production delays.[193, 194, 195, 196] These policies transcend into the plastic road industry as well, which relies on environmental benchmarks to conduct environmental toxicity evaluations, as emphasized by previous environmental assessments.[28, 33]

Shifting environmental and infrastructural policies are key components in the scalability potential of the plastic road industry. The absence and further retraction of environmental standards will create more complicated risk evaluations during the current experimental stages of laboratory and pilot studies of plastic roads.

2.5 Ethics

While plastic roads facilitate a downstream solution to alleviate the burden on current waste management systems, there are several ethical questions about their long-term sustainability and impact on producers, localities, and current upcycling streams.

Failing downstream waste management systems already demonstrate the insufficient long-term sustainability of downstream solutions. Sole reliance on end-of-pipe solutions obscures the vast accumulation of plastic waste and foregoes attaching accountability to more inherent issues in materials regulation, pollution, and unethical producers. The concept of waste plastic-modified pavements should adhere to a more circular economic model rather than traditional end-of-pipe principles, which burden consumers and municipalities with issues created by producers.[197, 198] Although plastic roads theoretically offer a more circular model through RAP, the environmental risks in this practice remain uncertain.[50, 52, 53]

It should be clarified that waste disposal systems like plastic roads are not completely ineffective; rather, a short-term remedy is critical to resolving current waste municipalities burdens and preventing further plastic accumulation in ecosystems. However, there needs to be greater emphasis on upstream solutions in order to promote the development of a circular plastic economy and phase out traditional linear end-of-life plastic life cycles. Ethical motivators for future research should explore whether plastic roads can strengthen existing downstream waste management systems with a less ecotoxic, socially ethical, and sustainable model.

2.6 Conclusion

Today, plastic roads are underdeveloped in terms of performance, environmental impact, circularity, and regulation. Though plastic roads have proven to be more economical and certain compositions exhibit mechanical advantages, there still remain significant process gaps and disadvantages, such as worsened storage stability due to poor adhesion between asphalt and plastic constituents. The inconsistent material composition and chemical impurities of post-consumer stream plastics also introduce microstructural and chemical inconsistencies that can alter the mechanical properties of the final modified pavement. This applies, in particular, to heterogeneous copolymers, which retain a wider range of polymer structural variations. Thus, future research should consider these factors and account for potential inconsistencies in post-consumer stream plastics. Additive methods such as integrating nanocomposites into the asphalt mix should be highlighted in future works, while being considerate to limit the contribution of increased chemical toxicity.

Increased attention to environmental impact should also be a key area of future work. The characterization of MPs and other chemical leachates yields contrasting results, proposing a direction for future research. It is also imperative to establish more concrete environmental benchmarks, such as MP pollution thresholds, to calibrate environmental hazards in a standardized way. Lastly, sustainability research on plastic roads should emphasize developing long-term, circular pipelines from raw plastic waste to pavement rejuvenation cycles. This includes viably repurposing plastic-modified pavements with RAP technology, conducting further investigations on the potential mobilization of toxic compounds, and developing effective strategies to mitigate them.

Overall, the challenges of plastic road implementation are the chemical persistence and toxicity hazards of incorporating plastic into geological infrastructure. Future work should highlight these crucial factors. Moving towards a circular economy necessitates greater emphasis on upstream recycling efforts with downstream solutions as temporary alternatives. Plastic roads should be a part of a larger environmental strategy to curb the U.S. plastic crisis, treated as a temporary solution to alleviate the burden from landfills, while sustainable solutions in upcycling and extended producer responsibility are emphasized for the long-term.

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