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REVIEW ARTICLE

Emerging Downstream Plastic Waste Disposal Solutions in the United States: A Review of 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 pavement's 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, and the establishment of MP release thresholds and relevant environmental standards.

KEYWORDS: Materials Science, Polymers, Waste Plastic Modified Asphalt, Chemical Leaching, Economic Feasibility.

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 doesn't 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 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.[49] 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 incorpora-

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tion 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 process, 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 process. The plastic partially melts to form a coating around the aggregate, similar to the results of the dry process, 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.[16-19] 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 process asphalt, where red shaded regions represent plastic-modified content. The dry process contains plastic in the form of dry aggregates, while the wet process contains plastic in its binder, and the mixed method comprises partially coated plastic aggregates and plastic-modified binder.

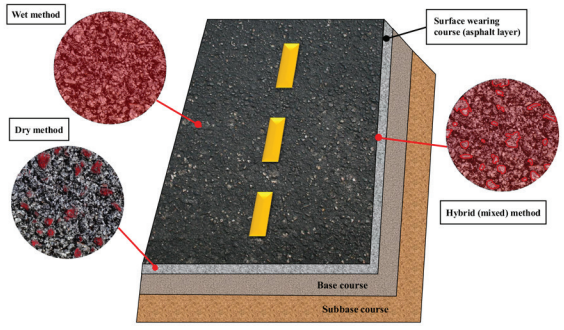

Figure 1: Diagram of pavement course as well as wet, dry, and mixed process asphalt, where red shaded regions represent plastic-modified content. The dry process contains plastic in the form of dry aggregates, while the wet process contains plastic in its binder, and the mixed method comprises partially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

Discussion

Environmental Impact:

A potential risk associated with incorporating a persistent environmental pollutant into public infrastructure is the abrasion of microplastics (MP) 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.[21-23] In fact, life expectancy projections for plastic-modified roads are three times longer than those for unmodified asphalt roads.[20] Additionally, quantifying MP release from roads in real-world environments remains challenging primarily due to the difficulty in distinguishing road-derived MP from those originating from tire wear, as well as interference from external environmental factors that may reduce the accuracy of MP collection and measurement.[24-27] 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 processes of plastic road construction, where various plastic types and dosages were observed under environmental stress factors such as duration, water pH, and temperature.[28] Post-consumer low-density polyethylene and linear low-density polyethylene (LDPE/LLDPE) and commingled post-consumer polyethylene and polypropylene (PE/PP) were each incorporated into a bitumen matrix via wet process mixing (w) and evaluated at plastic dosages of 1, 2, 4, and 6 weight percent (wt%) of bitumen, respectively. Post-consumer polyethylene terephthalate (PET) and acrylonitrile butadiene styrene (ABS) were combined into the asphalt matrix as plastic-coated aggregates via dry process 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 MP.

Enfrin *et al.* observed no correlation between MP loss and increasing temperature in ABS (w), where a consistent release rate of 0.43 ± 0.07 g/m^2 was maintained. On the other hand, lower temperatures facilitated notably high MP release rates in the LDPE/LLDPE (w) sample. At 5 °C, the release rate was nearly triple that observed at 25 °C. This trend was attributed to potential brittle tendencies of LDPE/LLDPE (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 LDPE/LLDPE (w) sample exhibited no correlation with water pH values, maintaining an average release of 0.53 ± 0.15 g/m^2 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 weaken-

ing. 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 LDPE/LLDPE (w) and ABS (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 process, 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/m^2/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 LDPE/LLDPE (w) concentration is lower and more evenly dispersed. In comparison, the plastic content in the dry process is more homogeneously distributed throughout the entire asphalt matrix, resulting in a linear MP release trend.

LDPE/LLDPE (w) initially exceeded ABS (d) by three times more MP released, but was then surpassed by ABS (d) at the 30-minute mark, suggesting differing cumulative release trajectories between the two mix types over the duration of the simulation. It is important to note that this abrasion simulation represents an accelerated, idealized model of surface wear that does not account for the gradual, variable nature of real-world mechanical stress, weathering, or environmental exposure over a road's service life. As such, the crossover trends observed within the 60-minute window should be interpreted as indicative patterns rather than direct predictions of field behavior. Nevertheless, these simulated release trajectories carry implications when considered alongside real-world road lifespans. Road resurfacing typically occurs every 11-26 years, depending on traffic volume and conditions.[21-23,32] Based on the logarithmic release behavior observed for wet-process roads, MP release would be expected to spike initially following construction or resurfacing when the plastic-concentrated surface layer is most exposed and then gradually decline as the surface weathers. This cycle would resurge with each subsequent resurfacing event. Although dry-process roads introduce approximately 1.5 times more plastic content overall, their uniform dispersion throughout the full matrix depth may moderate MP release over the complete life cycle compared to the wet process.[28]

Boom *et al.* extended the scope established by Enfrin *et al.* by using a hybrid mixing process of plastic roads.[33] Two asphalt samples were tested, one of which was a combination of LDPE/LLDPE (68/32 wt%, respectively), and the latter consisted of PE/PP. Both samples were prepared using the hybrid mixing process (m). Given the absence of standardized MP release environmental thresholds, the plastic-modified samples were benchmarked against commercially produced polymer-modified asphalt consisting of ethylene-vinyl acetate (EVA) and styrene-butadiene-styrene (SBS).

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.

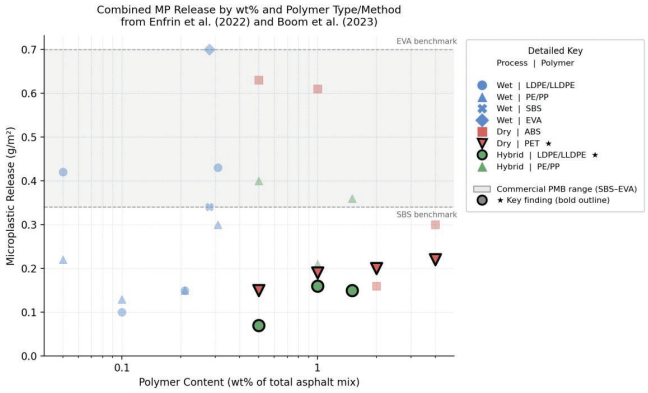

Figure 2: Combined MP release data by plastic content from Enfrin et al. and Boom et al. (excluding error bars). It reveals a logarithmic trend with increasing plastic content in mixed method LDPE/LLDPE and dry process PET, while other plastic-modified samples exhibit no correlation.[28,33]

Over a plastic content range from 0.05-0.31 wt% of asphalt, MP release of LDPE/LLDPE (w) and PE/PP (w) exhibited no clear relationship with plastic content, and followed similar high fluctuation patterns, with LLDPE/LDPE (w) having 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 LDPE/LLDPE (m) released the lowest quantities of MP 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 PET (d) by Enfrin *et al.*, but with slightly elevated MP release in PET (d), 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 of PET (d) and LDPE/LLDPE (m). Across the overall graphical relationship between plastic content, all recycled plastic modified samples demonstrated lower MP release than the EVA benchmark; however, the samples LDPE/LLDPE (w), ABS (d), and PE/PP (m) exceeded the SBS benchmark at some period. Overall, the two simulations of MP erosion demonstrated that LDPE/LLDPE (m) and PET (d) released the least amounts of MP and exhibited the most evident correlations in MP release trends with plastic content, both following logarithmic curves. Boom *et al.* suggested that this particular trend occurred due to the larger surface area of PET (d) and ABS (d) in contact with bitumen in their respective asphalt when reducing particle size. This may lead to increased adhesive interactions between the binder and polymer-modified aggregate interface compared to other mix configurations. This is beneficial, given that the interfacial adhesion influences the formation of air voids, which in turn affects properties such as water permeability that govern key mechanical characteristics such as abrasion resistance.[34-37] This phenomenon

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was also revealed in the analysis, where MP release of PET (d) and ABS (d) was mainly driven by the aggregate surface area in contact with bitumen, suggesting a positive correlation with the interfacial interactions between plastic additives and bitumen and MP abrasion. Given that PET (d) and LDPE/LLDPE (m) simultaneously released the lowest amounts of MP while also accommodating moderate and upper plastic content thresholds tested in the study, this indicates that more plastic can be recycled as road content per stretch of road while minimizing MP pollution compared to the other mix designs and plastic incorporation methods.

Duan *et al.* investigated LLDPE and recycled polyethylene (PE) pellets modified binder compared to virgin PE powder in a bitumen binder, and quantified MP release in conditions of extreme rutting and moisture.[38] 2.5 wt% of bitumen LLDPE pellets, 1 wt% of bitumen PE pellets, and 1 wt% of bitumen virgin PE powder of the asphalt mix's mass were incorporated via the dry process. To simulate MP abrasion, the Hamburg Wheel Tracking Test (HWTT) was employed for the modified asphalt samples in 40,000 wheel-passes, two times greater than the amount established by HWTT testing guidelines. This represents an upper limit of MP release by three orders of magnitude. The particles were filtered and collected through a series of gravitational, density, and chemical separation methods. These simulation results suggested that 1 wt% of bitumen PE pellets (d) and 1 wt% of bitumen virgin powder had a notably higher MP release rate than 2.5 wt% of bitumen LLDPE pellet (d) modified asphalt. Their rates were estimated to be 0.17–0.26%, 0.0674–0.102%, and 0.0355–0.053% of total embedded plastic content, respectively. These data were extrapolated to infer a maximum of 2600 g of lifetime generation of MP and a minimum of 355 g of MP for the highest and lowest release rates in this study, corresponding to 1% PE pellet (d) and 2.5% LLDPE pellet (d) asphalt mixtures, respectively.

From the HWTT results of LLDPE 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 have an annual release rate of 0.0053% of the total embedded plastic content. This corresponds to an upper limit of 2209 g of MP/km by a 4-lane interstate road annually, and 920.6 g MP/km/year on a 2-lane local road. To contextualize this degree of MP release, they further compared MP emissions from the plastic-modified asphalt samples 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. This suggests 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 compared to projected real-world scenarios.

Once MP are abraded from the road surface, released MP are subject to environmental transport via multiple pathways. Surface runoff during precipitation events is the primary vector, carrying road-derived MP into stormwater drainage networks and ultimately into receiving freshwater and coastal marine environments.[200] Aeolian transport of fine MP particles may also contribute to atmospheric dispersal and deposition in nearby soils and water bodies, though the relative magnitude of wind-driven versus runoff-driven transport remains poorly quantified for road-derived MP specifically.[201]

These studies provide baseline insights into the MP release potential of plastic roads for future work. It can be inferred that MP release potential depends on the engineering properties of the pavement, particularly the bitumen-aggregate adhesion, which contributes to erosion behavior under abrasive and environmental stress. These properties vary with plastic content, construction method, and plastic types. The detailed analysis of which will be discussed in the performance section of this article. For MP release, results and extrapolations from previous studies demonstrate reduced wear-induced MP emission potential in comparison to commercially available polymer-modified bitumen (PMB) roads and virgin polymer-modified roads. Not all dynamic environmental scenarios were modeled; hence, further study and experimentation should be conducted to assess the impact of aging and other factors that cannot be rapidly simulated. There was also a notable lack of environmental thresholds for MP release to interpret the results of these risk evaluation studies. Concrete standards should be established to foster standardized environmental evaluations for risk assessment and decision-makers.

Volatile organic compounds (VOCs) are often emitted during the construction and laying process of traditional hot-mix asphalt (HMA) pavement. This raises concerns about exposing workers to carcinogenic fumes, thereby posing health risks.[39] Additionally, observations of non-carcinogenic fumes like polycyclic aromatic hydrocarbons (PAH) have also been reported during the production process at high heating temperatures, particularly the presence of benzo[a]pyrene.[40,41] Other VOC and PAH observed included benzene, trichloroethylene, tetrachloroethylene, styrene, and dibenz[a,h] anthracene, although those typically constitute low carcinogenic risk.[42] Notably, Boom *et al.* reported that VOC and PAH emissions increased with higher processing temperatures but decreased with greater plastic content in the asphalt mixture. 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 levels than the A35P binder.

Beyond processing-stage emissions, the plastic constituents embedded within road surfaces may continuously leach chemical additives, including phthalate plasticizers, brominated flame retardants, and heavy metal-based thermal stabilizers, into adjacent soils and water bodies throughout the pavement service life under thermal cycling and wet-dry exposure. Prolonged UV and oxidative weathering of road-surface plastics can further generate transformation products, such as styrene oligomers from ABS or PS fractions, which may exhibit greater environmental mobility or toxicity than their parent compounds.[202]

Plastic tends to become more toxic with increasing recycling cycles due to the accumulation of non-intentionally

added substances like external chemical contaminants.[43-45] This particularly applies to non-recyclable waste plastics like copolymers or chemically degraded plastics, which tend to be more chemically complex due to heterogeneous polymer compositions, additives, or contaminants.[46] Reclaimed Asphalt Pavement (RAP) is often associated with considerable amounts of PAH and toxic metals, which can form due to incomplete combustion during the RAP recycling process.[47] Since these compounds are primarily physically dispersed within the asphalt matrix via non-covalent interactions, recent studies have raised concerns about their potential mobilization upon the addition of maltene-based rejuvenators during the renewal process, which may result in chemical leachates contaminating soil and groundwater.[48,49] Studies on chemical leaching of RAP pavement and stockpiles report inconsistent findings. A study on RAP modified with waste plastic and conventional polymers suggests no apparent groundwater leaching or PAH.[50] Heavy metals were commonly observed as VOC, though some studies indicated that their quantities did not exceed U.S. Environmental Protection Agency environmental thresholds, and one observed no correlation between plastic content and chemical leaching.[51-56] Others reported leaching of metals and PAH occurring in excess and suggested that RAP constitutes a high environmental toxicity risk. This included Naphthalene and Dibenzo[a,h]anthracene and metals such as Pb, Zn, Cu, As, Mn, Sb found in both RAP stockpiles and pavements.[47,57-59]

There are limited findings regarding RAP performance over rejuvenation cycles. Di Mino *et al.* found comparable mechanical properties of an RAP asphalt sample modified with recycled hard plastics and graphene nanomaterial across three rejuvenation cycles. Additionally, each aging cycle required similar dosages of rejuvenator, suggesting no significant performance degradation with increasing rejuvenation cycles over the course of three life cycles. However, there remain uncertainties in the mechanical performance of RAP mixtures as studies present controversial findings.[59,60]

Significant gaps remain regarding the physical and long-term limitations of RAP, particularly in the context of its circularity. While recent studies have performed multiple life cycle analyses with RAP, the long-term feasibility of continuous rejuvenation remains uncertain without prolonged field assessments. If the number of viable rejuvenation cycles constrains RAP implementation, the eventual disposal of pavement materials becomes problematic. Even with assumptions of minimal chemical leaching, these materials may still pose hazardous risks and face the same challenges as current disposal methods, particularly the safe management of large volumes of chemically contaminated waste. The main challenge involves the handling of persistent, toxic compounds, which often requires active physical intervention and deliberate chemical stabilization strategies. Additionally, the environmental toxicity of plastic-modified pavements during their service life remains uncertain and entails prolonged and comprehensive life-cycle assessments of environmental pollutants, including chemical leachates and microplastics.[61,62]

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 low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (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 homogeneous 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]

Table 1: Summary of key points regarding pavement performance advantages and disadvantages of LDPE-, HDPE-, PP-, PS-, PET-, PVC-, ABS-, PU-, PC-based waste plastic modified asphalt.

Plastic Type	Observed Performance Key Points	Processing and Structural Characteristics
LLDPE/LDPE	- Improves moisture susceptibility and high-temperature deformation resistance.[15,74-79] - Often increases viscosity and elastic recovery, but can suffer phase separation at higher dosages.[26,78,80,89,91-93]	- Low average melting point (105-120 °C)[15,74-76] - Suitable for wet-mixing methodologies.[15,74-76] - Forms a 3D plastic-asphalt network via molecular chain entanglement.[15,82-86] - Requires chemical stabilization (e.g., polyphosphoric acid or sulfur cross-linking) to reduce phase dissociation.[68,91-93]
HDPE	- Improves the moisture susceptibility and viscosity, but storage stability and elastic recovery are inconsistent and may require additives.[15,68,76,88,89,94-103]	- Rigid, dense homopolymer with high molecular weight that promotes viscous behavior[15,94-96] - Melting point is ~135 °C; recommended for wet process mixing.[15,94-96] - Stability issues are minimized at a 4 wt% dosage.[68] - Polyphosphoric acid at 0.8 wt% minimizes component dissociation and increases viscosity.[68]
PP	- Increases asphalt stiffness, rutting resistance, tensile strength, and fatigue life.[68,106-109] - Micronized PP (optimally 177 μm, 55 min curing) improves hydrophobicity by up to 41.81% increase in contact angle, while storage stability is dosage-sensitive.[87,112]	- Thermoplastic with wide-ranging molecular weight and a melting point between 160-170 °C.[15,96,104-106] - Well-suited for wet process.[15,96,104-106] - Incorporating elastomeric additives (crumb rubber, SBS, or SBR) significantly remedies stability, moisture, and rutting deficiencies.[113,114]
PS	- Generally increases stiffness and viscosity.[115,130] - Can worsen low-temperature brittleness, compactibility, adhesion, and abrasion resistance.[115,130]	- Semicrystalline isotactic polystyrene possesses a melting range between 264-272 °C.[120] - High melting points (e.g., in high-impact PS) hinder the formation of a stable, covalently bonded polymer-asphalt network during wet process mixing.[122]

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PET	- Improves stiffness, viscosity, elastic recovery (e.g., 29% rut depth reduction and 16% increase in elastic recovery at 4 wt%) and high-temperature rutting resistance.[86,131,132,142] - Conflicting findings on adhesion and moisture resistance, potentially increasing air voids and raising structural vulnerability.[36,128,132,137-141]	- Inert thermoplastic with very high molecular weight and a melting point around 250-265 C°.[131-135] - Processing temperature significantly exceeds average bitumen mixing limits, rendering it unsuitable for conventional wet process mixing according to some studies.[15,68,135]
PVC	- Increases stiffness, viscosity, rutting resistance, and elastic recovery, while also improving adhesion and moisture resistance.[146-157] - High melting points can disrupt homogeneous blending during wet process mixing.[68] - Studies observed threshold effect in air void content: it initially decreases with dosage but then increases significantly at elevated concentrations.[156,157] - Generates highly toxic, corrosive HCl gas, benzene, and halogenated hydrocarbons at elevated processing temperatures.[158-161]	- Highly crystalline polymer with a melting point of 100-260 C° aligning with or exceeding crumb rubber-modified Hot Mix Asphalt temperatures (166-204 C°).[134,144,146] - Applicable for both wet and dry processes[144,146] - Chlorine gas mobilization requires mitigation techniques. Ragab et al. suggests absorption via di-2-ethylhexylphthalate.[162]
ABS	- Usually improves stiffness, viscosity, high-temperature deformation resistance, and sometimes elastic properties.[104,122,124,166,167] - High melting point variants of ABS introduce severe wet-mixing incompatibility.[68] - Highly variable composition and chemical contamination within consumer waste streams result in unpredictable mechanical properties.[163-165] - High dosages (e.g., 9 wt%) degrade rheological and fatigue performance due to excessive stiffness and low-temperature brittleness.[124,167,168] - Releases hazardous VOC and toxic benzene byproducts via styrene volatilization at processing temperatures (140-180 °C).[164,170-172]	- Heterogeneous, multiphase amorphous terpolymer with a glass transition temperature around 100 C° but no definitive melting point.[42,163] - Chemical degradation initiates at 120 °C; major benzene emissions occur above 140 °C.[164] - Recommended maximum dosage threshold is restricted to 4-5 wt% of bitumen.[124,167,168]
PU	- Recycled PU particles enhance low-temperature cracking resistance and aging resistance.[178] - Recycled PU improved rutting resistance relative to SBS-modified PMB and enhanced low-temperature cracking and aging resistance; thermal decomposition products were additionally found to improve rutting resistance.[178] - Reactive PU yields better homogeneity and storage stability than recycled PU alone due to the formation of new chemical structures rather than physical dispersion.[67,69,72]	- Storage stability deficiencies in recycled PU can be mitigated and improved by 42.3% through the inclusion of SBS elastomeric additives.[178] - For reactive prepolymer PU, achieves stability through active chemical cross-linking rather than weak, physical van der Waals physical dispersion.[67,69]

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 105–120 °C.[15,74-76]

The most notable and consistently observed improvements associated with LDPE-modified asphalt are moisture susceptibility and high-temperature deformation resistance.[77-79] 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 unmodified bitumen, and in certain cases, gel-like behavior with the addition of LDPE.[82-84] 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 LDPE; 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 LDPE content (2–8 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] LDPE 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, LDPE-modified binder exhibited higher viscosity overall with high-molecular-weight LDPE, 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 LDPE-modified asphalt further. Polyphosphoric acid (PPA) (0.8 wt% bitumen) with a dosage of 4 wt% bitumen LDPE 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]

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 °C), which is just below the average mixing temperature of bitumen.[94,95] Thus, it is generally recommended for wet process mixing.[15,96]

Several studies have demonstrated that incorporating post-consumer HDPE into asphalt binder can improve the moisture susceptibility of pavement compared to unmodified specimens. Köfteci (2016) reported that an HDPE 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 HDPE has also been associated with increased binder viscosity compared to unmodified bitumen, 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 HDPE due to its high molecular weight.[99]

Inconsistency remains for the stability behavior of HDPE-modified bitumen across studies. While some studies have reported enhanced stability in correlation with increased moisture resistance relative to unmodified bitumen, others have observed adverse effects.[89,97,100,101] Poor storage stability was noted by Casey *et al.* and Appiah *et al.*, where the HDPE modifiers propagated inconsistencies in mechanical properties and durability under thermal stresses in comparison to proprietary PMB and unmodified bitumen, respectively.[68,100] Furthermore, Appiah *et al.* compared HDPE with PP and associated a disproportionate and fluctuating effect on rheological and vis-

coelastic properties with the incomplete blending of HDPE, thus concluding that HDPE is unsuitable for pavement applications. Similarly, Casey *et al.* found HDPE 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 HDPE 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 commercial PMB, such as those incorporating EVA and SBS; nevertheless, it still adhered to standard deformation thresholds.[68,88,101-103]

There are limited reports regarding elasticity. Similar to findings by Costa *et al.* and Dalhat *et al.*, who found that HDPE 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]

PP:

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

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 post-consumer PP modifiers.[68,106-108] 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% PP by 27% compared to the unmodified bitumen.[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, indicating an excessive stiffening effect that may contribute to brittleness and heightened fatigue susceptibility.[106,110] However, other studies report contrasting trends. Dalhat found that micronized PP 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 PP-modified asphalt mixtures remains insufficiently characterized, with limited and variable findings reported in the literature. Otuoze *et al.* consistently observed a deterioration in viscoelastic and rheological properties when PP was incorporated into asphalt binders, while Dalhat *et al.* reported no clear trend or adherence with PP in relation to elastic recovery adhering to AASHTO TP 70 elastic recovery standards.[88,111] Without elastomeric polymer additives, PP-modified binders consistently exhibited deteriorated elastic recovery values below 20. The initially poor elasticity associated with solely PP 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; higher concentrations required the inclusion of an elastomeric polymer. Separately, Chiang *et al.* and Vamegh *et al.* supported this conclusion, noting significant improvements in thermal stability, as well as moisture and rutting resistance when using elastomeric polymer additives (crumb rubber and SBS in the former, and synthetic styrene-butadiene rubber (SBR) in the latter), opposed to solely PP-modified bitumen.[113,114]

In contrast, other studies have reported that the sole use of PP 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 PP, which supports earlier observations by Ho *et al.* linking lower molecular weight polymer modifiers to higher storage stability.[89] Furthermore, Appiah *et al.* found PP more favorable compared to HDPE due to its slight, linear improvements to the viscosity, deformation properties, and storage stability compared to the inconsistent mechanistic qualities of HDPE.[100]

PS:

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

Generally, PS 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.[120-124] Though thermal deterioration has been documented at both high and low temperature extremes. Hasan *et al.* noted PS-modified bitumen to have a faster stiffening rate at low temperatures in comparison to unmodified bitumen, which may lead to excessive rigidity and increase susceptibility to brittle fractures, and such susceptibility in low temperatures has been noted in other studies.[122,123]

PS has also been associated with increased air void content in asphalt mixtures compared to traditional stone aggregate asphalt. Using the dry process, Vasudevan *et al.* compared re-

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cycled 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 PS-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 unmodified bitumen.[127]

Vila-Cortavitarte *et al.* reported increased air voids and higher Cantabro loss at 1 wt% of asphalt PS content, indicating reduced abrasion resistance compared to the unmodified bitumen.[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 PS 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 PS 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.

PET:

PET is an inert thermoplastic polymer with a very high molecular weight and melting point at around 250-265 °C.[131-134] This high melting point significantly exceeds the average bitumen mixing temperature and is deemed by some studies as unsuitable for the wet process mixing.[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 process implementation with Quartzite and Granite aggregates by Ghabchi *et al.*, who found improved stripping resistance to unmodified bitumen, 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 PET, 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.[137-141] Overall, the possibility of weakened adhesion and air voids necessitates further research on the crystallization behavior of PET in the binder mix, as it can catalyze adverse effects on performance under certain conditions.

Rheology and fatigue remain mostly unaffected by the contradictory 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 PET 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 PET within the asphalt.[86]

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 °C, which falls level with or slightly above average crumb rubber-modified Hot Mix Asphalt mixing temperature (166 - 204°C), thus making it suitable for both the wet and dry processes.[134,144,146] Though PVC is often incorporated via the wet process, some studies found the high melting point to hinder mixing and perform unsuitably when utilizing the wet process.[68]

Post-consumer PVC-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.[148,149-152] Further evidence of an extended low-temperature fatigue life is suggested by the higher asphalt stiffness relative to unmodified bitumen, 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 PVC-modified asphalts can potentially achieve balanced deformation characteristics.

PVC 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, PVC 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 PVC-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 PVC dosage but later increased as the dosage reached higher levels. Overall, there appears to be an effective PVC 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]

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 processes, owing to its amorphous structure. Although it lacks a definitive melting point, ABS exhibits a glass transition temperature around 100 °C.[42] Notably, ABS is documented to experience chemical degradation at temperatures starting from 120 C° and significant benzene emissions at temperatures exceeding 140 °C. 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 ABS that hindered conventional wet process mixing.[68] In contrast, other studies expressed no issues. ABS 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 PMB.[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 unmodified bitumen at an ABS concentration of 9 wt% of bitumen. They attributed this to excessive stiffness that may have led to low-temperature brittleness. Additionally, ABS 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 ABS 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 PET via dry process modification, as ABS 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 VOCs harmful to humans when heated to high temperatures ranging from 170 to 240 °C.[170-172] Tiganis *et al.* documented the mobilization of benzene byproducts via the volatilization of styrene when ABS was heated to temperatures higher than 140 °C.[164] The asphalt processing temperatures utilized in the study (140-180 °C) approximated industry standard wet process mixing thresholds, which indicates credible potential for harmful emissions during the asphalt mixing process.[42,134]

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

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yielded rutting resistance comparable to SBS-modified mixtures, it still outperformed base asphalt.[177] Similarly, Hao *et al.* found that recycled PU 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 recycled PU, resulting in broken-down molecular products that improved the rutting resistance. Overall, the mechanical properties of recycled PU similarly reflect those enhancements produced by virgin or prepolymer PU in comparison to unmodified bitumen. Thermal susceptibility is improved, and mechanical properties are well-balanced so that the pavement is neither overly rigid nor pliable.

The main difference between recycled PU and reactive PU-modified asphalts is storage stability. Unlike reactive PU prepolymers, adding recycled PU 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 SBS compared to formulations without elastomer enhancement.[178]

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 unmodified bitumen or PMB 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 LDPE 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.[182-186] 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.

Policy:

The shifting U.S. regulatory landscape is 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 UK's 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 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 rescissions 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.[193-196] 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.

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 sustainabil-

ity 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 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.

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 MP 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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