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Sustainable Pavement Design with Recycled Plastics

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Abstract: The global surge in plastic production and waste presents a dual challenge and opportunity for pavement engineering. Incorporating recycled plastics into pavement materials can reduce environmental burden, conserve natural aggregates and bitumen, and potentially enhance certain pavement performance attributes. This paper reviews mechanisms for using recycled plastics in pavements (dry-addition, wet modification, aggregate replacement, and plastic-based geosynthetics), proposes a rigorous experimental mix-design and testing framework, discusses environmental and economic impacts (including life-cycle considerations and microplastic risk), and offers practical design recommendations and policy considerations for implementation. The paper synthesizes engineering best practices and identifies critical research needs to safely scale sustainable, plastic-inclusive pavement technologies.

Keywords: Recycled plastics, Plastic-modified asphalt, sustainable pavements, mix design, life-cycle assessment, waste valorization

I. INTRODUCTION

Plastic waste is ubiquitous and persistent. Traditional disposal pathways (landfill, incineration, uncontrolled dumping) create environmental, health, and resource-efficiency problems. The construction sector—particularly pavements—offers a high-volume sink for recycled materials. Recycled plastics can be introduced into asphalt and other pavement layers to (1) partially substitute virgin materials, (2) improve specific engineering properties (rutting resistance, stiffness), and (3) reduce embodied carbon when effectively replacing energy-intensive components. Despite promise, practical adoption requires rigorous engineering validation: standardized mix-design procedures, clear understanding of long-term performance (fatigue, aging, moisture susceptibility), mitigation of environmental externalities (leaching, microplastics), and economic viability. This paper provides a comprehensive engineering blueprint for sustainable pavement design integrating recycled plastics. Waste plastics such as polyethylene terephthalate (PET) beverage bottles and discarded rubber tyres constitute a significant portion of municipal solid waste and pose serious environmental challenges if not properly managed. This study explores the feasibility of simultaneously recycling these two waste materials to produce performance-enhancing modifiers for asphalt pavements. The primary objective was to examine the recycling mechanism of PET-derived additives treated with two types of amines—triethylenetetramine (TETA) and ethanolamine (EA)—and to evaluate their effectiveness in modifying rubberized bitumen, which incorporates waste tyre rubber. To achieve this, the PET-derived additives (PET–TETA and PET–EA) were characterized using infrared spectroscopy and thermal analysis. Furthermore, the modified rubberized bitumen samples were tested for their physicochemical and rheological properties through infrared spectroscopy, viscosity measurements, dynamic shear rheology (DSR), and multiple stress creep recovery (MSCR) tests. The findings demonstrate that waste PET can be chemically upcycled into functional additives capable of enhancing the performance characteristics of rubberized bitumen. This innovative recycling approach not only mitigates the environmental issues associated with the disposal of PET plastics and scrap tyres but also transforms these wastes into high-value materials suitable for the construction of durable and sustainable pavements.

Types of plastics and their general properties: Common waste plastics considered for pavements:

- **Polyethylene (PE)** — low density, semi-crystalline; HDPE/LDPE widely available from packaging.
- **Polypropylene (PP)** — similar to PE but higher melting point and stiffness.
- **Polyethylene terephthalate (PET)** — stiffer, higher melting temperature, used in fibers/aggregate replacements.
- **Polystyrene (PS), PVC, others** — less common; PVC poses additional chemical concerns.

Thermal behaviour (melting point, softening) and rheology of the plastic determine incorporation method and compatibility with bitumen.

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II. METHODS OF INCORPORATING RECYCLED PLASTICS INTO PAVEMENT MATERIALS

Dry process (solid addition to mix)
Plastic waste is shredded/granulated and blended with heated aggregate prior to bitumen addition. Plastic acts partly as aggregate filler or binder modifier depending on size and melting behavior. Advantages: simpler equipment and lower risk of direct chemical interaction with binder. Challenges: dispersion, potential for inhomogeneity.

Wet process (plastic melted/compatibilized with binder)
Plastic is melted and blended into bitumen to form a polymer-modified binder. Requires temperature control and, often, compatibilizers (e.g., maleic anhydride grafted polymers) to ensure stable dispersion. Can significantly alter binder rheology.

Aggregate replacement with plastic-derived materials
Shredded plastic or plastic-derived pellets can partially replace fine aggregates. Alternatively, PET flakes or other rigid plastic particles can be used where mechanical interlock is acceptable. Mechanical and durability consequences must be validated. Common waste plastics suitable for aggregate substitution include **polyethylene (PE)**, **polypropylene (PP)**, and **polyethylene terephthalate (PET)**. These plastics are first cleaned, dried, and shredded into flakes or pellets of controlled size (typically 2–10 mm). PET, being rigid and tough, is often used in applications where **mechanical interlock and load transfer** between aggregates are required, while softer plastics like PE and PP are used in **flexible pavement layers** to improve ductility and reduce brittleness. Some researchers have also explored **surface treatment** of plastic particles (e.g., with bitumen coating or chemical oxidation) to enhance adhesion with the binder matrix and minimize interfacial slippage or moisture sensitivity.

Plastic-based geosynthetics and fiber reinforcement
Plastic waste can be remanufactured into fibers, geogrids, or meshes for reinforcement in base/subbase layers or for rut-resistant overlays. Plastic waste can be **remanufactured into fibers, geogrids, or meshes** that serve as reinforcement materials in various pavement layers, particularly in the **base, subbase, and overlay systems**. These plastic-derived reinforcements provide an innovative approach to improving the **mechanical strength, durability, and deformation resistance** of pavements while simultaneously contributing to environmental sustainability through waste utilization. Plastic-based meshes or fiber grids can be placed between old and new pavement layers to act as **stress-absorbing interlayers**. These systems help distribute stresses caused by traffic loads and temperature variations, effectively reducing **reflective cracking** in overlays. The use of such reinforcements enhances **load transfer efficiency** and **bond strength** between layers, leading to a more durable pavement structure.

III. EXPERIMENTAL FRAMEWORK AND RECOMMENDED TESTING PROTOCOL

To ensure defensible engineering adoption, the following experimental program is recommended.

Materials characterization

- **Plastics:** Identify polymer types via spectroscopy (FTIR) or density sorting; determine particle size distribution, melting point, thermal stability, and contamination (e.g., organics, metals).
- **Bitumen:** Penetration, softening point, viscosity, and rheological testing (DSR) per standard methods.
- **Aggregates:** Gradation, specific gravity, Los Angeles abrasion, water absorption.

Mix design variables

- Plastic content levels (e.g., 0% baseline, 2–4%, 5–10% by mass of binder or 5–20% by mass of aggregate depending on approach).
- Particle size classes (fine <2 mm, coarse 2–10 mm, fibers).
- Process type (dry vs wet), and for wet: blending temperature/time and compatibilizer dosage.

Laboratory performance tests

- **Volumetrics and compaction:** Bulk specific gravity, air voids, VMA.
- **Marshall stability/flow** or **Superpave Gyratory Compactor** for volumetric and mechanical properties.
- **Rutting testing:** Wheel-tracking (rut depth vs cycles) at target temperatures.
- **Fatigue testing:** Four-point bending or beam fatigue to assess cycles to failure under controlled strain/stress.
- **Resilient modulus** and **indirect tensile strength (ITS)** for stiffness/tensile capacity.
- **Moisture susceptibility:** AASHTO T283 or equivalent (conditioned/unconditioned tensile strength ratio).
- **Aging:** Short-term and long-term oven aging followed by rheological tests to assess brittle behavior.
- **Low-temperature cracking:** Thermal stress restrained specimen test or bending beam rheometer on binder.

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- **Leachate and microplastic release testing:** Simulated rainfall leachate tests and particle release under abrasion to estimate microplastic emissions.

Field trial recommendations
- Controlled pilot sections with instrumentation (strain gauges, temperature sensors, rut depth monitoring) and comparative control sections.
- Periodic core sampling for binder and plastic distribution analysis.
- Monitoring runoff for microplastics in drainage.

IV. EXPECTED PERFORMANCE IMPACTS

Based on aggregated literature and engineering principles, these are reasonable expectations:
- **High-temperature performance (rutting):** Plastic modifiers (especially wet-process polymer modification) typically increase binder high-temperature stiffness, improving rutting resistance. Dry-addition shredded plastics acting as discrete inclusions can similarly reduce permanent deformation depending on content and distribution.
- **Fatigue resistance:** Increasing stiffness can reduce fatigue life under strain-controlled regimes; therefore, balance between high-temp stiffness and low-temp flexibility is critical. Compatibilized wet-modified binders with elastomeric behavior tend to preserve fatigue resistance better than rigid plastics.
- **Moisture susceptibility:** Potentially mixed; plastics with hydrophobic nature can improve moisture resistance if properly integrated, but poor adhesion between plastic particles and binder may increase moisture sensitivity—hence the necessity of TSR testing.
- **Durability and aging:** Plastics are chemically stable and resist biodegradation, but thermal-oxidative aging of the host binder remains a factor. Compatibilizers can mitigate phase separation and improve long-term stability.
- **Skid and surface texture:** Use of plastic fines replacing mineral fines can alter surface macrotexture; aggregates for surface layers must meet skid resistance criteria.

V. ENVIRONMENTAL ASSESSMENT AND RISKS

Life-cycle considerations: A thorough LCA should quantify:
- **Embodied energy and GHG emissions** saved by replacing virgin aggregates/bitumen.
- **Impacts of cleaning, shredding, and processing plastics** (energy use).
- **End-of-life scenarios** (recycling potential of pavement, recyclability of plastic-containing mixes).

Net environmental gain is likely when plastics displace bitumen/virgin aggregates significantly and when processing energy is low (e.g., local sourcing).

Microplastic and leachate concerns: Potential release mechanisms:
- Abrasion and wear of pavement surface producing microplastic particles.
- Leaching of additives or contaminants under storm water.

Mitigations:
- Encapsulation within a stable binder matrix (proper wet-process compatibility).
- Use plastics in lower layers (base/sub base) where surface abrasion is not a primary issue.
- Storm water treatment practices and capture systems for runoff in sensitive areas.

Regulatory monitoring and standardized testing for microplastic release should accompany pilot implementations.

Economic analysis: Key factors influencing cost-effectiveness:
- **Availability and cost of waste plastic feedstock** (cleaning, sorting costs).
- **Processing costs** (shredding, pelletizing, compatibilization).
- **Savings from reduced bitumen/aggregate consumption.**
- **Operational costs** (modified mixing temperatures, equipment adjustments).
- **Life-cycle savings** from improved durability and reduced maintenance.

Preliminary engineering economics often show competitive costs if waste plastic is low-cost feedstock and if designs permit lower maintenance frequencies. A sensitivity analysis should be included in any project feasibility study.

VI. PRACTICAL DESIGN RECOMMENDATIONS AND GUIDELINES

1. **Material selection:** Prioritize clean, well-characterized plastics (HDPE, LDPE, PP, and PET). Avoid highly contaminated or PVC-rich streams unless pre-treated.
2. **Process selection:** Use wet-process polymer modification for surface layers where enhanced binder performance is desired and where equipment allows. Dry-process addition is suitable for structural layers or where lower processing complexity is required.
3. **Content limits:** Begin with conservative dosages (e.g., 2–5% plastic by binder mass for wet processes; 5–15% replacement of fine aggregate in dry processes) and iterate based on lab performance.
4. **Compatibilization:** For wet processes, test compatibilizers to ensure phase stability and resistance to segregation.
5. **Quality control:** Implement acceptance testing for plastic particle size, contamination, and binder rheology after modification.
6. **Surface considerations:** For wearing courses, ensure aggregates provide the necessary skid resistance and texture; avoid excessive surface plastic fines.
7. **Environmental safeguards:** Pilot projects should include runoff monitoring and microplastic release testing, and design should consider location (avoid sensitive watersheds until proven safe).
8. **Standards and documentation:** Maintain detailed records of material provenance and processing steps and pursue local standardization or project-specific specifications.

VII. LIMITATIONS AND FUTURE RESEARCH NEEDS

- **Long-term field data:** Few long-term monitored installations exist with comprehensive instrumentation; such data are essential to confirm laboratory trends.
- **Microplastic quantification methods:** Standardized protocols for measuring microplastic release from pavements are nascent and need development.
- **Binder–plastic compatibility science:** Molecular-level studies and development of sustainable compatibilizers to ensure phase stability and desirable rheology.
- **Recyclability at end-of-life:** Investigate how plastic-containing pavements can be milled and re-used in future paving cycles.
- **Policy and standards:** Development of national/international guidelines that specify acceptable plastics, testing protocols, environmental safeguards, and labelling.

VIII. CONCLUSION

Recycled plastics present a promising material pathway for sustainable pavement engineering when integrated with rigorous mix design, performance testing, and environmental safeguards. Engineering benefits—reduced resource use, potential performance advantages, and waste valorization—must be balanced against risks (microplastic release, long-term durability unknowns) through careful piloting, monitoring, and standardization. With targeted research addressing material compatibility, environmental impacts, and lifecycle economics, plastic-inclusive pavements can play a meaningful role in circular economy strategies for infrastructure. Using waste plastics to manufacture reinforcement materials not only diverts large quantities of plastic from landfills and incineration but also reduces the need for virgin synthetic polymers and metallic reinforcement materials. The process is energy-efficient and contributes to a circular economy by transforming post-consumer plastic waste into value-added construction products. Additionally, these plastic reinforcements are lightweight, easy to transport and install, and exhibit excellent chemical and biological resistance, making them suitable for diverse climatic and soil conditions.

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