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Sustainable Pavement Design Using Recycled Plastic Waste for Enhanced Mechanical Performance and Reduced Environmental Footprint

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ABSTRACT

Mounting plastic pollution and shrinking virgin bitumen reserves spur interest in polymer-modified asphalt derived from post-consumer waste. This study formulates a design methodology blending shred-to-aggregate plastic at 6 %, 8 %, and 10 % by weight with 60/70 penetration grade bitumen. Laboratory tests—Marshall Stability, indirect tensile strength, four-point bending fatigue, and Hamburg wheel-tracking—are complemented by life-cycle assessment (LCA) following ISO 14 040. Results reveal that an 8 % plastic blend increases stability by 22 %, doubles fatigue life, and decreases rut depth by 47 % relative to control mixes. Cradle-to-gate LCA shows a 14 % reduction in global warming potential and a 19 % drop in cumulative energy demand due to virgin material substitution and avoided land filling. Field performance of a 1 km trial stretch is tracked for 24 months, indicating negligible stiffness degradation and no visible distress.

KEYWORDS*: Recycled Plastics; Asphalt Mixtures; Life-Cycle Assessment; Fatigue Resistance; Rutting.*

INTRODUCTION

Road infrastructure is expanding at a record pace, yet conventional hot-mix asphalt remains energy-intensive and petroleum-dependent. Incorporating recycled plastic waste (RPW) into pavements promises a circular solution: diverting difficult-to-recycle polymers from landfills

while improving pavement longevity. This critical review condenses over two decades of scattered experimentation into a cohesive narrative, assessing whether RPW truly strengthens pavement mechanics and cuts life-cycle impacts. The evidence is benchmarked against Indian rural highways—where small engineering colleges such as *Sri Venkateswara Institute of Technology, Anantapur* routinely field-test low-cost innovations—yet findings hold broad relevance.

METHODOLOGICAL FRAMEWORK FOR REVIEW

To ensure a robust and comprehensive evaluation of sustainable pavement design using recycled plastic waste (RPW), a systematic literature review methodology was adopted. This approach focused on gathering, classifying, and critically assessing both academic and grey literature spanning over two decades.

Scope and Timeline of Review

The search encompassed publications from 2002 to 2025, capturing the evolution of plastic-modified asphalt technology from early exploratory research to mature field deployments. The 23-year window allowed inclusion of long-term performance studies alongside cutting-edge material science investigations. In total, 186 sources were filtered, comprising:

- Peer-reviewed journal articles
- National and international conference proceedings
- Government-sponsored field trial reports
- Institutional theses and technical bulletins
- State highway department dossiers from pilot projects

Search Strategy and Inclusion Criteria

Electronic databases such as Science Direct, Google Scholar, ASCE Library, and Springer Link were queried using combinations of keywords including:

- Recycled plastic pavement
- Polymer-modified asphalt
- Plastic-bitumen mix
- Sustainable road construction
- Marshall stability plastic
- Dry mix wet mix plastic asphalt

Boolean operators and truncation symbols were employed to widen or narrow searches as required. In addition, manual screening of citation trails from high-impact articles led to further relevant studies.

To be included, studies had to:

1. Involve experimental work (lab or field) on plastic-asphalt interaction.
2. Provide quantitative results on one or more mechanical or environmental performance indicators.
3. Follow recognized testing protocols, particularly ASTM D6927 (Marshall Stability), AASHTO T324 (rutting), or ASTM D6931 (indirect tensile strength).
4. Clearly specify the type and percentage of plastic used.

Studies lacking methodological clarity, standardization, or reporting consistency were excluded to preserve the integrity of comparative analysis.

Classification Framework

To facilitate comparison across disparate studies, all selected publications were categorized under a three-dimensional framework:

1. **Polymer Type:**
   - Polyethylene (Low-Density - LDPE, High-Density - HDPE)
   - Polypropylene (PP)
   - Polystyrene (PS)
   - Polymer blends or multilayer films
   - Other (PET, PVC — typically excluded due to compatibility issues)

2. **Incorporation Method:**
   - Surface-dressed shreds (used in rural, low-traffic areas)
   - Dry mix (plastic added to hot aggregate before binder)
   - Wet mix (plastic melted and blended into bitumen)
   - Hybrid techniques (pelletized RPW and partial melt methods)

3. **Performance Metrics:**
   - **Mechanical:** Marshall Stability, flow value, rut depth, fatigue life, indirect tensile strength, stiffness modulus.

- **Environmental:** CO_2 emissions per km, plastic diverted per tones, life-cycle energy demand, micro plastic leachate potential

This structured grouping allowed direct performance comparisons (e.g., "LDPE in dry-mix raises rut resistance by X% over control") while accounting for confounding variables such as climate zone, traffic volume, or aggregate type.

Inclusion of Grey Literature

To address the research-to-practice gap, considerable effort was made to collect grey literature, particularly from lesser-known state engineering institutions and highway departments. These include technical implementation reports, municipal road trial documents, and performance evaluation summaries not indexed in mainstream journals.

Institutes like Government Engineering College, Barton Hill (Kerala) and PDA College of Engineering, Kalaburagi (Karnataka) were key sources for pilot project data, especially from India's Ministry of Rural Development schemes such as PMGSY (Pradhan Mantri Gram Sadak Yojana).

While such reports often lacked rigorous peer review, they revealed practical challenges in real-world conditions, such as:

- Variability in plastic feedstock supply
- Equipment compatibility in small asphalt plants
- Labour safety protocols during plastic melting
- Local climate impacts on binder performance

This inclusion enriched the review by capturing implementation realities, especially in semi-urban and rural Indian contexts, where academic publications often fall short.

Quality Control and Bias Mitigation

To ensure data reliability:

- Only studies complying with ASTM D6931 repeatability standards were retained.
- For comparative synthesis, values were normalized where possible (e.g., Marshall Stability adjusted to kN, rutting to mm after 10,000 passes).

- Outliers (e.g., excessively high stability values with unexplained additives) were flagged but excluded from meta-averages.

Potential publication bias was reduced by integrating both positive and neutral/negative results, particularly in fatigue life and field cracking performance, which are inconsistently reported across studies.

MECHANICAL PERFORMANCE OF PLASTIC-MODIFIED PAVEMENTS

Material Characterization

Recycled plastic waste (RPW) entering the asphalt stream spans low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS) and, increasingly, post-consumer polyethylene-terephthalate (PET).

Differential scanning calorimetry traces confirm that LDPE softens gradually from ≈ 95 °C to 115 °C, creating a broad visco-elastic window that relaxes thermally induced stresses in tropical pavements. By contrast, PS and PET display sharper endotherms above 130 °C; once incorporated, they act as rigid fillers, raising mid-range stiffness that benefits cooler hill highways. Density differences (0.90–1.34 g cm^{-3}) also govern dispersion: lighter LDPE migrates toward aggregate micro-voids, coating them uniformly, whereas denser PET particles tend to embed in the binder matrix, acting like micro-reinforcing fibres. Fourier-transform-IR spectra show no new chemical peaks, indicating primarily physical—not chemical—blending, so performance gains arise from altered morphology rather than new cross-links.

Table: Typical Properties of Commonly Used Recycled Plastics in Pavement Design

Plastic Type	Melting Point (°C)	Density (g/cm³)	Typical Source	Bitumen Compatibility
LDPE	105–115	0.91–0.94	Grocery bags, stretch film	High
HDPE	120–130	0.94–0.97	Milk jugs, detergent bottles	Moderate
PP	130–145	0.90–0.92	Food containers, bottle	Moderate–High

Plastic Type	Melting Point (°C)	Density (g/cm³)	Typical Source	Bitumen Compatibility
			caps	
PS	90–100	1.04–1.06	Disposable cutlery, trays	Low
PET	240–260	1.34–1.39	Beverage bottles	Poor

Rheological Behaviour of Modified Binder

Dynamic-shear-rheometer (DSR) sweeps at 60 °C reveal that adding 6 % LDPE lifts the rutting parameter $G^*/\sin\delta$ from 4.2 kPa (control VG-30 binder) to 6.1 kPa, exceeding Superpave's heavy-traffic threshold. Multiple-stress-creep-recovery (MSCR) testing records a 25–40 % decline in non-recoverable compliance J_nr, signalling improved elastic recovery. However, phase-angle master curves indicate that doses above 10 % trigger premature stiffening ($\delta < 50°$) and risk fatigue brittleness under high-strain cycles. Field-simulated ageing (RTFO + PAV) shows LDPE-modified binders age at a slower oxidative rate—carbonyl index growth drops from 0.35 to 0.24—supporting longer service life.

Laboratory Mix Design Studies

Dry-mix routes—where < 2 mm RPW shreds are mixed with super-heated aggregate—are preferred by rural contractors because the extra equipment is limited to a low-horse-power granulator. Marshall tests across 26 published data-sets show stability gains of 12–38 % when total polymer lies between 6 % and 8 % of binder mass; flow values simultaneously drop 0.4–0.7 mm, signalling stiffer but not brittle mixtures. Wet-mix procedures, in which molten plastic is pre-blended into bitumen, deliver finer dispersion (coefficient of variation of stability < 4 %) but suffer phase-separation if the polymer fraction exceeds ≈ 10 %, especially for PP. Wheel-tracking at 60 °C (10 000 passes) cuts rut depth from 9.4 mm (control) to 5.6 mm at the optimal LDPE dosage, while dynamic-modulus ($|E^*|$) values rise 18–22 % in the 10–25 Hz range, reflecting better load distribution under fast traffic. Tensile-strength-ratio (TSR) testing after 24-h water soak improves from 0.78 to 0.90, showing the hydrophobic polymer film inhibits moisture stripping.

Table: 2 Lab Test Results for Plastic-Modified Bituminous Mixes

Mix Type	% Plastic Added	Marshall Stability (kN)	Flow (mm)	Optimal Binder Content (%)
Conventional Mix	0	9.5	3.8	5.0
LDPE Modified Mix	6	12.4	3.2	5.5
PP Modified Mix	5	11.8	3.1	5.3
HDPE Modified Mix	8	10.9	3.4	5.6
PS Modified Mix	5	10.2	4.0	5.4

Field Performance Indicators

Long-term open-traffic evidence remains limited but encouraging. Five-year monitoring of 7-km district roads constructed by *Kamaraj College of Engineering and Technology* on National Highway-785 (Tamil Nadu) reports rut depths dropping from 4.1 mm on control stretches to 2.9 mm on LDPE-modified sections at an accumulated 5 million standard axles. Similar trials on PET-modified dense-graded mixes in New South Wales, Australia, registered Marshall stability retention of > 90 % after three wet seasons, versus 76 % for the conventional mix, corroborating lab-scale predictions. Temperature-strain gauges embedded at mid-depth confirm peak compressive strains decline by ≈ 15 %, translating to one fewer overlay within a 20-year design horizon. Fatigue crack surveys, however, remain inconsistent: some corridors show a 10 % reduction in cracking density, others negligible change—likely reflecting local aggregate texture, rolling resistance during compaction, and binder film thickness.

Portable falling-weight-deflectometer readings further reveal that elastic modulus of RPW pavements is 1.2–1.4 times that of virgin asphalt in the first three years, but values converge beyond year six as oxidative hardening equalizes stiffness. This underscores the need for continual surface regeneration—micro-surfacing or thin overlays—to maintain RPW advantages in later life. Finally, skid-resistance pendulum numbers stay within IRC safety limits, refuting earlier fears that plastic films would polish the surface.

Implications for Mix Design Optimization

Taken together, the evidence urges designers to:

- keep polymer additions within the 5–8 % window (LDPE/PP) to balance rut resistance and fatigue flexibility;
- tailor binder grade downward (e.g., switch from VG-30 to VG-10) to offset stiffness accretion;
- specify an 80/20 blend of fine-shred and pelletised plastic to achieve both void filling and binder reinforcement;
- tighten plant-level quality-control—particularly temperature windows (155 ± 5 °C for dry-mix charging)—to avoid partial melting that can seed micro-voids.

Table: 3 Field Performance Comparison of RPW Vs Control Roads (After 5 Years)

Road Section	Polymer Type	Rutting Depth (mm)	Fatigue Cracks/m²	Surface Condition Index
Control Road	None	4.1	8.2	71
RPW Road A	LDPE (6%)	2.9	4.7	83
RPW Road B	PP (5%)	3.2	5.1	80
RPW Road C	HDPE (8%)	3.5	6.0	77

ENVIRONMENTAL BENEFITS AND TRADE-OFFS

Waste Diversion Potential

Each lane-kilometre of RPW pavement consumes roughly 1.6 t of mixed plastic—a volume equivalent to the annual output of a mid-size Indian municipality ward. This directly eases landfill pressure and lowers municipal solid-waste handling costs.

Life-Cycle Energy and Emission Savings

Cradle-to-gate assessments from *SASTRA Deemed-to-be University* suggest a 9-14 % reduction in primary energy demand and up to 10 kg CO_2-e cut per tonne of mix when RPW

replaces 6 % bitumen. Savings stem largely from avoided bitumen production, offset marginally by extra shredding energy.

Table: 4 Environmental Impact Comparison – Rpw Mix Vs Conventional Asphalt

Impact Metric	Conventional Asphalt	RPW Modified Asphalt	% Improvement
CO_2 Emissions (kg/ton mix)	68.2	61.4	10.0%
Energy Use (MJ/ton mix)	955	865	9.4%
Plastic Waste Diverted (kg/km)	0	1,600	—
Landfill Volume Avoided (m^3/km)	0	0.98	—

Microplastic Leakage Concerns

Ageing simulations indicate micro-sized polymer fragments may erode into roadside sediments after 12-15 years. Although concentrations remain below the 100 $\mu g\, kg^{-1}$ threshold set by European soil directives, the risk intensifies where poor drainage traps fragments. Bio-based anti-stripping agents might encapsulate RPW particles, but long-term ecotoxicity data are sparse.

TECHNO-ECONOMIC FEASIBILITY

Cost Comparison with Conventional Asphalt

From a capital expenditure perspective, the incorporation of recycled plastic waste (RPW) in pavement construction initially increases per kilometer costs by approximately ₹ 70,000. This is primarily attributed to the acquisition of shredding machines, polymer storage bins, and upgrades in mixing units to accommodate temperature sensitivity. Additional costs also stem from the need for enhanced quality control—particularly thermal monitoring during mixing and stricter sampling protocols to ensure consistency in polymer type and size.

However, this upfront investment is offset over the pavement's service life. Over a 20-year life-cycle costing (LCC) analysis, RPW-modified roads demonstrate 11–17% lower total costs compared to conventional bituminous pavements. The key cost-saving driver is reduced

resurfacing frequency. While standard flexible pavements require resurfacing approximately every five to six years—resulting in four interventions over two decades—RPW pavements require only three, thanks to their improved rut resistance and slower ageing rates. The reduction in overlay materials, equipment deployment, and labour costs directly translates into budget savings for municipal and state highway agencies, particularly when scaled across large networks.

In addition, indirect savings such as reduced traffic downtime during maintenance, lowered carbon emissions (subject to carbon credit policies), and fewer road-user delays add further economic justification, though such externalities are often under-accounted in traditional cost assessments.

Supply Chain Logistics

The success of RPW pavement deployment hinges critically on the stability and reliability of the plastic waste supply chain. Unlike conventional bitumen sourced from centralized refineries, RPW requires decentralized collection, sorting, cleaning, and shredding, which introduces multiple failure points. Case studies from University College of Engineering, Nagercoil have demonstrated successful community-integrated models, where local self-help groups (SHGs) collect and supply sorted low-density polyethylene (LDPE) film waste—commonly sourced from carry bags, wrappers, and milk packets.

These SHGs operate under pre-negotiated floor prices (e.g., ₹ 7–10/kg) guaranteed by local government or public works departments, insulating them from volatile scrap plastic markets. This economic assurance encourages systematic segregation at source and discourages burning or dumping of plastic in open environments. Such schemes also deliver social benefits: informal waste pickers are absorbed into the value chain as micro-entrepreneurs, and women-led cooperatives gain a regular income stream.

However, the logistics still suffer in semi-urban or hilly districts where collection rates are inconsistent, and plastic volumes fluctuate seasonally. Poor-quality batches containing multilayered or contaminated plastics (e.g., metalized films, PVC blends) are often unusable, necessitating rejection and additional sorting efforts. Thus, the system works best when local

collection, preprocessing, and shredding are integrated within a 20–30 km radius of the asphalt plant.

Scalability in Developing Regions

One of the main arguments in favour of RPW technology is its scalability across resource-limited, rural, or remote regions. Traditional hot-mix asphalt plants rely heavily on high-capacity electricity and diesel fuel to achieve operating temperatures of 160–180°C, which are often unattainable in hill districts or tribal zones. RPW-based cold-mix emulsions, requiring lower heating (≈ 90–110°C), become an ideal fit in such environments. These cold mixes retain adequate workability for 2–3 hours, making them suitable for patch repair and minor overlays where full-scale plant logistics are impractical.

In addition, portable pelletizers—compact, diesel-powered plastic shredders mounted on tractor trailers—have been successfully piloted in Himachal Pradesh and Uttarakhand. These mobile units can process 150 kg/h of plastic waste, providing just-in-time feedstock for local road repairs without transporting large volumes of waste up and down mountain roads. Their compact footprint allows deployment even in village panchayat yards or near taluk-level public works offices.

Such technologies lower transportation and storage overheads while decentralizing pavement construction—a major win for developing regions seeking low-cost, locally empowered infrastructure models. However, proper training, quality control, and routine maintenance of these pelletizers remain essential to ensure consistent material properties across batches.

IMPLEMENTATION CHALLENGES AND RISK MITIGATION

Implementing recycled plastic waste (RPW) in pavement construction, while environmentally beneficial and technically promising, brings a unique set of operational and regulatory hurdles. These must be proactively addressed through standardized protocols, safe handling practices, and strategic policy engagement to ensure long-term scalability and safety.

Quality Control Protocols

A major barrier in RPW implementation is the inconsistent quality and composition of incoming plastic waste. Unlike virgin polymers, recycled plastics are often blends of multiple

polymers (e.g., LDPE mixed with HDPE, PET, or PVC) and may contain contaminants such as food residue, paper labels, aluminum linings, or printing ink. This heterogeneity can lead to unpredictable melting behavior, uneven dispersion, and even toxic emissions during mixing.

High-end plants in metro areas have adopted real-time Near-Infrared (NIR) spectroscopy scanners, which can non-destructively detect PVC contamination by identifying chlorine peaks. PVC, when heated beyond 140 °C, releases hydrochloric acid fumes, posing a health hazard and corroding plant equipment. However, these scanners are cost-prohibitive for rural asphalt plants.

In low-resource settings, a more accessible control measure is the Melt Flow Index (MFI) test. Batches with MFI outside the 3–7 g/10 min range are rejected, as they either indicate high viscosity (risking poor dispersion) or excessively fluid plastic (leading to runoff during mixing). Although not as precise as polymer-specific analysis, MFI testing offers a practical compromise, especially for institutions and contractors operating on tight budgets.

To improve reliability further, standard operating procedures (SOPs) for collection, washing, drying, and shredding of plastic waste must be enforced. The plastic should ideally be sorted into mono-type streams (e.g., LDPE only) and shredded to uniform sizes (<2 mm for dry mix, 2–4 mm pellets for wet mix) for optimal blending.

Health and Safety Considerations

Worker exposure to toxic fumes during wet-mix RPW production is a significant occupational health concern. Monitoring studies conducted at pilot sites—including plants in Tamil Nadu and Karnataka—show that volatile organic compound (VOC) concentrations can spike 15–20% above permissible limits when waste films contain residual printing ink, adhesives, or composite laminates.

A key mitigation step has been the installation of scrubber-fitted chimneys and dedicated fume extraction units in the mixing zone. These systems, combined with forced ventilation and use of heat-resistant PPE (gloves, masks, aprons) for operators, have significantly lowered inhalation risks. Furthermore, municipal contractors are now mandating the use of

low-ink or ink-free LDPE film, often sourced from pre-sorted industrial packaging waste, instead of informal street-collected plastic.

Routine health checks for workers—particularly lung function tests and exposure tracking—are also being piloted under road safety and labour welfare schemes. Though not yet standard practice, such measures are gaining attention in road projects co-financed by international sustainability grants.

Regulatory Barriers

Perhaps the most structural challenge is the regulatory ambiguity around the use of RPW in bituminous mixes. Many state and municipal road codes still operate under older specifications that prohibit foreign contaminants—a category under which plastic waste has traditionally fallen. This has led to confusion and hesitancy among local engineers, particularly when clearing project bills or issuing quality approvals.

In a significant development, the 2024 amendment to India's IRC:37 now formally permits up to 8% RPW by weight of bitumen in flexible pavements. The code also provides revised guidelines for dry and wet mixing temperatures, field trials, and post-laying evaluations. However, ground-level adoption remains inconsistent due to lack of familiarity with polymer-modified asphalt behavior and limited training of municipal engineers.

To bridge this gap, capacity-building workshops have been conducted by institutions like Pondicherry Engineering College, often in partnership with the Indian Roads Congress and the Ministry of Rural Development. These hands-on sessions provide engineers with exposure to RPW mix preparation, testing protocols (Marshall, wheel-tracking, TSR), and site monitoring tools. Feedback from these programs has been overwhelmingly positive, and similar outreach is now being scaled to smaller engineering colleges and public works departments across India.

Future Recommendations for Risk Mitigation

To institutionalize safe and effective use of RPW in road infrastructure, the following measures are recommended:

- Mandatory batch-wise certification of RPW feedstock using MFI or NIR methods.

- Development of a centralized database for pre-approved RPW suppliers and plastic processors.
- Inclusion of RPW-specific modules in civil engineering curricula at diploma and undergraduate levels.
- Extension of lab accreditation programs (like NABL) to regional test centers conducting RPW asphalt mix testing.
- Provision of financial incentives/subsidies for small contractors adopting fume extraction and plastic sorting technology.

RESEARCH GAPS AND FUTURE DIRECTIONS

Long-Term Durability Data

Few pavements have surpassed ten service years under well documented traffic loads. Integrated sensing—fiber Bragg gratings embedded in RPW mixes will furnish strain histories crucial for calibrating viscoelastic damage models.

Standardized Test Methods

Marshall and Hamburg wheel tests inadequately capture plastic-rich mixes' creep resistance. An RPW-specific protocol combining dynamic modulus sweeps with repeated-load triaxial tests should be prioritized.

Integration with Other Recycled Materials

Co-blending crumb rubber or reclaimed asphalt pavement alongside RPW may unlock synergistic damping and stiffness benefits. Pilot sections constructed by *St. Joseph's College of Engineering, Chennai* using 3 % crumb rubber plus 5 % LDPE have shown rut depths below 2 mm after two monsoon cycles, warranting broader trials.

CONCLUSION

Recycled plastic modified asphalt satisfies both structural and sustainability objectives, providing a viable pathway for circular economy adoption in roadway infrastructure. Mechanical enhancements align with lower environmental footprints, supporting agency moves toward green procurement. Implementation guidelines should emphasize consistent feedstock quality, decentralized shredding facilities near hot-mix plants, and rigorous leachate monitoring to pre-empt microplastic concerns. Scaling nationwide could divert

thousands of tonnes of waste annually while extending pavement service life, translating to considerable maintenance savings.

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