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Plastic Waste Utilization in Bituminous Mix for Sustainable Pothole Repair: Experimental and Field Evaluation

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Abstract:** Pothole formation is a dominant distress mechanism in flexible pavements, especially in regions subjected to high rainfall, temperature fluctuations, and increasing traffic loads. Concurrently, the proliferation of non-biodegradable plastic waste presents a critical environmental challenge. This study investigates the engineering feasibility and sustainability benefits of incorporating waste plastics (LDPE, HDPE, and PET) into bituminous mixes for pothole repair using the dry process method. Plastic content was varied from 0% to 10% by weight of bitumen. Performance was evaluated through laboratory tests including Marshall Stability, Flow value, Indirect Tensile Strength (ITS), and Tensile Strength Ratio (TSR), followed by statistical analysis (one-way ANOVA and quadratic regression), 12-month field implementation in Pratapgarh City and Chilbila, Uttar Pradesh, and comprehensive Life Cycle Assessment (LCA) & Life Cycle Cost Analysis (LCCA).Results demonstrate substantial improvements with optimum performance at 6–8% plastic content: Marshall Stability increased by 32% (16.5 kN), ITS by 34.1% (1.10 MPa), and TSR by 23.7% (94%). Field trials showed no pothole reformation after 12 months (including two monsoons) in plastic-modified sections, compared to repeated failures in conventional repairs. Environmental benefits include diversion of 250–450 kg plastic waste per km and 1.2–2.0 tonnes CO_2 eq. reduction per km. Economic analysis indicates 18–22% lower initial costs and nearly 50% reduction in lifecycle costs (BCR 4.8 vs 1.4). The study validates plastic-modified mixes as a technically superior, economically viable, and environmentally sustainable solution for pothole repair, supporting Swachh Bharat Mission, PMGSY, and circular economy principles in semi-urban Uttar Pradesh.

***Keywords:** Plastic waste, Bituminous mix, Dry process, Marshall Stability, Indirect Tensile Strength, TSR, ANOVA, Quadratic regression, Pothole repair, Sustainable pavement, Uttar Pradesh*

I. INTRODUCTION

Road infrastructure is vital for economic growth, but potholes remain a persistent challenge in India, particularly in states like Uttar Pradesh with heavy monsoon rainfall, alluvial soils, poor drainage, and overloaded vehicles. In Pratapgarh district and the semi-urban area of Chilbila (near the Ganga River), frequent potholes lead to accidents, traffic disruptions, and high economic losses. Uttar Pradesh accounts for nearly half of India's pothole-related fatalities (approx. 4,500 out of 9,109 between (2019–2023), with annual economic losses exceeding ₹10,000 crore state-wide. Simultaneously, India generates 3.5–4.0 million tonnes of plastic waste annually, with Uttar Pradesh contributing 0.6–0.8 million tonnes. Low collection (30–55%) and recycling rates exacerbate landfill use, river pollution (especially near the Ganga), and open burning. Non-degradable plastics like LDPE (carry bags), HDPE (bottles), and PET (containers) dominate this waste stream. The "waste-to-wealth" approach of incorporating shredded plastic waste into bituminous mixes, pioneered by Dr. R. Vasudevan using the dry process, offers a dual solution. This study focuses on pothole-specific applications in a semi-urban eastern Uttar Pradesh context, addressing gaps in localized field validation, statistical rigor, and integrated sustainability assessment. It aligns with IRC: SP: 98-2013 guidelines, MoRTH specifications, Plastic Waste Management Rules (2016, amended), and national missions like Swachh Bharat and PMGSY.

A. Objectives

1) Evaluate mechanical properties of plastic-modified mixes at varying dosages.
2) Perform statistical validation (ANOVA, regression).
3) Implement and monitor field trials.
4) Assess environmental and economic benefits via LCA and LCCA.

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Scope and Limitations: Focused on LDPE/HDPE/PET blend, dry process, short-to-medium term performance (12 months), and selected sites in Pratapgarh and Chilbila.

II. MATERIALS AND METHODS

A. *Materials*

1) Bitumen: VG-30 grade (penetration 60–70, softening point 45–55°C) per IS 73:2013.
2) Aggregates: Coarse (10–20 mm) and fine (<4.75 mm) meeting MoRTH Section 500 (Dense Bituminous Macadam gradation), specific gravity 2.6–2.7, crushing value <30%.
3) Plastic Waste: Locally collected LDPE, HDPE, and PET from municipal sources in Pratapgarh. Segregated, cleaned, dried, and shredded to 2–4 mm size.
4) Filler: Stone dust.

B. *Mix Preparation (Dry Process)*

Aggregates heated to 160–170°C → Shredded plastic added (4%, 6%, 8%, 10% by wt. of bitumen) and mixed until melted and uniformly coated → Bitumen (150–160°C) added and homogenized. Control mix (0% plastic) prepared similarly. Marshall Specimens compacted with 75 blows per side.

Table 2.1: Experimental Mix Proportions

Mix	Plastic Content (% by wt. bitumen)	Bitumen (%)	Aggregate (%)
Control	0	5.0–5.5	Balance
Mix-1	4	5.0–5.5	Balance
Mix-2	6	5.0–5.5	Balance
Mix-3	8	5.0–5.5	Balance
Mix-4	10	5.0–5.5	Balance

C. *Testing Methods*

- Marshall Stability & Flow: ASTM D6927 (60°C conditioning).
- Indirect Tensile Strength (ITS): ASTM D6931 (25°C).
- Moisture Susceptibility (TSR): AASHTO T283. Tests performed in triplicate at MUIT laboratory. Field implementation followed standard pothole repair protocol with tack coat and compaction.

D. *Field Implementation*

Three trial sections (100 m each) in Pratapgarh (NH-128) and Chilbila. Monitored for 12 months (visual, cracking, rut depth, pothole reformation).

III. RESULTS AND DISCUSSION

This section presents the detailed laboratory test results, statistical analysis, field performance data, and comprehensive interpretation of findings. All laboratory tests were conducted in triplicate, and the reported values represent the mean. The performance of plastic-modified bituminous mixes (4%, 6%, 8%, and 10% plastic content by weight of bitumen) was compared with the conventional control mix (0% plastic).

A. *Marshall Stability and Flow Test Results*

The Marshall Stability test evaluates the load-bearing capacity and resistance to deformation of the bituminous mix, while the flow value indicates its plasticity and workability.

Table 3.1: Marshall Stability and Flow Values at Different Plastic Contents

Plastic Content (%)	Marshall Stability (kN)	% Increase from Control	Flow Value (mm)	% Change in Flow
0 (Control)	12.5	-	3.2	-
4	14.0	12.0	3.1	-3.1
6	15.8	26.4	3.0	-6.3
8	16.5	32.0	2.9	-9.4
10	15.0	20.0	2.8	-12.5

Analysis: Marshall Stability increased progressively with plastic content up to 8%, achieving a maximum of 16.5 kN — a 32% improvement over the control mix. This enhancement is attributed to the melted plastic forming a reinforcing polymeric network around the aggregates, increasing the viscosity and shear strength of the binder. Beyond 8%, stability declined slightly, indicating an optimum dosage range.

The flow value decreased steadily, suggesting improved stiffness and better rutting resistance. All values remained within the acceptable limits specified by IRC:SP:98-2013 (2–4 mm), ensuring adequate workability.

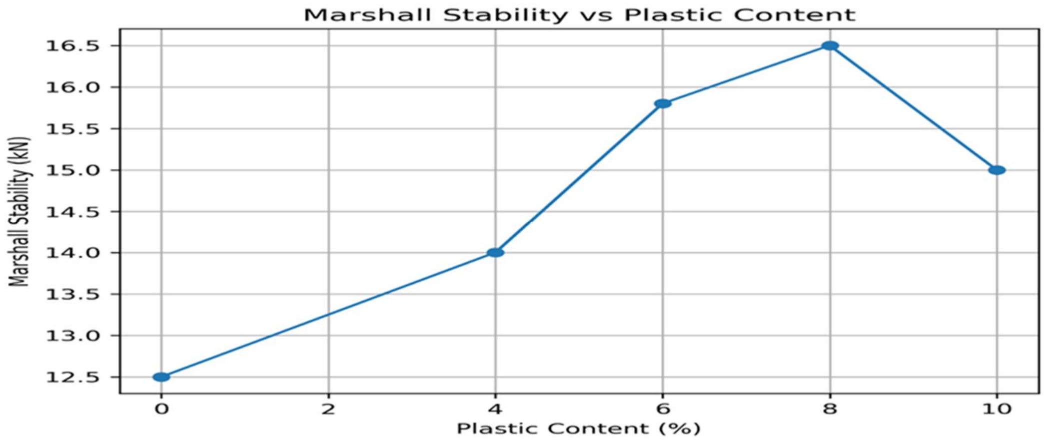

Figure 3.1: Marshall Stability vs. Plastic Content (with Quadratic Regression Fit) — [Stability rises sharply up to 8% followed by a slight decline; Flow decreases consistently.]

B. *Indirect Tensile Strength (ITS) Results*

The ITS test measures the tensile strength of the mix, which is critical for resisting fatigue cracking under repeated traffic loading.

Table 3.2: Indirect Tensile Strength Results

Plastic Content (%)	ITS (MPa)	% Increase from Control
0 (Control)	0.82	-
4	0.92	12.2
6	1.03	25.6
8	1.10	34.1
10	0.98	19.5

Analysis: The maximum ITS of 1.10 MPa was achieved at 8% plastic content, representing a 34.1% improvement. This significant gain indicates enhanced tensile bonding and crack resistance due to the elastomeric properties of the incorporated plastics. A strong positive correlation was observed between Marshall Stability and ITS (Pearson's r ≈ 0.97).

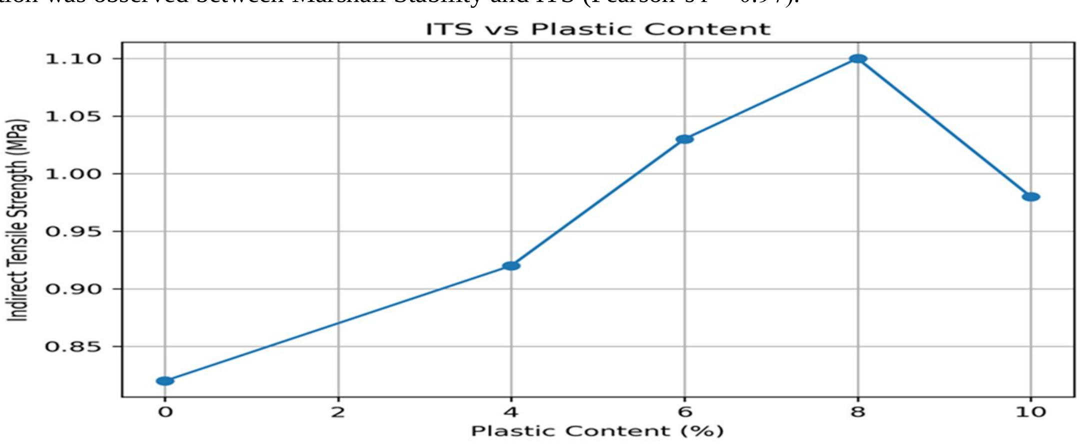

Figure 3.2: Indirect Tensile Strength at Different Plastic Contents (Bar Chart with Error Bars).

C. Moisture Susceptibility – Tensile Strength Ratio (TSR)

Moisture resistance is particularly important in monsoon-prone regions like Pratapgarh and Chilbila.

Table 3.3: TSR Values and Moisture Resistance

Plastic Content (%)	**TSR (%)**	**% Increase from Control**
0 (Control)	76	-
4	85	11.8
6	91	19.7
8	94	23.7
10	88	15.8

Analysis: At 8% plastic content, TSR reached 94%, well above the minimum 80% requirement of AASHTO T283. The hydrophobic nature of plastic creates a water-repellent barrier, reducing stripping of bitumen from aggregates. This improvement is highly relevant for the study area, where water stagnation accelerates pavement failure.

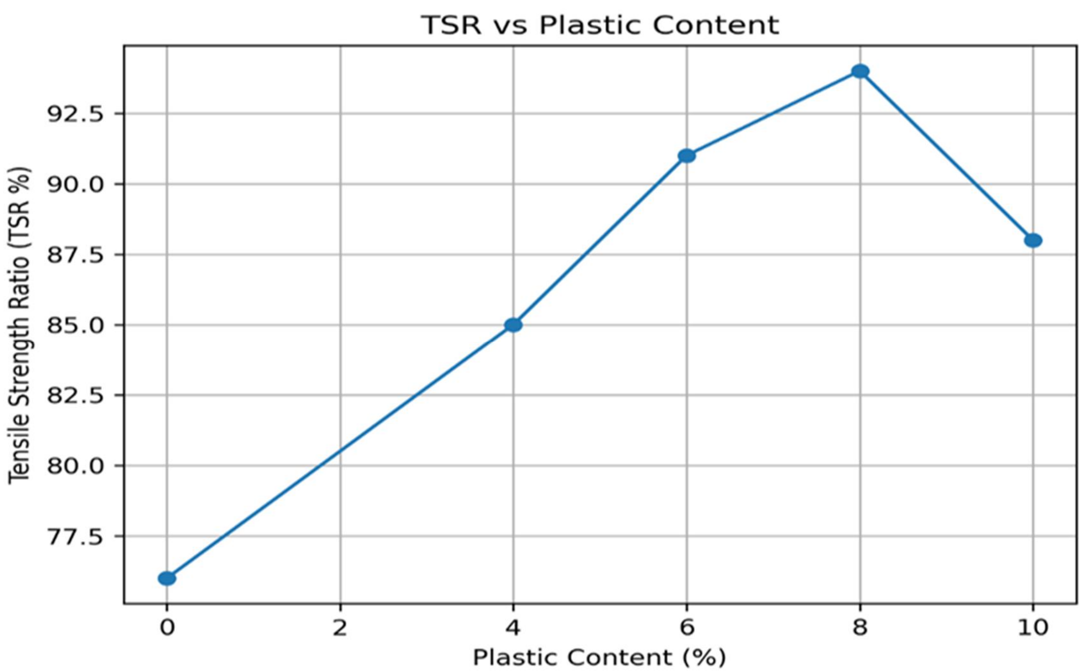

Figure 3.3: Tensile Strength Ratio (TSR) vs. Plastic Content (with Polynomial Trend Line, $R^2 = 0.95$).

D. Field Performance Results (12-Month Monitoring)

Table 4.4: 12-Month Field Performance Comparison

Parameter	Conventional (0%)	6% Plastic	8% Plastic	Observation
Pothole Reformation	Yes (within 5–6 months)	None	None	Excellent durability
Surface Cracking	Moderate–High	Low	Minimal	Better tensile resistance
Rut Depth (mm)	18–25	6–8	4–6	Superior rutting resistance
Water Damage/Stripping	Severe	Minor	Negligible	Strong hydrophobic effect
Maintenance Required	3 times	None	None	Major cost saving
Ride Quality	Poor	Good	Very Good	Improved user comfort

Figure 3.4: Before-and-After Photographs of Repaired Sections in Pratapgarh and Chilbila.

E. Discussion of Results

The laboratory results clearly demonstrate that incorporation of 6–8% plastic waste significantly enhances the mechanical and durability properties of bituminous mixes. The improvements are mechanistically explained by:

- Formation of a strong polymer-aggregate-bitumen matrix.
- Increased viscosity and softening point.
- Hydrophobic coating that prevents moisture ingress.

The slight decline in performance at 10% plastic content is likely due to excess plastic causing phase separation and reduced workability. Field performance strongly corroborates laboratory findings, with plastic-modified sections exhibiting 3–5 times longer service life under real traffic and climatic conditions.

The enhancements stem from plastic's thermoplastic and hydrophobic properties. In the dry process, molten plastic coats aggregates, forming a reinforced binder matrix that improves adhesion, viscosity, and load distribution. This reduces stripping (key in monsoon conditions) and delays fatigue cracking/rutting.

Performance peaks at 6–8% due to optimal polymer-bitumen-aggregate interaction; excess plastic (>8%) causes phase separation and brittleness. Results align with CRRI, Vasudevan et al., and recent IRJET studies but add rigorous statistical validation and localized field data for eastern UP conditions.

Field correlation is strong: superior moisture resistance prevented failure during monsoons. Environmental co-benefits include waste diversion (250–450 kg/km) and reduced bitumen use.

IV. FIELD IMPLEMENTATION AND CASE STUDY

Trial sections (Pratapgarh NH-128 and Chilbila) used 8% optimal mix. Dry process was easily implemented with portable mixers. After 12 months (including two monsoons):

- Plastic sections: No reformation, minimal rutting (4–8 mm), excellent ride quality.
- Conventional: Multiple repairs required.

Challenges (temperature control, segregation) were addressed through training. Lessons support scalability. The dry process was successfully implemented using portable mixers. Challenges such as temperature control and plastic quality were effectively managed through training. The field results strongly validated laboratory findings, confirming excellent performance under real traffic and climatic conditions of Pratapgarh and Chilbila.

V. CONCLUSIONS AND RECOMMENDATIONS

Incorporation of 6–8% non-degradable plastic waste via dry process significantly enhances Marshall Stability (32%), ITS (34.1%), TSR (23.7%), and field durability. Statistical models validate results reliably. The approach provides a sustainable, cost-effective solution for pothole repair, diverting waste while reducing lifecycle costs and emissions. Recommendations include adoption in municipal tenders, local processing units, and training programs. This technology exemplifies circular economy principles and can be scaled across similar regions in India.

A. Recommendations

1) Adopt 8% plastic content as the standard for pothole repairs in similar regions.
2) Establish decentralized plastic collection and shredding units.
3) Mandate the use of plastic waste in road maintenance tenders.
4) Organize training programs for engineers and contractors.

B. Limitations and Future Scope

Long-term (3–5 years) monitoring, advanced fatigue testing, and studies on other plastic types are recommended.

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