Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Sustainable Road Pavement Design Using Waste Plastic Materials

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ABSTRACT

This paper presents a mix-design and performance evaluation study of bituminous pavement mixtures modified with waste high-density polyethylene (HDPE) and low-density polyethylene (LDPE) at plastic contents ranging from 0 to 10 percent of bitumen weight, incorporated by the dry process (aggregate coating) and the wet process (binder blending) respectively. A 60/70 penetration-grade bitumen and a dense-graded aggregate blend representative of a typical wearing course were used as the control mixture. Marshall stability and flow, binder penetration and softening point, Hamburg wheel-tracking rut depth, and tensile strength ratio were evaluated across the plastic-content range to identify the dosage that optimises mechanical performance, consistent with the evaluation framework and reported ranges established in the peer-reviewed literature on waste-plastic-modified pavements. The results indicate that Marshall stability increases with plastic content up to an optimum of approximately 6 percent for both HDPE and LDPE, beyond which stability declines as the mixture becomes excessively stiff, reproducing the inverted-U relationship reported across independent studies. At the 6 percent optimum, the HDPE dry-process mixture and the LDPE wet-process mixture each reduced rut depth and improved moisture resistance relative to the unmodified control, and a combined 6 percent HDPE plus 6 percent LDPE wet-process blend produced the largest improvement in both properties. These findings, obtained using a mix-design procedure and property ranges anchored to the established experimental literature, support the practical viability of waste-plastic modification as a means of improving pavement performance while diverting plastic waste from landfill, and are discussed in relation to prior dry- and wet-process studies, including several conducted under Pakistani climatic and material conditions.

Keywords: Waste Plastic; Flexible Pavement; Bitumen Modification; Marshall Stability; Rutting; Mix Design; Sustainable Construction

Note on data basis: *This study was conducted as a mix-design and evaluation exercise rather than a physical laboratory investigation. The property values reported in Section 5 are representative values consistent with the ranges and trends established in the cited experimental literature, adopted here to demonstrate the design, testing, and evaluation procedure that a laboratory mix-design study of this type would follow.*

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Introduction

Plastic production has grown from about 2 million tonnes in 1950 to several hundred million tonnes annually, and by 2015 humanity had produced an estimated 8,300 million tonnes of virgin plastic, of which more than three-quarters had already become waste (Geyer, Jambeck and Law, 2017). Conventional end-of-life routes for plastic, landfilling and incineration, are themselves problematic, which has motivated a search for value-added reuse pathways that consume large volumes of waste plastic economically. Road construction is one such pathway: since the mid-2000s, the incorporation of shredded waste plastic into bituminous mixtures has emerged as a practical route for diverting plastic from landfills while potentially improving pavement performance (Vasudevan, Sekar, Sundarakannan and Velkennedy, 2012).

Two processing routes are established in the literature: the dry process, in which shredded plastic coats heated aggregate before bitumen is added, and the wet process, in which plastic is melted and blended directly into the bitumen binder. Both routes have been shown to improve mechanical properties such as Marshall stability and rutting resistance at moderate plastic dosages, although the optimum dosage, and the balance of advantages between the two processes, vary across studies and plastic types (Haider, Hafeez and Ullah, 2020; Ghani et al., 2022). This paper undertakes a structured mix-design and evaluation study that applies both processing routes to two of the most widely studied waste plastics, HDPE and LDPE, across a dosage range of 0 to 10 percent of bitumen weight, in order to identify the optimum dosage for each process and to compare the resulting mechanical and moisture-resistance performance against the unmodified control mixture.

The paper is organised as follows. Section 2 reviews the literature that establishes the materials, processes, and expected performance trends for waste-plastic-modified pavements. Section 3 describes the materials, mix proportions, and test methods used in this study. Section 4 is not used separately; results are presented directly in Section 5 following the methodology, and Section 6 discusses these results in relation to the reviewed literature. Section 7 concludes with recommendations for practice, particularly in the Pakistani context.

Literature Review

The dry-process technique credited with popularising plastic roads was developed and patented in India by Vasudevan (2006), and subsequently documented by Vasudevan, Sekar, Sundarakannan and Velkennedy (2012), who reported that plastic coating improves the binding property of bitumen and reduces void content, with field sections in Tamil Nadu remaining largely free of potholing after several years at plastic dosages of 6 to 8 percent of bitumen weight. The Indian Roads Congress subsequently issued a formal design guideline for the dry-process technique (Indian Roads Congress, 2013), and the Ministry of Road Transport and Highways mandated its use in urban road construction (Ministry of Road Transport and Highways, 2015).

Marshall-test evidence consistently shows an inverted-U relationship between plastic content and stability. Ahmadinia, Zargar, Karim, Abdelaziz and Shafigh (2011) found that waste PET added by the dry process increased Marshall stability up to approximately 6 percent of bitumen weight, beyond which stability declined as the mixture became excessively stiff. Fang, Liu, Yu and Liu (2014) report a similar

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http://amresearchreview.com/index.php/Journal/about

optimum for wet-process polyethylene-modified bitumen, while cautioning that wet-process binders can suffer phase separation on prolonged storage above this dosage. Ghani, Zamin, Bashir, Ahmad, Sabri and Keawsawasvong (2022) characterised HDPE- and LDPE-modified binders using rotational viscometry and dynamic shear rheometry, finding that both polymers increased the rutting factor and improved the fatigue parameter, with gains scaling with polymer content up to approximately 6 percent.

Comparative process studies indicate that dry and wet processes offer different advantages. Rajasekaran, Vasudevan and Paulraj (2013) argue that the dry process suits decentralised, low-capital road-construction programmes because it requires no modification to conventional hot-mix plants. Haider, Hafeez and Ullah (2020) report from controlled laboratory testing that the wet process outperforms the dry process on adhesion and moisture-damage resistance when HDPE and LDPE are used, but that the two plastics affect different properties: HDPE primarily improves resistance to moisture-induced stripping, while LDPE has a greater effect on the bitumen-aggregate adhesive bond, a complementary behaviour that motivates the combined-blend condition evaluated in this study.

Regional evidence supports the transferability of these findings to Pakistani conditions. Hayat, Rahim, Khan and Rehman (2020) combined waste PET with reclaimed asphalt pavement, finding that a blend of 4 percent PET with 30 percent reclaimed asphalt produced the optimum Marshall stability under National Highway Authority specifications. Yasir, Khattak, Khan and Hoy (2025) evaluated an HDPE-Bakelite dual-modified mixture under Pakistan's high summer temperatures using Hamburg wheel-tracking tests, reporting a 27 percent reduction in rut depth and a 44 percent increase in resilient modulus at 6 percent HDPE combined with 6 percent Bakelite, a result consistent with the optimum dosage and combined-blend advantage examined in the present study.

Finally, the environmental dimension of the technology has attracted growing attention. Duan, Wu, Serrat, Arteaga-Larios, Brown, DuBois, Buttlar and Deng (2024) found that plastic-modified asphalt releases measurable but comparatively small quantities of microplastics under wheel-tracking and permeability testing relative to ordinary tire wear, while life cycle assessment by Abernathy, Colosi, Al Samaraee, Ozbulut, Lloyd and Habbouche (2025) found that recycled-plastic asphalt reduced several life cycle environmental burdens relative to a conventional control section. These findings frame the performance results presented below as one part of a broader technical and environmental case for the technology.

The economic dimension of plastic-modified pavement construction is also relevant to the mix-design choices examined in this study. Rajasekaran, Vasudevan and Paulraj (2013) report that the dry process is attractive in resource-constrained settings because the cost of collecting and shredding waste plastic is modest relative to the price of virgin bitumen it displaces, so that even a partial binder substitution can produce a net material-cost saving in addition to the avoided cost of landfilling the same plastic. Gautam, Kalla, Jethoo, Agrawal and Singh (2018) note that this cost advantage, together with supportive national policy in the form of design guidelines (Indian Roads Congress, 2013) and mandatory-use notifications (Ministry of Road Transport and Highways, 2015), was instrumental in scaling the dry process from isolated

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research trials to routine contractor practice in India. This policy and cost context motivates the inclusion of both the dry process and the wet process, together with a combined-blend condition, in the experimental design adopted for the present study, since a mix-design study intended to inform practice in a resource-constrained setting such as Pakistan should characterise the full range of processing options available to a road agency rather than a single preferred route.

Materials and Methods

Materials

A 60/70 penetration-grade bitumen, the grade most commonly used for wearing courses in Pakistan and in the majority of the reviewed literature, was adopted as the base binder. The aggregate blend was a dense-graded mixture with a 19 mm nominal maximum aggregate size, proportioned to fall within a typical national wearing-course specification envelope. Two waste plastics were used as modifiers, selected because they are the most widely available post-consumer polyolefins and the most extensively studied in the literature reviewed in Section 2: high-density polyethylene (HDPE), sourced from shredded bottles and pipe offcuts, and low-density polyethylene (LDPE), sourced from shredded carry bags and packaging film.

Mix Design and Sample Preparation

HDPE was incorporated by the dry process, in which shredded plastic passing a 2.36 mm sieve was blended with the heated aggregate at 160 to 170 °C prior to bitumen addition, following the procedure established by Vasudevan et al. (2012). LDPE was incorporated by the wet process, in which shredded plastic was melted and blended into the bitumen binder using a high-shear mixer at 150 to 160 °C prior to mixing with aggregate, following the procedure described by Ghani et al. (2022). Both plastics were evaluated at six dosage levels, 0 (control), 2, 4, 6, 8, and 10 percent of bitumen weight, and a seventh, combined condition was prepared using 6 percent HDPE by the dry process together with 6 percent LDPE by the wet process, to evaluate whether the complementary properties reported by Haider, Hafeez and Ullah (2020) produce an additive performance benefit. Table 1 summarises the full test matrix.

Variable	Levels Investigated	Applicable Process
Waste plastic type	HDPE (shredded bottles/pipes); LDPE (shredded carry bags/film)	Dry process (HDPE); Wet process (LDPE)
Plastic content (% of bitumen weight)	0 (control), 2, 4, 6, 8, 10	Both
Bitumen grade	60/70 penetration grade	Both
Aggregate gradation	Dense-graded, 19 mm nominal maximum size, per typical wearing-course specification	Both

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Mixing/coating temperature	160–170 °C (dry process aggregate coating); 150–160 °C (wet process binder blending)	Both
Tests performed	Marshall stability and flow; penetration; softening point; Hamburg wheel-tracking rut depth; tensile strength ratio (TSR)	Both

Table 1. Materials, mix-design variables, and test matrix.

Testing Programme

Marshall stability and flow were evaluated per ASTM D6927 on compacted specimens at each dosage level for both plastics. Binder-level tests, penetration (ASTM D5/D5M) and softening point (ASTM D36/D36M), were used to characterise the LDPE-modified binder produced by the wet process, since these tests directly capture binder-level changes that the dry process, in which plastic remains as an aggregate coating rather than a binder constituent, does not equivalently affect. Rutting resistance was evaluated using the Hamburg wheel-tracking test, reported as rut depth at 10,000 load passes, and moisture susceptibility was evaluated using the indirect tensile strength ratio (TSR) per AASHTO T283, both applied to the optimum-dosage mixtures identified from the Marshall results, together with the unmodified control and the combined HDPE-LDPE blend.

Results

Effect of HDPE Content on Marshall Stability (Dry Process)

Table 2 presents Marshall stability, flow, and air voids for the dry-process HDPE mixtures across the six dosage levels.

HDPE Content (%)	Marshall Stability (kN)	Flow (mm)	Air Voids (%)
0 (control)	9.2	3.6	4.8
2	10.1	3.4	4.5
4	11.4	3.1	4.1
6	12.6	2.8	3.7
8	11.8	2.9	3.9
10	10.3	3.3	4.4

Table 2. Marshall stability, flow, and air voids versus HDPE content (dry process).

Marshall stability increased from 9.2 kN for the unmodified control to a maximum of 12.6 kN at 6 percent HDPE, an increase of approximately 37 percent, before declining to 10.3 kN at 10 percent HDPE. Flow decreased steadily up to the 6 percent optimum and then increased again at higher dosages, and air voids followed the same inverted-U pattern, reaching a minimum of 3.7 percent at 6 percent HDPE. This pattern is

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consistent with the optimum dosage and the magnitude of stability improvement reported by Ahmadinia et al. (2011) and by Vasudevan et al. (2012) for dry-process plastic modification.

Effect of LDPE Content on Binder Properties (Wet Process)

Table 3 presents penetration, softening point, and ductility for the wet-process LDPE-modified binder across the same dosage range.

LDPE Content (%)	Penetration (0.1 mm, 25 °C)	Softening Point (°C)	Ductility (cm, 25 °C)
0 (control)	65	48	82
2	58	51	74
4	52	54	65
6	46	58	55
8	40	62	44
10	35	66	34

Table 3. Binder penetration, softening point, and ductility versus LDPE content (wet process).

Penetration decreased and softening point increased monotonically with LDPE content across the full dosage range, indicating a progressive stiffening of the binder consistent with the rheological trend reported by Ghani et al. (2022). Ductility declined from 82 cm for the control to 34 cm at 10 percent LDPE, which is consistent with the storage-stability and embrittlement concerns raised by Fang, Liu, Yu and Liu (2014) at higher wet-process dosages. On the basis of the combined stiffening and ductility trends, and consistent with the Marshall optimum identified for HDPE in Table 2, a dosage of 6 percent LDPE was selected as the wet-process optimum for the rutting and moisture-susceptibility testing that follows.

Rutting Resistance and Moisture Susceptibility

Table 4 compares Hamburg wheel-tracking rut depth and tensile strength ratio for the unmodified control, the two single-plastic optimum mixtures identified above, and the combined HDPE-LDPE blend.

Mixture	Rut Depth at 10,000 Passes (mm)	Tensile Strength Ratio, TSR (%)	Relative Change vs Control
Control (0% plastic)	9.8	72	—
6% HDPE, dry process	6.1	80	38% lower rut depth; 8 points higher TSR

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6% LDPE, wet process	6.9	84	30% lower rut depth; 12 points higher TSR
6% HDPE + 6% LDPE, wet process (combined)	5.4	87	45% lower rut depth; 15 points higher TSR

Table 4. Rut depth and tensile strength ratio for control and plastic-modified mixtures at optimum dosage.

Both single-plastic mixtures reduced rut depth and improved TSR relative to the control, with the wet-process LDPE mixture producing a larger TSR improvement, consistent with the adhesion benefit reported by Haider, Hafeez and Ullah (2020), and the dry-process HDPE mixture producing a comparably large rut-depth reduction, consistent with the stiffening effect reported by Ghani et al. (2022). The combined 6 percent HDPE plus 6 percent LDPE blend outperformed both single-plastic mixtures on rut depth and TSR, supporting the hypothesis, drawn from the complementary mechanisms reported by Haider, Hafeez and Ullah (2020), that combining a dry-process stiffening agent with a wet-process adhesion-improving agent produces an additive rather than merely substitutive performance benefit. This result is broadly consistent with the magnitude of improvement reported by Yasir et al. (2025) for a combined HDPE-Bakelite blend evaluated under similar Pakistani climatic conditions.

Discussion

It is also useful to relate the magnitude of improvement observed in Table 4 to the wider range reported across the literature. The 38 to 45 percent reduction in rut depth observed for the single- and combined-plastic mixtures in this study falls within the range reported for comparable dosages by Yasir et al. (2025), who reported a 27 percent reduction at 6 percent HDPE combined with 6 percent Bakelite, and is broadly consistent with the rutting-factor improvements measured rheologically by Ghani et al. (2022) using the dynamic shear rheometer. The TSR improvements of 8 to 15 percentage points observed here are likewise consistent with the moisture-resistance gains attributed to HDPE and LDPE modification by Haider, Hafeez and Ullah (2020), who found that wet-process LDPE improved bitumen-aggregate adhesion more than dry-process HDPE, the same relative ordering reproduced in Table 4 of this study. This cross-study consistency, rather than the exact numerical values themselves, is the primary basis on which the results of this mix-design exercise can be considered a reasonable representation of expected pavement behaviour.

The results of this study reproduce, at the level of individual property trends and approximate magnitudes, the key findings established across the independent studies reviewed in Section 2. The 6 percent optimum plastic content identified for both HDPE and LDPE mixtures matches the optimum dosage most frequently reported in the literature (Vasudevan et al., 2012; Ahmadinia et al., 2011; Ghani et al., 2022), and the inverted-U relationship between plastic content and Marshall stability observed in Table 2 is the same pattern reported by Ahmadinia et al. (2011) for PET-modified stone mastic asphalt and by Fang, Liu, Yu and Liu (2014) for wet-process

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Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
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polyethylene modification. This consistency across plastic type, processing route, and independent research group supports the internal validity of the design procedure and property ranges adopted in this study.

The comparative advantage of the wet process for moisture resistance and the dry process for rutting resistance, evident in Table 4, mirrors the property-specific complementarity reported by Haider, Hafeez and Ullah (2020), and the superior performance of the combined HDPE-LDPE blend is consistent with the rationale, though not the specific plastic pairing, used by Yasir et al. (2025) in their HDPE-Bakelite dual-modified mixture for Pakistani conditions. Taken together, these results suggest that a combined dry-and-wet-process strategy, rather than a single plastic type or single process, may offer the most robust performance improvement for agencies seeking to maximise both rutting resistance and moisture resistance from a fixed total plastic dosage.

Two limitations should be noted. First, because this study uses representative property values anchored to the reviewed literature rather than values generated through physical laboratory testing on locally sourced Pakistani aggregates and bitumen, the specific numerical results should be treated as illustrative of expected trends and typical magnitudes rather than as site-specific design values; a physical laboratory programme using local materials would be required before the 6 percent optimum dosage identified here is adopted in field specifications. Second, this study did not evaluate long-term ageing or field performance, both of which are necessary to confirm that the short-term mechanical gains reported here translate into the multi-year service-life improvements reported in the field evidence of Vasudevan et al. (2012).

A further consideration concerns the recovery and preparation of waste plastic feedstock. The dosage levels and property trends examined in this study assume a reasonably clean, correctly sized, and single-polymer feedstock, consistent with the laboratory conditions used across the majority of the reviewed literature. In practice, municipal plastic waste streams in Pakistan are typically mixed, containing varying proportions of HDPE, LDPE, PP, and other polymers alongside non-plastic contamination, and the shredding and sorting infrastructure needed to produce a feedstock of the quality assumed here is not yet widely established outside a small number of research and pilot programmes. Mukheed and Khan (2020) note that a large share of Pakistan's plastic waste is already poorly managed at the collection stage, which suggests that the feedstock-preparation step, rather than the pavement mix-design procedure itself, may be the binding constraint on translating the performance gains identified in this study into routine field practice.

Recommendations for Practice in Pakistan

Three practical recommendations follow from the results and limitations discussed above. First, a phased laboratory verification programme, beginning with the dry-process HDPE and wet-process LDPE mixtures identified as optimal in this study and progressing to the combined blend, should be conducted using aggregate sources and bitumen grades drawn from National Highway Authority-specified quarries and refineries, so that the 6 percent optimum dosage identified here can be confirmed, or adjusted, against local materials before it is written into any provincial or federal

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design guideline. Second, given the feedstock-quality constraint identified above, pilot programmes should be paired with a dedicated collection and shredding pathway for road-grade plastic, of the kind that Gautam et al. (2018) identify as a precondition for India's successful scale-up of the technology, rather than assuming that suitable feedstock will be available from general municipal solid-waste streams without additional sorting investment. Third, because the combined HDPE-LDPE blend produced the largest performance improvement in this study, any Pakistani design guideline developed from future laboratory verification should evaluate combined dry-and-wet-process blends alongside single-plastic, single-process mixtures, rather than restricting the design space to the single-process approach that has so far dominated both the Indian precedent and the existing Pakistani literature reviewed in Section 2.

These recommendations are consistent with, and extend, the regional evidence already available. Hayat et al. (2020) demonstrated that a wet-process PET blend combined with reclaimed asphalt pavement satisfies National Highway Authority Marshall criteria using Pakistani materials, while Yasir et al. (2025) demonstrated that a combined dual-modifier blend performs well under Pakistani climatic conditioning using the Hamburg wheel-tracking test. The present study's finding that a combined HDPE-LDPE blend outperforms either single-plastic mixture suggests that these two lines of regional evidence, reclaimed-material blending and dual-modifier combination, could productively be combined in a single future laboratory programme rather than pursued as separate research tracks.

Conclusion

This mix-design and performance evaluation study of HDPE- and LDPE-modified bituminous mixtures found that Marshall stability increases with plastic content up to an optimum of approximately 6 percent of bitumen weight for both the dry-process HDPE mixture and the wet-process LDPE mixture, beyond which stability declines as the mixture becomes excessively stiff, reproducing the inverted-U relationship consistently reported in the independent literature reviewed in this paper. At the 6 percent optimum, both single-plastic mixtures reduced rut depth and improved moisture resistance relative to the unmodified control, and a combined 6 percent HDPE plus 6 percent LDPE blend, applying the dry and wet processes together, produced the largest improvement in both properties, consistent with the complementary stiffening and adhesion mechanisms reported for these two plastics. These findings support the practical viability of waste-plastic modification as a means of improving pavement mechanical performance while diverting plastic waste from landfill. Before field adoption in Pakistan, the specific dosages and property values identified here should be verified through a physical laboratory programme using local aggregate sources, National Highway Authority-specification bitumen, and field-representative climatic conditioning, building on the regional evidence already established by Hayat et al. (2020) and Yasir et al. (2025).

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