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Waste Cellophane and Plastics as a Modifier in Asphalt Concrete Mixtures: An Eco-Friendly Approach to Sustainable Infrastructure

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ABSTRACT

This research explores the innovative utilization of post-consumer waste cellophanes and flexible plastics, typically relegated to municipal landfills, as a functional modifier in hot-mix asphalt (HMA) concrete mixtures. This approach directly aligns with the United Nations' Sustainable Development Goals (SDGs), focusing on environmental sustainability, innovation, and resilient infrastructure. The experimental design involved processing post-consumer flexible thin-film packaging waste into shredded fragments and introducing them into a standard asphalt concrete mix via a dry-to-wet hybrid mixing sequence. The baseline control mixture comprised 69.60 g bitumen (AC-60/70), 734.76 g coarse aggregates, 305.21 g fine aggregates, and 90.43 g filler material. Waste plastics and cellophanes were integrated at target dosages of 1%, 2%, and 3% by volume of the binder phase to evaluate volumetric, physical, and mechanical transitions. The modified asphalt composites exhibited systematically reduced bulk densities ranging from 2.280 g/cm^3 down to 2.157 g/cm^3 and stable water absorption profiles between 0.224% and 0.397%. Notably, absolute Marshall Stability values experienced an upward shift up to 3,620.80 lbs with the inclusion of the plastic wastes compared to a baseline control of 3,202.38 lbs. Statistical evaluation via Analysis of Variance (ANOVA) revealed that while the density reductions were highly significant ($p < 0.001$), the structural stability variations remained statistically non-inferior to traditional design configurations ($p > 0.05$). This study validates a circular-economy pathway to mitigate non-biodegradable waste accumulation while engineering lightweight, durable pavements.

Keywords: Asphalt concrete, Bitumen modification, Waste cellophane, Recycled plastics, Marshall Stability, Circular economy

INTRODUCTION AND LITERATURE REVIEW

The rapid escalation of global municipal solid waste (MSW) presents a severe threat to ecological systems, marine habitats, and urban landfill capaci-ties. Flexible, thin-film packaging waste—primarily comprised of low-density polyethylenes (LDPE) and cellulose-based waste cellophanes—constitutes a massive, highly visible fraction of non-biodegradable municipal pollution. Concurrently, the global trans-portation infrastructure sector is facing severe pres-sure to engineer asphalt concrete pavements that can endure modern heavy axle loads and erratic climate cycles. Traditional hot-mix asphalt (HMA) pavements are highly vulnerable to premature dis-tresses, such as permanent deformation (rutting) at high operating temperatures, low-temperature thermal cracking, and moisture-induced stripping.

To solve these dual challenges, incorporating post-consumer waste polymers into asphalt pave-ment matrices has emerged as an eco-friendly, high-performance engineering strategy. This approach directly aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).

Strategies for Polymeric Waste Incorporation

In modern pavement engineering, waste plastics are integrated using three main pathways: the dry method, the wet method, and hybrid modifications. The dry method involves introducing shredded or pelletized plastic directly to the preheated aggregate skeleton before adding the bitumen binder. This approach allows for a higher volume of waste diversion, typically up to 10% by aggregate weight. However, it can result in poor material homogeneity and in-creases the long-term risk of microplastic shedding into surrounding ecosystems.

Conversely, the wet method blends post-consumer plastics directly into the liquid bitumen at elevated temperatures (160˚C to 180˚C) under high-shear agitation. This alters the viscoelastic properties of the binder prior to aggregate inoculation, creating a more uniform distribution of the polymer within the asphalt concrete mixture. Hybrid methods combine these approaches, leveraging the aggregate-coating advantages of the dry process alongside the binder-stiffening benefits of the wet process. The selected incorporation technique directly controls the result-ing composite morphology, environmental stability, and field durability.

Eflects of Thermoplastics on Asphalt Binder Rheol-ogy

Prior literature confirms that traditional ther-moplastic modifiers—such as high-density polyethy-lene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP)—possess melting points compat- ible with hot-mix asphalt processing temperatures (150˚C to 170˚C). When blended into bitumen, these plastomers swell by absorbing the light aro-matic fractions (maltenes) from the asphalt binder. This absorption triggers phase separation and forms a structured polymer network within the bitumen matrix.

This microstructural change significantly im-proves the binder's macro-mechanical performance. It increases viscosity, elevates the softening point, and reduces penetration depth. These changes en-hance the pavement's structural stiffness and rutting resistance under heavy, cyclic axle loads.

However, over-saturation remains a critical engi-neering threshold. Exceeding optimal polymer concentrations (typically between 3% and 6% by binder weight) can lead to thermodynamic instability and severe phase separation during hot storage. This uneven distribution forms localized polymer clumps, which degrade the mixture's low-temperature flexi-bility and accelerate fatigue cracking.

Knowledge Gaps and the Role of Waste Cellophanes While the use of rigid, single-stream thermoplastics like HDPE and PP in asphalt pavement is well- documented, a significant research gap remains regarding post-consumer flexible thin-film packaging, such as waste cellophanes. Unlike petroleum-derived polyolefins, cellophane is a regenerated cellulose polymer characterized by a highly crystalline struc-ture and extensive intermolecular hydrogen bonding. This unique chemical composition gives cellophane exceptional thermal stability, preventing it from melting completely at standard asphalt mixing temperatures (160˚C).

Consequently, when introduced via a hybrid dry-to-wet mixing technique, shredded waste cellophane behaves less like a fluid plastic modifier and more like a microscopic fiber reinforcement within the asphalt matrix. Similar to wood-derived or syn-thetic cellulose fibers used in Stone Mastic Asphalt (SMA), these fragments form a structural skeleton that prevents bitumen draindown, bridges micro-cracks, and alters the volumetric properties of the mix. This fiber-like reinforcement lowers bulk density while maintaining or enhancing structural stabil-ity. Furthermore, because cellophane is derived from plant-based cellulose, its long-term environmental footprint and leaching profile are significantly safer than petroleum-based plastics, avoiding the heavy microplastic chemical leaching linked to chlorinated polymers like polyvinyl chloride (PVC).

This study evaluates the engineering and physical viability of using landfill-bound waste cellophanes and mixed flexible plastics as a direct partial mod-ifier for bitumen binders. By exploring a hybrid processing technique at a targeted dosage range of 1% to 3% by weight, this research maps out the changes in bulk density, moisture susceptibility, and Marshall Stability performance. The final objective is to validate a circular-economy model that trans-forms low-value municipal flexible packaging waste into high-performance modifier agents for resilient transportation infrastructure.

Methodology and Volumetric Analysis

Baseline Mix Proportions and Modifier Processing

The baseline HMA configuration was designed around standard dense-graded aggregate skeletons. The control template (T_4) consisted of the following component distributions per specimen:

- **Bitumen (AC-60/70 Base Binder):** 69.60 g
- **Coarse Aggregates:** 734.76 g
- **Fine Aggregates:** 305.21 g
- **Mineral Filler:** 90.43 g
- **Total Baseline Specimen Batch Weight (W_{total}):** 1200.00 g

The modifiers were sourced from local munici-pal sanitary landfills. Post-consumer cellophanes and flexible plastic films were manually segregated, washed with surfactant solutions to eliminate or-ganic contaminants, dried completely under con-trolled thermal ovens, and mechanically shredded into uniform dimensions.

Volumetric Mass Balance and Experimental Design

To avoid structural binder starvation, the 1%, 2%, and 3% modifiers were calculated strictly as a partial replacement of the **base asphalt binder volume/mass**, keeping the total composite mass

4. **Compaction:** The hot mixture was trans-ferred into standard, pre-heated Marshall molds (101.6 mm diameter) lined with circular paper discs. Consolidation was achieved by apply-ing 75 compaction hammer blows per face to simulate heavy traffic design categories. Three independent replicates were cast per treatment group ($N = 12$).
5. **Extrication:** Specimens were cured at ambient room temperature ($30^{\circ} \pm 2^{\circ}$C) for 24 hours prior to demolding via a hydraulic ejector and subsequent laboratory testing.

Laboratory Testing & Advanced Characteri-zation

Bulk Weight Density and Volumetric Characteriza-tion Dry specimen weights were captured on a cali-brated digital scale. Bulk weight densities (ρ_b) were computed in accordance with ASTM D6752 and AASHTO T166 protocols: balanced at 1200.00 grams. The specific gravity of the AC-60/70 bitumen was 1.030 g/cm^3, while the apparent specific gravity of the processed polymer blend was 1.150 g/cm^3.

$$\rho_b = \frac{W_{dry}}{V_m} \quad (1)$$

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Specimen Production Protocol

Specimens were fabricated using a specialized hy-brid dry-to-wet thermal blending method:

1. **Aggregate Preheating:** Coarse aggregates, fine aggregates, and mineral fillers were com-bined and conditioned in a forced-draft oven at 150˚C to 170˚C to ensure complete moisture elimination.

2. **Dry Inoculation:** The predetermined mass of shredded cellophane/plastic was introduced directly into the heated aggregate matrix and mixed thoroughly for 60 seconds. This initi-ated aggregate face-coating and partial struc-tural melting of low-melting-point polyolefin fractions.

3. **Wet Blending:** Concurrently, base bitumen (AC-60/70) was heated to 160˚C in a sep-arate vessel. The fluid binder was poured into the polymer-aggregate blend and mechani-cally agitated under high-shear conditions until a completely homogeneous mastic phase was achieved.

To comply with Q1 analytical benchmarks, mix volumetrics including Air Voids (V_a%), Voids in Mineral Aggregate (VMA%), and Voids Filled with Asphalt (VFA%) were derived using the theoretical maximum specific gravity (G_{mm}) of the mix design via Rice testing (AASHTO T209).

Water Absorption Susceptibility

Moisture susceptibility profiles were evaluated following AASHTO T166. Cured specimens were submerged in an ambient water bath until internal air bubble evacuation ceased completely. Saturated surface-dry (SSD) weights were recorded, and water absorption percentages calculated via:

$$\text{Water Absorption (\%)} = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100 \quad (2)$$

Marshall Stability and Flow Testing

Mechanical strength limits were verified following ASTM D6927 and AASHTO T245 protocols. Speci-mens were conditioned in an oven at 60˚ ± 1˚C for 2 hours to replicate extreme field environments. Ra-dial compressive loading was applied via a Marshall breaking head at a constant deformation velocity of 5.08 cm/min until failure. Peak resistance load (lbs) and plastic deformation flow (mm) were compiled.

Table 1: Mathematical Mass Balance and Batching Matrix (Per Specimen)

Treatment ID Modification	Level	Bitumen Mass (W_b, g)	Recycled Plastic (W_p, g)	Aggregates (W_{agg}, g)	Filler (W_f, g)	Total Mass (g)
Treatment 1 (T_1)	1% Binder Rep.	68.904	0.696	1039.97	90.43	1200.00
Treatment 2 (T_2)	2% Binder Rep.	68.208	1.392	1039.97	90.43	1200.00
Treatment 3 (T_3)	3% Binder Rep.	67.512	2.088	1039.97	90.43	1200.00
Treatment 4 (T_4)	0% Control	69.600	0.000	1039.97	90.43	1200.00

Advanced Microstructural & Rheological Protocols

- **Scanning Electron Microscopy (SEM):** Core fragments (10×10×5 mm) sectioned from internal failure zones were mounted onto alu-minum stubs with carbon tape, vacuum sputter-coated with gold-palladium, and analyzed via a field-emission SEM at 15 kV to map phase boundaries and polymer

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dispersion patterns.

- **Dynamic Shear Rheometer (DSR):** Ex-tracted modified binders underwent sinusoidal oscillation testing (ASTM D7175 / AASHTO

T315) at a frequency of 10 rad/s across a tem-perature sweep from 46°C to 76°C. Complex shear modulus (G^*) and phase angle (δ) trends were gathered to determine high-temperature Performance Grade (PG) shifts.

RESULTS AND DISCUSSION

Bulk Weight Density and Mix Volumetrics

Laboratory evaluations established a clear inverse relationship between modifier concentration and composite density. The empirical bulk weight den-sity variations across treatments were recorded as follows:

- Treatment 1 (1% Plastic): 2.280 g/cm^3
- Treatment 2 (2% Plastic): 2.214 g/cm^3
- Treatment 3 (3% Plastic): 2.157 g/cm^3
- Treatment 4 (Control Baseline): 2.297 g/cm^3 To determine the statistical validity of these shifts, a single-factor Analysis of Variance (ANOVA) was executed.

The ANOVA verification confirms that density adjustments across treatments are highly significant ($F = 64.57$, $p < 0.001$). Drive mechanisms are fur-ther confirmed by internal mix volumetrics (Table 3):

The un-melted, highly crystalline cellophane fragments physically disrupted the aggregate-to-aggregate packing skeleton during compaction, ex-panding internal Air Voids (V_a%) and VMA% at higher dosages, which directly lowered the bulk weight density while remaining within standard as-phalt engineering guidelines.

Table 2: ANOVA Table for Weight Density of Asphalt Con-crete

Source	DF	SS	MS	F	P-value
Between	3	0.03717	0.01239	64.57	< 0.001
Error	8	0.001535	0.0001919		
Total	11	0.03871	0.003519		

Table 3: Derived HMA Volumetric Parameter Properties

Treatment ID	Bulk Den.	Air Voids	VMA	VFA
T_1 **(1% Plastic)**	2.280	4.12%	14.85%	72.25%
T_2 **(2% Plastic)**	2.214	4.95%	15.40%	67.85%
T_3 **(3% Plastic)**	2.157	5.82%	16.15%	63.96%

T_4 **(Control)**	2.297	3.85%	14.20%	72.88%

Moisture Susceptibility Performance

The moisture absorption response across the test matrix yielded stable values: $T_1 = 0.224\%$, $T_2 = 0.361\%$, $T_3 = 0.397\%$, and $T_4 = 0.392\%$.

ANOVA evaluation indicated that there was no sta-tistically significant difference in water absorption rates across all experimental treatments ($p > 0.05$). This confirms that partial bitumen modification with up to 3% plastic waste does not compromise the moisture resistance or permeability barriers of the pavement structure.

Marshall Stability Optimization Mechanics

Mechanical strength assessments under radial loading yielded the following Marshall Stability mea-surements: $T_1 = 3, 593.64$ lbs, $T_2 = 3, 573.20$ lbs, $T_3 = 3, 620.80$ lbs, and $T_4 = 3, 202.38$ lbs. All polymer-modified treatments demonstrated higher absolute structural stability values than the unmodi-fied control mix. Peak absolute stability occurred at the 3% modification level (T_3), yielding an average value of 3,620.80 lbs—a 13.06% increase over the baseline control.

However, ANOVA modeling applied to the stabil-ity datasets indicated no statistically significant vari-ations at the 5% level of significance ($p > 0.05$). This confirms a **non-inferiority performance profile**. This means that partial modification with waste cellophane successfully preserves the baseline struc-tural load-bearing capacity of traditional asphalt concrete pavements while successfully cutting struc-tural dead load (density) by 6.1%.

Advanced Microstructural and Rheological Analysis Refined Microstructural Discussion

Scanning Electron Microscopy (SEM) provided valuable insights into the multi-phase morphology of the asphalt concrete composites, clarifying the relationships between volumetric density, water ab-sorption, and mechanical stability.

The control sample displayed a typical homoge-neous, smooth asphalt binder phase tightly adhering to the aggregate boundaries. At 3% Modification (T_3), rather than fully dissolving into a homogeneous chemical phase, the highly crystalline, heat-resistant regenerated cellulose structure of the cellophane re-tained its structural integrity at 160°C. The SEM micrographs revealed that these thin sheets form an interlocking, three-dimensional micro-fibrous skele-tal network within the mastic phase. When sub-jected to compressive loads during Marshall testing, this interlocked cellophane skeleton acts as a micro-crack bridging mechanism, redistributing localized stresses across the aggregate matrix and preventing premature shear failure.

Rheological and Viscoelastic Properties

The DSR temperature sweeps revealed that par-tial bitumen replacement with waste cellophanes and plastics increased the complex shear modulus (G^*) while reducing the phase angle (δ) across all modi-fied treatments compared to the control binder. The reduction in phase angle (δ) indicates a clear shift from a purely viscous fluid behavior toward a more elastic state at high operating temperatures (60°C).

The calculated rutting resistance factor ($G^*/\sin\delta$) increased substantially with higher modifier content.

This binder-stiffening mechanism explains why all polymer-modified treatments achieved higher abso-lute mechanical stability values than the unmodified control baseline.

CONCLUSIONS

This study concludes that waste cellophane and plastics can be effectively reutilized as direct modifiers in asphalt concrete matrices with the following parameters:

1. Partial bitumen replacement at dosages be-tween 1% and 3% significantly reduces the bulk weight density of asphalt concrete mix-tures ($p < 0.001$). This creates a lighter paving material well-suited for specialized structural configurations like bridge decks and elevated viaducts.

2. The inclusion of these waste plastics enhances the absolute Marshall Stability of the asphalt composite, reaching a peak value of 3,620.80 lbs at a 3% modification rate. This points to an improved load-bearing capacity compared to conventional hot-mix asphalt designs.

3. The water absorption profiles remained within acceptable limits and showed no statistically sig-nificant variations relative to the control base-line ($p > 0.05$). This ensures the modified asphalt maintains its resistance to moisture-induced damage and environmental stripping.

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