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Optimization of Polypropylene-Modified Asphalt Mixtures for Enhanced Road Durability in Tropical Regions: Advancing Sustainable Infrastructure Development Aligned with SDG 9 and SDG 12

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Abstract: Road pavements in tropical regions experience accelerated deterioration due to high temperatures; intense rainfall; and high humidity; necessitating innovative solutions that address both infrastructure durability and environmental sustainability. This experimental study evaluates asphalt mixtures modified with polypropylene (PP) plastic waste to enhance performance under tropical climate conditions. Laboratory samples containing 0% (control); 4%; 6%; and 8% PP by binder weight were subjected to Marshall stability; penetration; accelerated aging (Rolling Thin Film Oven Test and ultraviolet radiation); and moisture susceptibility testing. Results demonstrate that 6% PP incorporation yielded optimal performance; with Marshall stability increasing to 14.5 kN (22% improvement over control); penetration decreasing to 58 dmm (18% reduction); and post-aging stability retention of 85%. Moisture conditioning tests revealed reduced stability loss at 13.8% compared to 24.4% for control mixtures; indicating enhanced moisture resistance. Economic analysis confirms cost savings of approximately 30% when substituting recycled PP waste for conventional polymer modifiers such as SBS. These findings identify 6% PP as the optimal dosage for tropical asphalt applications; demonstrating the technical and economic feasibility of circular material approaches in infrastructure engineering.

Keywords: Modified asphalt; Plastic waste; Road durability; Sustainable materials engineering; Tropical regions.

Introduction

Road infrastructure is a critical component of economic development, enabling efficient transportation of goods and people (Lestari et al., 2025). However, road pavements in tropical regions face significant durability challenges due to extreme weather conditions, including high temperatures, intense rainfall, and high humidity (Borghetti & Marchionni, 2023). These environmental factors accelerate the deterioration of asphalt pavements, manifesting in common distresses such as rutting, cracking, and ravelling (G. Shaikh et al., 2022). The degradation increases maintenance costs and compromises road safety and serviceability, making pavement enhancement a pressing concern for civil engineers and infrastructure planners (Issa Sarsam, 2025; Hong et al., 2022).

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One promising approach to improve pavement performance is the modification of asphalt binder using additives that enhance mechanical and thermal properties (Ameur et al., 2025). Polymer additives have gained considerable attention due to their ability to improve elasticity, stiffness, and resistance to deformation of asphalt mixtures (Alsabri et al., 2022). However, conventional polymer modifiers such as styrene-butadiene-styrene (SBS) and ethylene-vinyl acetate (EVA) often incur high costs and raise environmental concerns related to production and disposal (Ciobanu et al., 2024).

In recent years, plastic waste has emerged as an innovative asphalt modifier that addresses two issues simultaneously: growing plastic waste pollution and the need for durable road materials (Pariyar et al., 2020; Aldrian & Dwi Susanto, 2003). Polypropylene (PP) plastic, a widely used thermoplastic in packaging and consumer products, constitutes a significant portion of municipal plastic waste and is difficult to degrade (Arifin et al., 2024). Incorporating PP waste into asphalt offers a recycling pathway while potentially enhancing mechanical properties and pavement longevity (Wong et al., 2022). Several studies have documented improvements in Marshall stability, rutting resistance, and aging characteristics with plastic waste modification (Hasan et al., 2021). For example, research conducted by the Indonesian Ministry of Public Works demonstrated that PP waste addition to asphalt concrete wearing course improved binder-aggregate adhesion, reducing ravelling damage. Additionally, PP incorporation reduced voids in mineral aggregate and abrasion values, indicating enhanced durability under traffic and environmental stresses (Prasetyo et al., 2018)(Contractor et al., 2020).

Despite encouraging findings from existing studies, three critical gaps remain in the literature on PP-modified asphalt (Lefevre et al., 2025). *First*, while polymer-modified asphalt has been extensively studied, most prior investigations have been conducted in non-tropical or temperate climates, with insufficient evaluation of the combined effects of high ambient temperature (>35°C) and high moisture exposure (>3,000 mm annual rainfall) that characterize tropical regions (Westra et al., 2014; Olagunju et al., 2025). Tropical environments impose synergistic stresses—elevated temperatures that soften asphalt and high rainfall that promotes moisture intrusion and accelerates oxidative aging—that have not been systematically evaluated in PP-modified asphalt systems (Yan et al., 2024; Taher & Ismael, 2023).

Second, existing literature lacks systematic economic comparison between PP-waste modification and conventional polymer modifiers (such as SBS), particularly for developing countries where material cost constraints directly influence adoption decisions (Xu et al., 2016)(Vijayan et al., 2024). Economic feasibility for developing-nation contexts remains underexplored (Ullah et al., 2024).

Third, prior studies have not quantified the relative aging resistance and moisture durability of PP-modified asphalt under combined tropical stressors, limiting understanding of long-term performance potential in high-temperature, high-moisture environments (AlSalehy & Bailey, 2025; Zhang et al., 2023).

This study addresses all three gaps through: (1) quantitative evaluation of PP-modified asphalt performance under simulated tropical aging (RTFOT + UV exposure for 500 hours) and moisture conditioning (60°C water immersion for 24 hours); (2) systematic economic comparison of material costs between 6% PP-modified asphalt and equivalent SBS-modified asphalt on a per-tonne-of-binder basis; and (3) optimization of PP dosage specifically for tropical-climate applications, identifying quantitative performance indicators at each dosage level (0%, 4%, 6%, 8% by weight of binder) (Supari et al., 2017; Emtiaz et al., 2023).

This study is limited to laboratory-scale simulations and does not include field trials, dynamic traffic loading cycles, or extended multi-seasonal environmental exposure (Swarinoto & Husain, 2012; Fauzi et al., 2023). While accelerated aging (RTFOT + UV) and water conditioning (60°C immersion) provide standardized proxies for tropical environmental stresses, they cannot fully replicate the complexity of field conditions including intermittent traffic loading, diverse moisture infiltration pathways, and long-term UV exposure variability (Hanifa & Wiratmo, 2024). Field validation through pilot projects and long-term monitoring is necessary to confirm that laboratory performance translates to real-world durability in tropical climates (Villalobos-Herrera et al., 2022; Dandrifosse et al., 2024).

Method

Research Design

Four asphalt mixture compositions were prepared with PP content varying at 0% (control), 4%, 6%, and 8% by weight of asphalt binder. Each composition was tested in triplicate ($n = 3$ independent replicates) to quantify experimental variability and enable statistical inference.

Statistical analysis: Mean values and standard deviations were calculated for each measurement across the three replicates. Statistical significance of differences among the four PP-content groups was assessed using one-way analysis of variance (ANOVA) with significance level $\alpha = 0.05$. When ANOVA indicated significant differences ($p < 0.05$), post-hoc pairwise comparisons were conducted using Tukey's honest significant difference (HSD) test. The sample size of n = 3 replicates per composition was selected to balance experimental replication with practical constraints and is consistent with ASTM guidance for materials characterization. All data were screened for outliers using the 1.5× interquartile range criterion; no values were excluded from analysis. Results are presented as Mean ± Standard Deviation, with p-values provided for all statistical comparisons.

Materials Characterization

Base Asphalt Binder: A conventional penetration-grade 60/70 asphalt was procured from a local refinery, representing the standard binder specification for tropical road construction. This grade provides balanced viscosity and temperature susceptibility appropriate for high-temperature environments. Baseline characterization included penetration (dmm), softening point (°C), and ductility (cm), determined per ASTM D5, ASTM D36, and ASTM D113 respectively.

Polypropylene (PP) Plastic Waste: Waste polypropylene was sourced from municipal solid waste collection centers. Material was processed through sequential cleaning, shredding, and sieving operations. Particle sizes were standardized between 2 and 4 mm to ensure uniform dispersion within the asphalt matrix. PP selection reflects its high availability, thermoplastic nature, melting point approximately 160°C (compatible with asphalt processing temperatures), and established effectiveness as an asphalt modifier documented in peer-reviewed literature.

Aggregates: Crushed granite aggregates with nominal maximum size 14 mm were employed, conforming to local road construction specifications. Aggregates were cleansed and dried (moisture content <0.5%) prior to mixing to eliminate impurities that could compromise binder-aggregate bonding.

Preparation of PP-Modified Asphalt Binder

The wet-mixing method was employed, wherein PP particles are directly incorporated into heated asphalt binder to maximize polymer-binder interaction and homogeneity. Base asphalt (60/70 penetration grade) was heated to 170°C. Waste polypropylene particles (2–4 mm) were gradually introduced into the heated binder while high-shear mixing at 3,000 rpm was maintained. Mixing continued for 30 minutes to promote uniform PP dispersion and partial polymer melting. Upon completion, the modified binder was cooled to room temperature and stored until use. These parameters were selected based on orthogonal experimental optimization documented in recent literature, balancing polymer dispersion against thermal degradation of the binder matrix.

Preparation of Asphalt Mixtures

Aggregates were heated to 160°C prior to mixing. Modified binder was then blended with heated aggregates at the optimum asphalt content (OAC) determined through preliminary volumetric analysis per Marshall Mix Design methodology (ASTM D3495). Manual mixing ensured uniform aggregate coating. For the control (0% PP) sample, identical mixing procedures were followed using unmodified binder. Marshall compaction (75 blows per face) produced cylindrical specimens of 101.6 mm diameter and 63.5 mm height, following ASTM D6927.

Performance Testing

Marshall Stability and Flow Testing: Marshall stability testing was conducted according to ASTM D6927 to evaluate the load-bearing capacity and deformation characteristics of the asphalt mixtures. Specimens were immersed in a 60°C water bath for 30 minutes before testing to simulate tropical temperature conditions. Stability (in kN) indicates the maximum load the specimen can withstand. Flow (in mm) measures the deformation at maximum load. These parameters provide insight into the mixture's resistance to rutting and structural failure.

Penetration Testing: Penetration tests on the modified and unmodified asphalt binders were performed per ASTM D5 at 25°C to assess binder hardness and consistency. Lower penetration values indicate a stiffer binder, which typically improves high-temperature performance.

Aging Simulation: To replicate the oxidative and thermal aging experienced in tropical climates, the Rolling Thin Film Oven Test (RTFOT) per ASTM D2872 was employed. The test simulates short-term aging during mixing and laying. Following RTFOT, samples were subjected to ultraviolet (UV) radiation exposure for 500 hours in a UV chamber to mimic prolonged sunlight exposure typical in tropical regions. Post-aging, Marshall stability and penetration tests were repeated to assess performance retention, expressed as a percentage of pre-aging values.

Moisture Susceptibility Testing: Moisture damage resistance was quantitatively assessed by measuring changes in Marshall stability following water conditioning. Specimens were immersed in water at 60°C for 24 hours, and stability was measured immediately before and after conditioning. The retained stability ratio was calculated as: (Stability after conditioning / Stability before conditioning) × 100%. A ratio below 80% indicates potential susceptibility to moisture damage per ASTM D4867.

Economic Analysis

Economic comparison was conducted on a per-ton-of-binder basis for the modified asphalt binder layer, following industry cost accounting standards.

Material Costs: Unit costs for PP waste feedstock and SBS polymer were obtained from local suppliers specializing in asphalt modifications. PP waste cost included collection, cleaning, and shredding to 2–4 mm particle size (IDR 4,500/kg). SBS polymer cost was sourced from industrial asphalt binder producers (IDR 35,000/kg). The base asphalt binder (60/70 penetration grade) cost was held constant at IDR 9,000/kg across all comparisons. Cost per tonne of modified binder was calculated as: (base binder cost × 940 kg) + (modifier cost × 60 kg per tonne of binder) for 6% modifier by weight.

Scope Definition: This analysis covers material costs only and does not include construction costs (mixing plant, transportation, placement, compaction), operational costs (labor, equipment), or end-of-life scenarios. Lifecycle cost analysis including maintenance and rehabilitation scenarios is recommended for future research but is beyond the scope of this laboratory-scale study.

Data Sources and Assumptions: Cost data reflect 2025 Jakarta-region supplier quotes (January 2026); no temporal adjustment or inflation escalation was applied. No sensitivity analysis was performed; future work should examine cost variation with feedstock availability and fluctuating commodity prices

Result and Discussion

This section presents the experimental findings on the performance of asphalt mixtures modified with polypropylene (PP) plastic waste. The results include data from Marshall stability tests, penetration tests, aging simulation, and moisture susceptibility assessments. The effects of varying PP content (0%, 4%, 6%, and 8% by weight of binder) on the mechanical and durability properties of the asphalt mixtures are analyzed. Additionally, graphical representations and tables summarize key performance indicators to facilitate comparison and interpretation.

Marshall Stability and Flow Test Results

Marshall stability testing quantified mixture structural capacity and permanent deformation resistance—critical performance indicators for pavement longevity under tropical conditions. Results from n=3 replicate specimens per composition are presented in Table 1 with corresponding standard deviations.

As shown in Table 1, the addition of PP waste significantly improves Marshall stability compared to the control. The highest stability of 14.5 kN was observed at 6% PP content, representing a 22% increase over the unmodified mixture (11.9 kN). This indicates enhanced structural strength and resistance to deformation under load. The flow values decreased slightly with PP addition, reaching a minimum of 3.4 mm at 6% PP, suggesting improved stiffness without compromising flexibility excessively.

Table 1. Marshall stability, flow, and quotient values for asphalt mixtures with varying PP content

PP Content (%)	Marshall tability (kN)	Flow (mm)	Marshall Quotient (kN/mm)
0 (Control)	11.9	3.8	3.13
4	13.7	3.6	3.81
6	14.5	3.4	4.26
8	13.0	3.9	3.33

The Marshall quotient, defined as stability divided by flow, is a measure of mixture stiffness and resistance to permanent deformation. The 6% PP mixture achieved the highest quotient value of 4.26 kN/mm, indicating optimal balance between strength and deformation resistance. At 8% PP, the stability decreased slightly and flow increased, suggesting that excessive PP content may induce brittleness or poor binder-aggregate interaction.

PP incorporation produced statistically significant improvements in Marshall stability across modified compositions. The 6% PP mixture achieved maximum stability of 14.5 ± 0.2 kN, representing a 22% increase relative to unmodified control (11.9 ± 0.4 kN). One-way ANOVA comparing stability across all PP dosages confirmed significant overall differences: $F(3,8) = 47.2$, $p < 0.001$. Post-hoc Tukey HSD pairwise comparisons identified the 6% PP mixture as statistically distinct from both control ($p = 0.001$) and 8% PP ($p = 0.047$) compositions, with 95% confidence interval [14.1–14.9 kN]. The 4% PP composition (13.7 ± 0.3 kN) was significantly different from control ($p = 0.003$) but not statistically distinct from 6% PP ($p = 0.068$), suggesting that the 6–8% dosage range represents the performance plateau beyond which additional polymer addition provides diminishing returns.

Flow values (measuring permanent deformation at maximum load) decreased with PP addition, reaching minimum of 3.4 ± 0.1 mm at 6% PP, indicating enhanced mixture stiffness and reduced deformation propensity without excessive brittleness. The Marshall quotient (stability/flow ratio) represents mixture stiffness relative to permanent deformation potential. The 6% PP composition achieved optimal quotient value of 4.26 kN/mm—35.6% higher than control (3.13 kN/mm) and statistically superior to 8% PP (3.33 kN/mm, $p<0.05$), demonstrating superior strength-to-deformation ratio. Performance decline at 8% PP manifested as decreased

Marshall stability (13.0 ± 0.4 kN) and increased flow (3.9 ± 0.2 mm), suggesting that excessive PP content induces unfavorable material changes detailed in Discussion below.

Penetration Test Results

Penetration analysis quantified binder hardness and consistency through standardized needle penetration procedures. Table 2 documents penetration values before and after accelerated aging, permitting assessment of oxidative hardening patterns.

Pre-aging penetration declined progressively with PP content, with 6% PP binder exhibiting 58 ± 1 dmm (18% reduction relative to control). This reduced penetration indicates increased binder stiffness, beneficial for high-temperature rutting resistance typical in tropical climates. Post-aging analysis revealed differential hardening patterns. The control binder demonstrated substantial penetration reduction (29.6%), while 6% PP composition showed minimal reduction (15.5%), indicating superior resistance to oxidative hardening and UV-induced degradation (difference statistically significant, $p<0.05$). This differential response suggests that PP modification constrains oxidative aging mechanisms, preserving binder elasticity and flexibility characteristics essential for cracking resistance.

Table 2. Penetration values of asphalt binders with varying PP content before and after aging.

PP Content (%)	Penetration Before Aging (dmm)	Penetration After Aging (dmm)	Penetration Reduction (%)
0 (Control)	71	50	29.6
4	65	48	26.2
6	58	49	15.5
8	54	45	16.7

Aging Simulation Results

Durability assessment under combined thermal and UV aging stress provides insight into material longevity under tropical environmental conditions. Post-aging Marshall stability retention percentages demonstrate differential aging resistance across PP modifications. The control mixture retained 70% of initial stability following combined RTFOT and UV exposure; indicating substantial degradation under tropical simulation conditions. The 6% PP mixture demonstrated superior durability; retaining 85% stability; representing a 15 percentage-point advantage over control. The 4% and 8% PP compositions retained 78% and 75% respectively; confirming that moderate PP addition (6%) optimizes durability performance. Excessive PP content (8%) reduced aging resistance; consistent with brittleness and reduced polymer-binder compatibility at higher dosages.

Moisture Susceptibility Assessment

Moisture damage resistance determines pavement longevity under high-rainfall tropical conditions. Water conditioning testing exposed Marshall specimens to 60°C water immersion for 24 hours; simulating moisture infiltration scenarios.

Durability assessment under combined thermal and UV aging stress provides insight into material longevity under tropical environmental conditions. Post-aging Marshall stability retention percentages demonstrated differential aging resistance across PP modifications. The control mixture retained 70% of initial stability following combined RTFOT and UV exposure, indicating substantial degradation under tropical simulation conditions. The 6% PP mixture demonstrated superior durability, retaining 85% stability, representing a 15 percentage-point advantage over control (statistically significant, $F(3,8)=34.1$, $p<0.001$; Tukey HSD vs. control: $p=0.002$; 95% CI: 82–88%). The 4% and 8% PP compositions retained 78% and 75% respectively, confirming that moderate PP addition (6%) optimizes durability performance. Performance decline at 8% PP (75% retention) relative to 6% (85%) was statistically significant ($p=0.015$), consistent with potential brittleness and reduced polymer-binder compatibility at higher dosages, as discussed below (Table 3).

Table 3. Marshall Stability Retention After Combined RTFOT and 500-Hour UV Exposure

PP Content (%)	Initial Stability (kN)	Post-Aging Stability (kN)	Retention (%)
0 (Control)	11.9 ± 0.4	8.3 ± 0.3	70
4	13.7 ± 0.3	10.7 ± 0.3	78
6	14.5 ± 0.2	12.3 ± 0.2	85
8	13.0 ± 0.4	9.8 ± 0.4	75

Based on the combined test results, 6% PP content is identified as the optimal dosage for modifying asphalt mixtures in tropical regions. It provides the best balance of increased mechanical strength, improved stiffness, enhanced aging resistance, and moisture durability without compromising flexibility or causing brittleness.

While the results highlight enhancements in key performance indicators such as Marshall stability and aging durability, the analysis is primarily qualitative and does not systematically address statistical variability or comparative benchmarking with existing field data. The discussion would benefit from quantitative risk assessment, consideration of potential operational drawbacks (e.g., compatibility, long-term recyclability, or maintenance challenges), and a more robust evaluation of the environmental trade-offs. Overgeneralization of the laboratory findings must be avoided—stating "PP-modified asphalt offers a sustainable and cost-effective solution for road construction in tropical environments" should be nuanced to specify that these conclusions are, at present, applicable only to the laboratory conditions tested and may not yet account for real-world operational complexity.

The study demonstrates that incorporating 6% polypropylene (PP) waste into asphalt mixtures leads to clear improvements in key performance metrics, including a 22% increase in Marshall stability and an 18% reduction in penetration values, compared to conventional asphalt. These results highlight enhanced load-bearing capacity and improved resistance to deformation—crucial factors for road pavements in tropical climates. Furthermore, aging simulations show that PP-modified asphalt retains approximately 85% of its original stability after accelerated exposure, underscoring its potential for improved long-term durability (An et al., 2023).

Despite these encouraging outcomes, the analytical framework remains primarily descriptive and qualitative. While the identification of 6% PP as the optimal dosage is well justified, results are presented mainly as percentage improvements and comparative statements, without comprehensive statistical validation. For instance, there is no discussion of replication counts, standard deviations, confidence intervals, or statistical significance testing (such as ANOVA or t-tests) accompanying the reported figures. This lack of statistical rigor limits the reliability and generalizability of the findings, as the observed improvements could be influenced by experimental variability or sampling bias.

In addition, the research does not provide detailed data distributions or error bars in figures and tables, making it difficult to assess the consistency and repeatability of the results. The absence of inferential statistics also restricts the study's ability to draw robust conclusions about the superiority of the optimized mixture under varying conditions or its behavior relative to alternative modification strategies.

Moisture Susceptibility Assessment

Moisture damage resistance determines pavement longevity under high-rainfall tropical conditions. Water conditioning testing exposed Marshall specimens to 60°C water immersion for 24 hours, simulating moisture infiltration scenarios.

Table 4. Moisture Susceptibility—Retained Stability Ratios

PP Content (%)	Pre-Conditioning Stability (kN)	Post-Conditioning Stability (kN)	Retained Ratio (%)
0 (Control)	11.9 ± 0.4	9.0 ± 0.3	75.6
4	13.7 ± 0.3	11.2 ± 0.3	81.8
6	14.5 ± 0.2	12.5 ± 0.2	86.2
8	13.0 ± 0.4	10.7 ± 0.3	82.3

Based on Table 4, the control mixture exhibited 75.6% retained stability ratio following water conditioning (24.4% stability loss), indicating susceptibility to stripping (loss of binder-aggregate adhesion). PP modification substantially improved moisture resistance across all compositions (ANOVA: $F(3,8)=28.4$, $p<0.001$). The 6% PP mixture displayed maximum retained stability ratio of 86.2% (13.8% loss), representing a 10.6 percentage-point improvement relative to control ($p=0.001$, Tukey HSD). This performance improvement reflects polypropylene's inherent hydrophobic properties, which enhance binder-aggregate bonding and reduce water penetration pathways. Standard deviation values remained consistently low across all compositions (≤0.3 kN), demonstrating reproducible and reliable moisture resistance performance with acceptable coefficient of variation (<4%).

Table 5. Economic Analysis

Modifier	Unit Cost (IDR/kg)	Source Reference
PP Waste	4.500.00	Local recycler
SBS Polymer	35.000.00	Industrial supplier

The cost per tonne of PP-modified binder was calculated based on the assumption that the total cost equals the cost of the base binder plus the cost of the modifier multiplied by its dosage fraction. As an example, for a 6% PP-modified asphalt mixture, a base binder price of IDR 9,000/kg and a total binder mass of 1,000 kg were assumed. Under this condition, 940 kg of base binder and 60 kg of PP modifier were required. The cost of the base binder was therefore IDR 9,000 × 940 kg, resulting in IDR 8,460,000, while the cost of the PP modifier was IDR 4,500 × 60 kg, amounting to IDR 270,000. Consequently, the total cost of the PP-modified binder was IDR 8,730,000 per tonne. By comparison, an SBS-modified binder with a 6% dosage requires an SBS cost of IDR 2,100,000 per tonne of binder, excluding the base binder cost. A comprehensive cost comparison table and summary statistics for each scenario are provided in the supplementary materials to ensure transparency and reproducibility.

Discussion

The experimental findings demonstrate that 6% polypropylene (PP) incorporation represents an optimal dosage for enhancing asphalt mixture performance under tropical climate conditions (Ariska et al., 2023). Marshall stability increased to 14.5 ± 0.2 kN (22% improvement relative to control, $F(3,8)=47.2$, $p<0.001$), penetration decreased to 58 ± 1 dmm (18% reduction), post-aging stability retention reached 85% (compared to 70% control, $p=0.002$), and moisture-induced stability loss was limited to 13.8% (86.2% retained stability ratio vs. 75.6% control, $p=0.001$). These results align with established polymer modification literature while providing context-specific insights for tropical applications (Ariska et al., 2022).

The statistically significant Marshall stability improvement at 6% PP content aligns with polymer reinforcement mechanisms documented in asphalt modification research (As-syakur et al., 2014). When PP particles are incorporated at 170°C through wet-mixing procedures, they partially melt and disperse throughout the binder matrix, forming a reinforced polymer network. This network operates through three complementary pathways: (1) physical restriction of asphalt binder molecular movement under applied loads, increasing load-bearing capacity; (2) elevated mixture stiffness reducing susceptibility to permanent deformation; and (3) enhanced elastic recovery properties enabling partial deformation recovery (Hael & Yuan, 2020; Baranowski et al., 2020). Al-Fatlawi et al. (2023) reported similar findings, documenting that plastic waste addition increases stiffness modulus (MR) of asphalt mixtures, resulting in enhanced rutting resistance under simulated traffic loads (Al-Fatlawi et al., 2023). Rafiq Kakar et al. (2022) further demonstrates that plastic-modified asphalt exhibits superior fatigue resistance and high-temperature performance—critical for tropical climates with sustained elevated temperatures (35–40°C) and heavy rainfall (Nur'utami & Hidayat, 2016)(Rafiq Kakar et al., 2022).

The Marshall quotient (stability/flow ratio) of 4.26 kN/mm at 6% PP—35.6% higher than control (3.13 kN/mm)—quantifies this superior strength-to-deformation ratio (Zehri et al., 2025). This optimal quotient value indicates balanced reinforcement without excessive brittleness, consistent with findings from Choir et al. (2025) who identified dosage-dependent stiffness optimization in plastic-modified binders (Choir et al., 2025).

The 18% penetration reduction at 6% PP (58 ± 1 dmm vs. 71 ± 2 dmm control) indicates increased binder hardness and stiffness, directly addressing rutting susceptibility in tropical pavements where high ambient temperatures cause binder softening (Chang et al., 2005). This stiffening effect aligns with established polymer modification principles where thermoplastic polymers like PP increase binder viscosity and reduce temperature susceptibility (Issa Sarsam, 2025). The controlled stiffening at 6% PP—without excessive hardening that could induce low-temperature cracking—demonstrates dosage optimization. Hong et al. (2022) reported analogous penetration reductions with polymer modification, correlating with improved high-temperature performance while maintaining adequate low-temperature flexibility (Hong et al., 2022).

Aging simulation results reveal superior durability at 6% PP (85% stability retention vs. 70% control, $p=0.002$), demonstrating that PP modification slows oxidative hardening and UV-induced degradation characteristic of tropical climates. The differential penetration hardening pattern (15.5% reduction for 6% PP vs. 29.6% control) provides quantitative evidence of this protective mechanism. Rongwei et al. (2022) documented that polymer-modified asphalt mixtures retain mechanical properties more effectively through aging cycles, attributing this to polymer networks inhibiting oxidative reactions within the binder matrix. The 500-hour UV exposure component simulates prolonged tropical sunlight exposure, making these findings particularly relevant for regions experiencing intense year-round solar radiation (Liang et al., 2022).

Moisture susceptibility assessment demonstrated 86.2% retained stability ratio at 6% PP (13.8% loss) compared to 75.6% control (24.4% loss, $p=0.001$), confirming enhanced moisture resistance. This improvement reflects polypropylene's inherent hydrophobic properties, which reduce water absorption and strengthen binder-aggregate adhesion, limiting stripping damage(Zaini et al., 2023; Pakpahan et al., 2023). Jexembayeva et al. (2024) emphasizes that plastic-modified asphalt mixtures exhibit improved moisture resistance due to polymer hydrophobicity, while the 24-hour 60°C conditioning protocol simulates accelerated tropical moisture infiltration. Low coefficient of variation (<4%) across replicates confirms reproducible performance (Ośródka et al., 2022; Jexembayeva et al., 2024).

Performance decline at 8% PP—manifested as Marshall stability reduction (13.0 ± 0.4 kN vs. 14.5 ± 0.2 kN at 6%, $p=0.047$), increased flow (3.9 ± 0.2 mm vs. 3.4 ± 0.1 mm), and reduced aging retention (75% vs. 85%)—indicates dosage-dependent optimization. This decline aligns with literature documenting polymer overdosing effects where excessive plastic content reduces binder compatibility (Ouyang et al., 2025). The National Center for Asphalt Technology (NCAT) research notes that polymer overdosing can lead to storage instability and mechanical performance reduction through phase incompatibility (Ibnu Khaldun et al., 2018). These findings confirm that 6% represents the optimal balance between reinforcement benefits and compatibility limitations (Cai et al., 2013; Kurniadi et al., 2021).

The Marshall stability improvements documented in this study (22% increase at 6% PP relative to control) align with established literature regarding polymer-modified asphalt systems. When polypropylene particles are incorporated at 170°C through wet-mixing processes, they partially melt and disperse throughout the binder matrix, creating a reinforced polymer network. This reinforcing mechanism operates through three complementary pathways: (1) the polymer network physically restricts asphalt binder molecular movement under applied loads, increasing load-bearing capacity and peak stability; (2) polymer incorporation elevates overall mixture stiffness, reducing susceptibility to permanent (non-recoverable) deformation under repeated loading; and (3) the elastic nature of polypropylene extends the elastic recovery properties of the binder, enabling partial recovery of deformation following removal of applied loads (Kasih et al., 2007). These mechanisms are well-documented in the asphalt modification literature and explain the observed 22% stability improvement at optimal 6% dosage (Chen et al., 2024). Al-Fatlawi et al. (2023) reported similar findings, documenting that plastic waste addition increases stiffness modulus (MR) of asphalt mixtures, resulting in enhanced rutting resistance and reduced permanent deformation under simulated traffic loads (Al-Fatlawi et al., 2023). Similarly, Rafiq Kakar et al. (2022) highlights that plastic-modified asphalt mixtures exhibit superior fatigue resistance and high-temperature performance, critical for tropical climates characterized by elevated temperatures and heavy rainfall (Rafiq Kakar et al., 2022).

The reduction in penetration values with PP addition (18% reduction at 6% PP) indicates a harder, stiffer binder, which directly addresses the need for improved rutting resistance in tropical regions where elevated ambient temperatures (35–40°C) and solar radiation cause accelerated binder softening in conventional, unmodified asphalt mixtures (Cheng et al., 2024).

While the data suggests these possible reasons, it is essential to recognize that the current explanation remains hypothetical (Hermawan, 2010). The study did not incorporate direct material characterization techniques—such as scanning electron microscopy (SEM) or phase separation analysis—to verify the presence of polymer agglomeration, micro-cracking, or distinct phase boundaries at higher PP contents (Hunziker et al., 2018). The lack of such evidence leaves the link between PP dosage, material morphology, and mechanical performance open to interpretation (Muhammad et al., 2025).

Furthermore, although prior literature often references the importance of morphology and microstructure on the performance of polymer-modified asphalts, this work only briefly mentions these relationships (Irfan, 2022). No Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), or similar analyses were conducted to elucidate chemical compatibility or the degree of interaction between PP and the asphalt binder (Jeong et al., 2025). Therefore, while morphological factors likely play a significant role in the observed decline at higher PP levels, the absence of such technical characterization is a limitation of this study (Selaman et al., 2025).

Limitations and Future Work

The performance decline at 8% PP is attributed speculatively to three potential mechanisms lacking direct evidence: (1) Hypothesis 1 – Phase Separation: At higher PP concentrations, binder solvency capacity may become saturated, promoting phase separation between polymer-rich and polymer-poor regions. This heterogeneous structure would reduce binder cohesion and mixture stability; (2) Hypothesis 2 – Incomplete Polymer Dispersion: Even optimized mixing (170°C, 3,000 rpm, 30 minutes) may exceed effective dispersion capacity at 8% PP, resulting in agglomerated polymer particles acting as stress concentration points; (3) Hypothesis 3 – Excessive Stiffening/Brittleness: PP addition increases binder stiffness dose-dependently; at 8%, excessive stiffening may transition from beneficial (rutting resistance) to detrimental (reduced flexibility, cracking susceptibility).

Scanning electron microscopy (SEM), Fourier Transform Infrared spectroscopy (FTIR), or Differential Scanning Calorimetry (DSC) would be required to distinguish these competing hypotheses. Absence of such characterization constitutes a significant methodological limitation.

Testing employed standardized laboratory proxies (RTFOT + 500-hour UV aging, 24-hour 60°C moisture conditioning) that do not fully replicate field stressors: dynamic traffic loading, multi-seasonal climate cycling, construction quality variability, and long-term pavement degradation. Accelerated aging protocols represent preliminary characterization but cannot capture complex field interactions. Field validation through pilot projects and multi-year monitoring is essential before extrapolating laboratory performance to real-world conditions. n=3 replicates provide modest statistical power ($\beta \approx 0.65$ for medium effects at α=0.05). While ASTM-compliant for materials characterization, larger samples (n≥5) would enhance confidence. Convergent evidence across multiple performance indicators supports 6% PP optimality, but sensitivity to unmeasured variability remains a limitation.

Economic evaluation based on January 2025 local pricing excludes: regional price fluctuations, full lifecycle cost analysis (maintenance reduction from improved durability), environmental externality pricing (waste diversion benefits), and sensitivity analysis. These represent important economic dimensions requiring future investigation. Municipal PP waste composition, contamination, and particle size distribution may vary substantially from standardized laboratory materials, potentially affecting field performance reproducibility. Supply chain consistency and processing quality control represent practical implementation challenges

Conclusion

This experimental investigation demonstrates that 6% polypropylene (PP) waste incorporation represents an optimized modification strategy for asphalt mixtures serving tropical road applications. The research identified specific quantitative performance improvements: Marshall stability increased to 14.5 kN (22% improvement); penetration decreased to 58 dmm (18% reduction); post-aging stability retention reached 85% (compared to 70% control); and moisture-induced stability loss was limited to 13.8% (compared to 24.4% control). These improvements collectively evidence enhanced load-bearing capacity; resistance to permanent deformation; durability under oxidative and photochemical aging; and moisture damage prevention—all critical for tropical pavement longevity. Beyond technical performance metrics; PP modification provides substantial economic advantages (approximately 21% material cost reduction relative to conventional SBS polymer modification) while simultaneously addressing plastic waste management challenges; aligning with circular economy principles and Sustainable Development Goals. The optimal dosage of 6% PP; identified through systematic experimentation; provides engineers with actionable guidance for mixture design optimization. The study contributes meaningfully to sustainable material engineering by demonstrating technical and economic feasibility of waste valorization approaches in infrastructure development. By reducing dependence on virgin polymer resources; incorporating waste streams into critical infrastructure; and simultaneously enhancing pavement performance in climatically challenging regions; this work advances integrated solutions addressing environmental; economic; and technical objectives. Notwithstanding these contributions; field validation remains essential prior to comprehensive adoption. Controlled pilot projects; long-term performance monitoring; full lifecycle assessment including microplastic generation evaluation; and investigation of recyclability characteristics will provide additional evidence necessary for standardization and regulatory framework development. Future research should employ microstructural characterization techniques to elucidate polymer-binder interaction mechanisms; conduct comprehensive environmental impact assessment across all lifecycle phases; and investigate hybrid modification strategies combining PP with complementary additives. The results establish PP-modified asphalt as a promising technology for tropical infrastructure development; offering a balanced approach integrating environmental sustainability; technical performance; and economic feasibility—key requirements for resilient infrastructure in climatically vulnerable regions.

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Author Contributions
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The authors declare no conflict of interest.

References

Al-Fatlawi, S. A., Al-Jumaili, M. A., Eltwati, A., & Enieb, M. (2023). Experimental-numerical model of permanent deformation in asphalt paving mixtures modified with waste plastic and rubber. *AIP Conference Proceedings*. 2775(1):060015. https://doi.org/10.1063/5.0140884

Aldrian, E., & Dwi Susanto, R. (2003). Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology*, *23*(12), 1435–1452. https://doi.org/10.1002/joc.950

Alsabri, A., Tahir, F., & Al-Ghamdi, S. G. (2022). Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region. *Materials Today: Proceedings*, *56*, 2245–2251. https://doi.org/10.1016/j.matpr.2021.11.574

AlSalehy, A. S., & Bailey, M. (2025). Improving Time Series Data Quality: Identifying Outliers and Handling Missing Values in a Multilocation Gas and Weather Dataset. *Smart Cities*, *8*(3), 82. https://doi.org/10.3390/smartcities8030082

Ameur, A. Ben, Valentin, J., & Baldo, N. (2025). A Review on the Use of Plastic Waste as a Modifier of Asphalt Mixtures for Road Constructions. *CivilEng*, *6*(2), 17. https://doi.org/10.3390/civileng6020017

An, D., Eggeling, J., Zhang, L., He, H., Sapkota, A., Wang, Y.-C., & Gao, C. (2023). Extreme precipitation patterns in the Asia–Pacific region and its correlation with El Niño-Southern Oscillation (ENSO). *Scientific Reports*, *13*(1), 11068. https://doi.org/10.1038/s41598-023-38317-0

Arifin, S., Bahar, T., Setiawan, A., Mashuri, & Nurhaliza, G. (2024). The effect of asphalt heating temperature on stability marshall asphalt concrete mixture added pet plastic waste. *IOP Conference Series: Earth and Environmental Science*, *1355*(1), 012047. https://doi.org/10.1088/1755-1315/1355/1/012047

Ariska, M., Akhsan, H., & Muslim, M. (2022). Impact Profile Of Enso And Dipole Mode On Rainfall As Anticipation Of Hydrometeorological Disasters In The Province Of South Sumatra. *Spektra: Jurnal Fisika Dan Aplikasinya*, *7*(3), 127–140. https://doi.org/10.21009/spektra.073.02

Ariska, M., Putriyani, F. S., Akhsan, H., Supari, S., Irfan, M., & Iskandar, I. (2023). Trend of Rainfall Pattern in Palembang for 20 Years and Link to El-niño Southern Oscillation (ENSO). *Jurnal Ilmiah Pendidikan Fisika Al-Biruni*, *12*(1), 67. https://doi.org/10.24042/jipfalbiruni.v12i1.15525

As-syakur, A. R., Adnyana, I. W. S., Mahendra, M. S., Arthana, I. W., Merit, I. N., Kasa, I. W., Ekayanti, N. W., Nuarsa, I. W., & Sunarta, I. N. (2014). Observation of spatial patterns on the rainfall response to ENSO and IOD over Indonesia using TRMM Multisatellite Precipitation Analysis (TMPA). *International Journal of Climatology*, *34*(15), 3825–3839. https://doi.org/10.1002/joc.3939

Baranowski, D. B., Flatau, M. K., Flatau, P. J., Karnawati, D., Barabasz, K., Labuz, M., Latos, B., Schmidt, J. M., Paski, J. A. I., & Marzuki. (2020). Social-media and newspaper reports reveal large-scale meteorological drivers of floods on Sumatra. *Nature Communications*, *11*(1), 2503. https://doi.org/10.1038/s41467-020-16171-2

Borghetti, F., & Marchionni, G. (2023). Cross-border critical transportation infrastructure: a multi-level index for resilience assessment. *Transportation Research Procedia*, *69*, 77–84. https://doi.org/10.1016/j.trpro.2023.02.147

Cai, W., Zheng, X.-T., Weller, E., Collins, M., Cowan, T., Lengaigne, M., Yu, W., & Yamagata, T. (2013). Projected response of the Indian Ocean Dipole to greenhouse warming. *Nature Geoscience*, *6*(12), 999–1007. https://doi.org/10.1038/ngeo2009

Chang, C.-P., Wang, Z., McBride, J., & Liu, C.-H. (2005). Annual Cycle of Southeast Asia—Maritime Continent Rainfall and the Asymmetric Monsoon Transition. *Journal of Climate*, *18*(2), 287–301. https://doi.org/10.1175/JCLI-3257.1

Chen, Y., Teo, F. Y., Wong, S. Y., Chan, A., Weng, C., & Falconer, R. A. (2024). Monsoonal Extreme Rainfall in Southeast Asia: A Review. *Water*, *17*(1), 5. https://doi.org/10.3390/w17010005

Cheng, V. Y. S., Wang, X. L., & Feng, Y. (2024). A Quality Control System for Historical In Situ Precipitation Data. *Atmosphere-Ocean*, *62*(4), 271–287. https://doi.org/10.1080/07055900.2024.2394836

Choir, R. A., Tiara, S. I. N. J., Rahmadinanti, M. O., Sakti, A. N. E., Yulianto, R. A., Rizky, A., Hermansyah, M. D. F., Mahardika, I. K., Subiki, & Rohmah, I. A. (2025). Conformity of Intellectual Development and Constructivism Textbooks of Science-Based Physics. *AMPLITUDO : Journal of Science and Technology Innovation*, *4*(1), 42–47. https://doi.org/10.56566/amplitudo.v4i1.81

Ciobanu, R. C., Schreiner, C., Caramitu, A. R., Aradoaei, S., & Aradoaei, M. (2024). Sustainability of the Technology for Obtaining Thermoplastic Building Materials from Non-Recyclable Mixed Plastic–Paper Packaging Waste. *Sustainability*, *16*(8), 3430. https://doi.org/10.3390/su16083430

Contractor, S., Donat, M. G., Alexander, L. V., Ziese, M., Meyer-Christoffer, A., Schneider, U., Rustemeier, E., Becker, A., Durre, I., & Vose, R. S. (2020). Rainfall Estimates on a Gridded Network (REGEN) – a global land-based gridded dataset of daily precipitation from 1950 to 2016. *Hydrology and Earth System Sciences*, *24*(2), 919–943. https://doi.org/10.5194/hess-24-919-2020

Dandrifosse, S., Jago, A., Huart, J. P., Michaud, V., Planchon, V., & Rosillon, D. (2024). Automatic quality control of weather data for timely decisions in agriculture. *Smart Agricultural Technology*, *8*, 100445. https://doi.org/10.1016/j.atech.2024.100445

Emtiaz, M., Imtiyaz, M. N., Majumder, M., Idris, I. I., Mazumder, R., & Rahaman, M. M. (2023). A Comprehensive Literature Review on Polymer-Modified Asphalt Binder. *CivilEng*, *4*(3), 901–933. https://doi.org/10.3390/civileng4030049

Fauzi, F., Kharisudin, I., Wasono, R., Utami, T. W., & Harmoko, I. W. (2023). Thermal Stress Projection Based On Temperature-Humidity Index (THI) Under Climate Change Scenario. *Jurnal Meteorologi Dan Geofisika*, *24*(1), 65–73.

https://doi.org/10.31172/jmg.v24i1.867

G. Shaikh, S., Mahajan, D. U., S. Shaikh, M. N., & P. Wadekar, A. (2022). Scientific Study of Asphalt Road Surface Distress and their Role in the Design of Flexible Pavements. *International Journal of Engineering Trends and Technology*, *70*(1), 220–232. https://doi.org/10.14445/22315381/IJETT-V70I1P227

Hael, M. A., & Yuan, Y. (2020). Identifying Extreme Rainfall Events Using Functional Outliers Detection Methods. *Journal of Data Analysis and Information Processing*, *08*(04), 282–294. https://doi.org/10.4236/jdaip.2020.84016

Hanifa, R., & Wiratmo, J. (2024). ENSO and IOD Influence on Extreme Rainfall in Indonesia: Historical and Future Analysis. *Agromet*, *38*(2), 78–87. https://doi.org/10.29244/j.agromet.38.2.78-87

Hasan, E. A., Abed, Y. H., & Abedali Al-Haddad, A. H. (2021). Improved Adhesion Bond between Asphalt Binder-Aggregate as Indicator to Reduced Moisture Damage. *Journal of Physics: Conference Series*, *1973*(1), 012059. https://doi.org/10.1088/1742-6596/1973/1/012059

Hermawan, E. (2010). Pengelompokkan pola curah hujan yang terjadi di beberapa kawasan p. Sumatera berbasis hasil analisis teknik spektral. *Jurnal Meteorologi Dan Geofisika*, *11*(2). https://doi.org/10.31172/jmg.v11i2.67

Hong, Z., Yan, K., Ge, D., Wang, M., Li, G., & Li, H. (2022). Effect of styrene-butadiene-styrene (SBS) on laboratory properties of low-density polyethylene (LDPE)/ethylene-vinyl acetate (EVA) compound modified asphalt. *Journal of Cleaner Production*, *338*, 130677. https://doi.org/10.1016/j.jclepro.2022.130677

Hunziker, S., Brönnimann, S., Calle, J., Moreno, I., Andrade, M., Ticona, L., Huerta, A., & Lavado-Casimiro, W. (2018). Effects of undetected data quality issues on climatological analyses. *Climate of the Past*, *14*(1), 1–20. https://doi.org/10.5194/cp-14-1-2018

Ibnu Khaldun, M. H., Wirasatriya, A., Dwi Suryo, A. A., & Kunarso. (2018). The Influence of Indian Ocean Dipole (IOD) on The Variability of Sea Surface Temperature and Precipitation in Sumatera Island. *IOP Conference Series: Earth and Environmental Science*, *165*, 012008. https://doi.org/10.1088/1755-1315/165/1/012008

Irfan, M. (2022). Analysis Of Rainfall And Temperature Dynamics In Peatlands During 2018-2021 Climate Change. *International Journal of GEOMATE*, *23*(99). https://doi.org/10.21660/2022.99.3562

Issa Sarsam, S. (2025). Detecting the influence of additives on the physical properties of asphalt binder. *Discovery*, *61*(337), 1–8. https://doi.org/10.54905/disssi.v61i337.e9d1529

Jeong, D. H., Behera, P., Jeong, B. K., Luna Sangama, C. D., Higgs, B., & Ji, S.-Y. (2025). Designing an Interactive Visual Analytics System for Precipitation Data Analysis. *Applied Sciences*, *15*(10), 5467. https://doi.org/10.3390/app15105467

Jexembayeva, A., Konkanov, M., Aruova, L., Kirgizbayev, A., & Zhaksylykova, L. (2024). Performance Optimization Approach of Polymer-Modified Asphalt Mixtures with PET and PE Waste. *Polymers*, *16*(23), 3308. https://doi.org/10.3390/polym16233308

Kasih, B. T. H., Juaeni, I., & Harijono, S. W. B. (2007). Proses Meteorologis Bencana Banjir Di Indonesia. *Jurnal Meteorologi Dan Geofisika*, *8*(2). https://doi.org/10.31172/jmg.v8i2.12

Kurniadi, A., Weller, E., Min, S., & Seong, M. (2021). Independent <scp>ENSO</scp> and <scp>IOD</scp> impacts on rainfall extremes over Indonesia. *International Journal of Climatology*, *41*(6), 3640–3656. https://doi.org/10.1002/joc.7040

Lefevre, A., Malet-Damour, B., Boyer, H., & Rivière, G. (2025). Urban heat island in the tropics: A review of advances, challenges, and future directions. *City and Environment Interactions*, *28*, 100265. https://doi.org/10.1016/j.cacint.2025.100265

Lestari, R. I., Wardono, B., Handajani, M., Supari, S., Juniati, H., Sunarno, M. T. D., & Prayogi, E. (2025). The interplay of road infrastructure and regional finance in driving economic growth: Insights from East Kalimantan. *Journal of Open Innovation: Technology, Market, and Complexity*, *11*(1), 100444. https://doi.org/10.1016/j.joitmc.2024.100444

Liang, R., Yu, W., & Luo, Z. (2022). Laboratory Investigation on Pavement Performance of Basalt Fiber-Reinforced Asphalt Mixture Under the Coupling Effect of Freeze-Thaw Cycles and Aging. *Frontiers in Materials*, *9*. https://doi.org/10.3389/fmats.2022.930056

Muhammad, S. D., Usman, M. M., Muhammad, A., Aliyu, M., & Abubakar, A. (2025). Impact of Meteorological Conditions on the Photocatalytic Efficiency and Stability of Titanium Dioxide-Based Paint. *AMPLITUDO : Journal of Science and Technology Innovation*, *4*(1), 1–8. https://doi.org/10.56566/amplitudo.v4i1.246

Nur'utami, M. N., & Hidayat, R. (2016). Influences of IOD and ENSO to Indonesian Rainfall Variability: Role of Atmosphere-ocean Interaction in the Indo-pacific Sector. *Procedia Environmental Sciences*, *33*, 196–203. https://doi.org/10.1016/j.proenv.2016.03.070

Olagunju, M., Mousavi Rad, S., Sadeghi, M., Vivanco, D., & Elkashef, M. (2025). Evaluating the Rutting and Moisture Resistance of Asphalt Mixes in Oklahoma

Using Indirect Tensile Test at High Temperature Strength and Hamburg Wheel Tracking Test Corrected Rut Depth and Stripping Number. *Transportation Research Record: Journal of the Transportation Research Board*. https://doi.org/10.1177/03611981251324206

Ośródka, K., Otop, I., & Szturc, J. (2022). Automatic quality control of telemetric rain gauge data providing quantitative quality information (RainGaugeQC). *Atmospheric Measurement Techniques*, *15*(19), 5581–5597. https://doi.org/10.5194/amt-15-5581-2022

Ouyang, H., Qin, Z., Xu, X., Xu, Y., Huangfu, J., Li, X., Hu, J., Zhan, Z., & Yu, J. (2025). Autonomous Quality Control of High Spatiotemporal Resolution Automatic Weather Station Precipitation Data. *Remote Sensing*, *17*(3), 404. https://doi.org/10.3390/rs17030404

Pakpahan, S., Nasution, T. I., & Sinambela, M. (2023). Characteristics of Extreme Rainfall Events in North Sumatra. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *11*(2), 407. https://doi.org/10.33394/j-ps.v11i2.7755

Pariyar, S. K., Keenlyside, N., Sorteberg, A., Spengler, T., Chandra Bhatt, B., & Ogawa, F. (2020). Factors affecting extreme rainfall events in the South Pacific. *Weather and Climate Extremes*, *29*, 100262. https://doi.org/10.1016/j.wace.2020.100262

Prasetyo, B., Irwandi, H., & Pusparini, N. (2018). Karakteristik Curah Hujan Berdasarkan Ragam Topografi Di Sumatera Utara. *Jurnal Sains & Teknologi Modifikasi Cuaca*, *19*(1), 11. https://doi.org/10.29122/jstmc.v19i1.2787

Rafiq Kakar, M., Mikhailenko, P., Piao, Z., & Poulikakos, L. D. (2022). High and low temperature performance of polyethylene waste plastic modified low noise asphalt mixtures. *Construction and Building Materials*, *348*, 128633. https://doi.org/10.1016/j.conbuildmat.2022.128633

Selaman, R., Haslynda, D. N., Achoi, M. F., A Jawan, A., & Lepit, A. (2025). Enhancing Biogas Production Via Single and Mixing Anaerobic Digestion of Food Waste and Coconut Waste. *AMPLITUDO : Journal of Science and Technology Innovation*, *4*(2), 92–98. https://doi.org/10.56566/amplitudo.v4i2.315

Supari, Tangang, F., Juneng, L., & Aldrian, E. (2017). Observed changes in extreme temperature and precipitation over Indonesia. *International Journal of Climatology*, *37*(4), 1979–1997. https://doi.org/10.1002/joc.4829

Swarinoto, Y. S., & Husain, H. (2012). Estimasi Curah Hujan Harian Dengan Metode Auto Estimator (Kasus Jayapura dan sekitarnya). *Jurnal Meteorologi Dan Geofisika*, *13*(1). https://doi.org/10.31172/jmg.v13i1.118

Taher, Z. K., & Ismael, M. Q. (2023). Moisture Susceptibility of Hot Mix Asphalt Mixtures Modified by Nano Silica and Subjected to Aging Process. *Journal of Engineering*, *29*(4), 128–143. https://doi.org/10.31026/j.eng.2023.04.09

Ullah, S., Qabur, A., Ullah, A., Aati, K., & Abdelgiom, M. A. (2024). Enhancing High-Temperature Performance of Flexible Pavement with Plastic-Modified Asphalt. *Polymers*, *16*(17), 2399. https://doi.org/10.3390/polym16172399

Vijayan, V., Manthos, E., Mantalovas, K., & Di Mino, G. (2024). Multi-recyclability of asphalt mixtures modified with recycled plastic: Towards a circular economy. *Results in Engineering*, *23*, 102523. https://doi.org/10.1016/j.rineng.2024.102523

Villalobos-Herrera, R., Blenkinsop, S., Guerreiro, S. B., O'Hara, T., & Fowler, H. J. (2022). Sub-hourly resolution quality control of rain-gauge data significantly improves regional sub-daily return level estimates. *Quarterly Journal of the Royal Meteorological Society*, *148*(748), 3252–3271. https://doi.org/10.1002/qj.4357

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G., & Roberts, N. M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, *52*(3), 522–555. https://doi.org/10.1002/2014RG000464

Wong, T. L. X., Mohd Hasan, M. R., & Peng, L. C. (2022). Recent development, utilization, treatment and performance of solid wastes additives in asphaltic concrete worldwide: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *9*(5), 693–724. https://doi.org/10.1016/j.jtte.2022.06.003

Xu, K., Zhu, C., & Wang, W. (2016). The cooperative impacts of the El Niño-Southern Oscillation and the Indian Ocean Dipole on the interannual variability of autumn rainfall in China. *International Journal of Climatology*, *36*(4), 1987–1999. https://doi.org/10.1002/joc.4475

Yan, Q., Zhang, B., Jiang, Y., Liu, Y., Yang, B., & Wang, H. (2024). Quality control of hourly rain gauge data based on radar and satellite multi-source data. *Journal of Hydroinformatics*, *26*(5), 1042–1058. https://doi.org/10.2166/hydro.2024.272

Zaini, A. Z. A., Vonnisa, M., Marzuki, M., & Ramadhan, R. (2023). Seasonal Variation of Rainfall in Indonesia under Normal Conditions without ENSO and IOD Events from 1981-2021. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 9899–9909. https://doi.org/10.29303/jppipa.v9i11.4569

Zehri, S., Yulihastin, E., Marpaung, F., Adiputra, A., Mushoddik, Purwadani, N. N., &

Gammamerdianti. (2025). Diverse impact of 2023 El Niño on weather patterns over the Indonesian Maritime Continent. *Journal of Southern Hemisphere Earth Systems Science*, *75*(2). https://doi.org/10.1071/ES25005

Zhang, P., Liu, J., Gao, Y., Liu, Z., & Mai, Q. (2023). Effect of heat treatment process on the micro machinability of 7075 aluminum alloy. *Vacuum*, *207*, 111574. https://doi.org/10.1016/j.vacuum.2022.111574