

Synergistic Effect of PET Modifier and Wetfix-Be Anti-Stripping Agent on the Time-Dependent Durability of AC-BC Mixtures under Prolonged Saline Immersion

Daud Nawir ^{1✉}, Achmad Zultan Mansur ²

(1,2) Civil Engineering Study Program, Universitas Borneo Tarakan, North Kalimantan, Indonesia

Abstract: Pavement degradation in coastal regions due to high salinity, moisture, and elevated temperatures presents a significant challenge in transportation infrastructure engineering. This study investigates the effects of hybrid modification using waste Polyethylene Terephthalate (PET) and an amine-based anti-stripping agent (Wetfix-Be) on the mechanical performance and durability of Asphalt Concrete-Binder Course (AC-BC) mixtures under prolonged saline immersion. Asphalt mixtures were modified with PET contents of 0%, 2%, 4%, 6%, and 8% by bitumen weight, combined with 0.3% Wetfix-Be at an Optimum Asphalt Content (OAC) of 5.3%. Conditioning was conducted in a saline solution (35 ppt NaCl) at 60°C for 0, 24, 48, 96, and 144 hours. Evaluations included volumetric properties, Marshall Stability, Retained Stability Index (RSI), and Cantabro Loss, analyzed using Two-Way ANOVA ($\alpha = 0.05$) and Tukey's HSD test. Results revealed a non-linear relationship between PET content and mixture performance. The P4W3 formulation (4% PET and 0.3% Wetfix-Be) achieved the highest initial performance, with Marshall Stability of 1380 ± 32 kg and Marshall Quotient of 383.3 ± 13.8 kg/mm. After 144 hours of saline immersion, the control mixture lost 57% of its stability ($RSI = 42.8\%$), whereas P4W3 exhibited only 19% stability loss, maintained an RSI of $80.8 \pm 1.4\%$, and limited Cantabro Loss to $11.2 \pm 0.5\%$. The interaction between mixture composition and immersion duration significantly affected all response variables ($p < 0.001$). These findings demonstrate that PET and Wetfix-Be synergistically improve adhesion and durability under saline exposure.

Article history:

Received: 05 September 2026

Revised: 13 October 2026

Accepted: 17 October 2026

Published: 21 October 2026

Keyword:

polyethylene terephthalate (PET), wetfix-be, saline immersion, retained stability index, cantabro loss

This is an open-access article under the [CC-BY-SA License](#).



How to cite: Nawir, D., & Mansur, A. Z. (2026). Synergistic Effect of PET Modifier and Wetfix-Be Anti-Stripping Agent on the Time-Dependent Durability of AC-BC Mixtures under Prolonged Saline Immersion. RESWARA: Jurnal Riset Ilmu Teknik, 4(4), 1752-1771. <https://doi.org/10.70716/reswara.v4i4.869>

INTRODUCTION

Road pavements in coastal regions, ports, and islands face harsher environmental conditions than inland pavements. High humidity, recurrent inundation, tidal wet-dry cycles, and saline seawater intrusion accelerate asphalt deterioration (D. Feng et al., 2025). Saline water penetrates the voids in mix (VIM) and reaches the asphalt-aggregate interface, weakening adhesion and internal cohesion. This process causes moisture-induced damage, particularly stripping, in which the bitumen film separates from aggregate surfaces. Chloride (Cl^-) and sodium (Na^+) ions further disrupt interfacial bonding through osmotic pressure, ionic migration, and hydrogen bond disruption (B. Feng et al., 2022). Stripping severity depends on aggregate mineralogy, binder composition, pore structure, temperature, and exposure duration. Progressive interfacial degradation reduces mixture stability, accelerates ravelling and crack initiation, and increases rutting susceptibility, ultimately shortening pavement service life and raising maintenance costs.

Bitumen modification has been developed to improve conventional asphalt, including 60/70 penetration-grade bitumen. Elastomeric polymers, such as styrene-butadiene-styrene (SBS), and

crumb rubber can enhance elasticity, high-temperature stiffness, and rutting resistance (B. Feng et al., 2022; Qiu et al., 2025). However, their widespread application is limited by high material costs, energy-intensive mixing, storage instability due to phase separation, and polymer-bitumen compatibility issues (Izaks et al., 2022). As a more economical and sustainable alternative, recycled polyethylene terephthalate (PET) has gained attention in pavement research. Incorporated through wet or dry processing, PET can improve asphalt mixture properties. At appropriate dosages and blending conditions, molten or dispersed PET increases binder viscosity, softening point, Marshall stability, and mixture stiffness (Chen et al., 2021; Yu et al., 2021).

Despite improving stiffness, PET alone has physicochemical limitations. Differences in solubility parameters, molecular weight, and density between PET and bitumen can cause phase instability, particle agglomeration, and uneven dispersion if temperature, mixing shear, and particle size are not properly controlled (Wang et al., 2025). Moreover, increased stiffness and viscosity do not necessarily improve asphalt-aggregate adhesion. PET's predominantly non-polar nature makes the binder coating vulnerable to displacement by water and chloride ions, particularly when hydrophilic aggregates are used (Qi & Hu, 2025). Therefore, PET modification requires complementary adhesion enhancers to maintain both mechanical strength and interfacial integrity under prolonged wet and saline exposure.

Anti-stripping additives improve asphalt-aggregate adhesion and reduce moisture sensitivity. Common options include hydrated lime and surfactant-based additives, such as the amine-based commercial product Wetfix-Be evaluated in this study. These additives reduce interfacial tension and modify the contact angle between bitumen and aggregate surfaces (Liu et al., 2026). Their polar amine groups interact with aggregate surfaces, while their lipophilic hydrocarbon chains integrate into the bitumen matrix. This mechanism improves aggregate wetting, limits water-induced displacement of the asphalt film, and strengthens interfacial stability. For coastal pavements, Wetfix-Be can complement PET by addressing its adhesion limitations. PET enhances stiffness, mechanical stability, and resistance to shear deformation, whereas Wetfix-Be helps protect the asphalt-aggregate interface against moisture-induced stripping and chloride attack (Solak et al., 2024). Combining these modifiers may therefore improve both initial mechanical performance and durability under saline and moisture exposure.

Despite extensive research on asphalt modification, the combined effects of PET and anti-stripping additives remain insufficiently understood. Previous studies have mainly examined these modifiers separately, with PET research focusing on Marshall stability, stiffness, and rutting resistance rather than long-term moisture susceptibility (Nawir & Mansur, 2022; Salakhov et al., 2022). Meanwhile, anti-stripping studies have largely used short-term freshwater conditioning, such as 24-hour Marshall immersion tests at elevated temperatures (Esmaeili et al., 2019). These methods do not adequately represent prolonged saline exposure, where osmotic pressure can accelerate progressive pavement degradation (D. Feng et al., 2025). Evidence on the combined effects of PET and Wetfix-Be in Asphalt Concrete-Binder Course (AC-BC) mixtures under saline conditions is particularly limited. The time-dependent changes in Marshall stability, Retained Stability Index (RSI), and Cantabro abrasion loss during saline immersion of up to 144 hours remain insufficiently investigated. This gap highlights the need to evaluate PET's mechanical reinforcement and Wetfix-Be's adhesion enhancement within a hybrid system under prolonged saline exposure.

This study investigates the time-dependent degradation of hybrid PET-Wetfix-Be modified AC-BC mixtures under simulated coastal conditions. Unlike previous studies that examined modifiers

separately or used short-term freshwater conditioning (Liu et al., 2026; Nawir & Mansur, 2022), this study applies a 35 ppt saline solution at 60°C for 0, 24, 48, 96, and 144 hours. This experimental design evaluates PET's contribution to mixture reinforcement and Wetfix-Be's role in maintaining interfacial adhesion. The study's novelty lies in integrating polymer modification, amine-based adhesion enhancement, prolonged saline conditioning, and a comprehensive assessment of volumetric properties, Marshall stability, time-dependent RSI, and Cantabro abrasion loss within a single experimental framework.

This study has four objectives: (1) to assess the effects of varying PET contents combined with 0.3% Wetfix-Be on the initial volumetric and mechanical properties of AC-BC mixtures; (2) to evaluate changes in Marshall stability, Retained Stability Index (RSI), and Cantabro loss during immersion in a 35 ppt saline solution at 60°C for 0, 24, 48, 96, and 144 hours; (3) to determine the optimum PET content for achieving high mechanical performance and saline durability; and (4) to explain the physicochemical and mechanical mechanisms governing moisture and salinity resistance through the relationships among material composition, volumetric void structure, and deformation behavior.

This study is expected to contribute to pavement materials engineering in three areas. Scientifically, it advances understanding of interfacial degradation in hybrid thermoplastic polymer-bitumen-amine surfactant systems under prolonged saline exposure. Practically, it provides guidance for designing AC-BC mixtures for coastal, port, and island roads exposed to seawater inundation. Environmentally, it promotes the use of waste PET bottles in asphalt mixtures as a value-added recycling strategy that supports plastic waste reduction and more sustainable road infrastructure.

RESEARCH METHOD

Research Location and Materials

This experimental study was conducted at the Highway Materials and Pavement Laboratory, Department of Civil Engineering, Faculty of Engineering, Universitas Borneo Tarakan. All raw material characterization tests, specimen fabrication, environmental conditioning, and mechanical evaluations were performed in accordance with AASHTO, ASTM standards, and the 2018 Bina Marga General Specifications (Rev. 2) for Asphalt Concrete-Binder Course (AC-BC).

The materials utilized in this research include:

- Asphalt Binder (Bitumen): 60/70 penetration grade asphalt binder produced by PT Pertamina. Laboratory characterization testing yielded a penetration value of 64.2 mm (AASHTO T 49), a softening point of 48.5 °C (AASHTO T 53), a ductility of >100 cm (AASHTO T 51), a flash point of 318 °C (AASHTO T 48), and a specific gravity of 1.032 g/cm³ (AASHTO T 228).
- Aggregates: Crushed stone aggregates were sourced from local quarries in Tarakan and Tanjung Selor, North Kalimantan, comprising coarse aggregate, fine aggregate, and Type I Portland cement as mineral filler. Aggregate characterization testing revealed a Los Angeles abrasion value of 22.4% (AASHTO T 96), asphalt-aggregate adhesion/stripping resistance of 95% (AASHTO T 182), coarse aggregate water absorption of 1.42%, fine aggregate water absorption of 1.85%, a sand equivalent value of 78.5% (AASHTO T 176), and a combined aggregate bulk specific gravity of 2.618 g/cm³ (AASHTO T 84 and AASHTO T 85).
- PET Modifier: Obtained from post-consumer polyethylene terephthalate (PET) beverage bottle waste that was thoroughly cleaned, dried, and mechanically shredded to pass the No. 4 sieve

(4.75 mm) and be retained on the No. 8 sieve (2.36 mm). The processed PET flakes exhibited a melting temperature of 252.0 °C (determined via differential scanning calorimetry/melting point apparatus) and an apparent specific gravity of 1.380 g/cm³ (ASTM D792).

- Anti-Stripping Additive (Wetfix-Be): An active liquid polyamine surfactant compound appearing as a dark brown viscous liquid with a specific gravity of 0.982 g/cm³ at 25 °C (ASTM D70) and an active amine value conforming to standard technical specifications. The Wetfix-Be dosage was held constant at 0.3% by total weight of bitumen, based on the manufacturer's recommended optimum dosage and prior empirical studies, to ensure complete interfacial wetting without inducing excessive over-plasticization of the asphalt binder.

Mix Design and Optimum Asphalt Content

The job mix design was developed in accordance with the combined aggregate gradation envelopes and criteria specified in the 2018 Bina Marga General Specifications (Revision 2) for Asphalt Concrete–Binder Course (AC-BC). The Optimum Asphalt Content (OAC) was initially determined using the standard Marshall method across five binder content increments: 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% by total weight of the mixture. Each binder level was evaluated using three replicate specimens ($n = 3$, yielding a total of 15 briquettes) compacted at 2×75 blows. The volumetric and mechanical parameters—comprising bulk density, Marshall stability, flow, Marshall Quotient (MQ), voids in mix (VIM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA)—were plotted as response curves against binder content. The design OAC was established at 5.3% by total weight of the mixture, which corresponds to the median binder content that concurrently satisfied all target volumetric and mechanical criteria: achieving peak Marshall stability (>800 kg), a design VIM target centered at 4.0% (within the 3.0%–5.0% specification limit), VMA exceeding the 14.0% minimum threshold, and VFA meeting the $>65\%$ requirement. This fixed OAC of 5.3% was subsequently adopted across all modified mixture formulations, ensuring that the comparative influence of PET content and Wetfix-Be addition was evaluated under equivalent binder proportions without confounding effects from varying bitumen volumes. The complete experimental workflow—spanning raw material characterization, OAC verification, hybrid mixture fabrication, time-dependent saline exposure (0–144 hours), mechanical evaluations (Marshall and Cantabro), and Two-Way ANOVA modeling—is illustrated in Figure 1.

Experimental Design and Matrix

The mechanical performance and durability evaluations of the Asphalt Concrete–Binder Course (AC-BC) mixture were designed using a Completely Randomized Design (CRD) with a 6×5 factorial arrangement. This design combined two independent factors—mixture composition variation (6 levels) and saline immersion duration (5 levels)—to observe time-dependent mechanical deterioration patterns under accelerated saline exposure.

The six evaluated mixture variations comprised:

- Control: Conventional asphalt mixture (60/70 penetration grade) without modification.
- W3: Baseline/positive control mixture modified with 0.3% Wetfix-Be without PET, serving to isolate and quantify the independent contribution of the anti-stripping agent.
- P2W3, P4W3, P6W3, and P8W3: Hybrid modified mixtures combining varying PET dosages of 2%, 4%, 6%, and 8% (by weight of bitumen) with a constant Wetfix-Be content held at 0.3%.

Coastal environmental simulation was engineered by immersing specimens in a saline solution of 35 ± 1 ppt at an accelerated temperature of $60 \pm 1^\circ\text{C}$. Immersion intervals were established at durations of 0, 24, 48, 96, and 144 hours to continuously capture the stages of stripping and mechanical strength decay.

The variable structure of this study is systematically classified as follows:

- Independent Variables: Asphalt mixture composition (6 variations) and saline immersion duration (0, 24, 48, 96, and 144 hours).
- Dependent Variables: Marshall stability (kg), flow (mm), Marshall Quotient (MQ, kg/mm), Retained Stability Index (RSI, %), and Cantabro loss (%).
- Controlled Variables: Optimum Asphalt Content (5.3%), Wetfix-Be dosage (0.3% in modified mixtures), compaction effort (2×75 blows), salinity concentration (35 ± 1 ppt NaCl), and immersion temperature ($60 \pm 1^\circ\text{C}$).

This rigorous control of variables ensures that all observed variations in mechanical response are exclusively governed by the interaction between PET polymer content and saline exposure duration. Details of the experimental matrix are presented in Table 1.

Tabel 1. Experimental Matrix of AC-BC Mixtures

Mixture Code	PET (%)	Wetfix-Be (%)	Salinity	Immersion Duration (60°C)	Mechanical Tests
Control	0	0.0	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss
W3	0	0.3	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss
P2W3	2	0.3	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss
P4W3	4	0.3	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss
P6W3	6	0.3	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss
P8W3	8	0.3	35 ppt	0, 24, 48, 96, 144 h	Marshall, RSI, Cantabro Loss

Sample Preparation and Compaction

Modified asphalt mixtures were prepared using the wet process, in which 60/70 penetration-grade bitumen was heated in a temperature-controlled vessel until it reached the required temperature and viscosity for modification.

For modified mixtures, 0.3% Wetfix-Be by bitumen weight was added and manually stirred for 3 minutes. Shredded waste PET was then introduced at 2%, 4%, 6%, and 8% by bitumen weight. The binder was homogenized using a high-shear mixer at 3,000 rpm for 45 minutes at the specified temperature to soften and disperse the PET throughout the bitumen matrix. Coarse aggregates, fine aggregates, and cement filler were separately heated at the specified temperature for at least 4 hours to remove moisture and minimize thermal shock. The heated aggregates were then mixed with the modified bitumen until uniformly coated.

The hot mixture was placed in a 101.6 mm-diameter Marshall mold and compacted at the specified temperature using a mechanical compactor with 75 blows per face to simulate heavy traffic conditions. After compaction, specimens were cooled at room temperature for 24 hours before demolding and conditioning. Each treatment combination was prepared in two specimen groups, with three replicates per group, yielding 90 specimens for Marshall testing and 90 for Cantabro testing. Including the 15 specimens used to determine the Optimum Asphalt Content (OAC), the study produced and evaluated 195 specimens in total.

Saline Conditioning and Mechanical Testing

The coastal environment simulation was engineered by immersing the specimens in a water bath containing a synthetic saline solution with a salinity level of 35 ± 1 ppt NaCl, representing the average salinity of coastal seawater. The solution temperature was maintained constantly at $60 \pm 1^\circ\text{C}$ using an automatic thermostatic circulator to accelerate moisture stripping reactions and chloride attack. Immersion was conducted across five time-dependent intervals: 0, 24, 48, 96, and 144 hours. The 0-hour duration represents the initial specimen condition (standard immersion at 60°C for 30 minutes). Upon completing each immersion interval, the specimens were removed, surface-dried to a saturated surface-dry (SSD) condition, and immediately subjected to mechanical testing.

Marshall testing was performed in accordance with AASHTO T 245 to determine the Marshall Stability (kg) and Flow (mm) values, which were subsequently used to calculate the Marshall Quotient (MQ, kg/mm). The retained strength resistance against saltwater attack was evaluated via the Retained Stability Index (RSI) using Equation (1):

$$RSI_t = \left(\frac{S_t}{S_0} \right) \times 100\%$$

where:

- S_t = Marshall Stability value after saline immersion for time t (hours);
- S_0 = Marshall Stability value at the initial condition (0 hours).

Flowchart of the experimental research stages for evaluating the resilience and durability of PET/Wetfix-Be hybrid modified AC-BC asphalt mixtures under 35 ppt saline conditioning (60°C). Ravelling resistance testing was conducted independently using the Cantabro Loss Test in accordance with ASTM C131. Dedicated Cantabro briquettes were placed into the drum of a Los Angeles Abrasion machine without steel charges and rotated for 300 revolutions at a speed of 30–33 rpm, with room temperature maintained at $25 \pm 2^\circ\text{C}$. The percentage of mass loss was calculated as an indicator of the degradation of cohesive and adhesive bonds at the bitumen–aggregate interface.

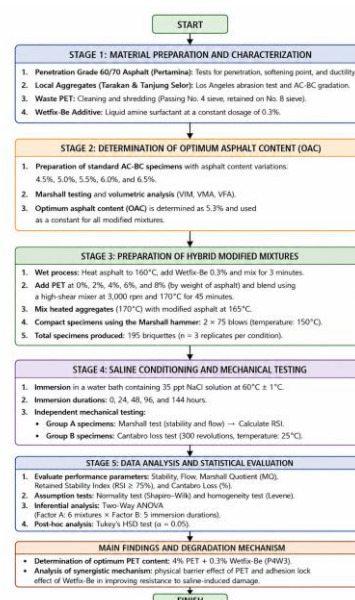


Figure 1. Flowchart of the experimental research stages

Statistical Analysis

All experimental data were analyzed using Two-Way Analysis of Variance (Two-Way ANOVA) at a preset significance level of $\alpha = 0.05$ (95% confidence level). The factorial design evaluated the main effect of mixture composition (Factor A, 6 levels: Control, W3, P2W3, P4W3, P6W3, and P8W3), the main effect of saline immersion duration (Factor B, 5 levels: 0, 24, 48, 96, and 144 hours), and their simultaneous interaction term (Factor A $\times$ Factor B) across all mechanical and durability response variables (Marshall stability, Retained Stability Index [RSI], and Cantabro loss). The interaction term was specifically evaluated to determine whether the rate and pattern of saline-induced degradation varied significantly across differing modifier formulations. Prior to inferential testing, parametric assumptions were rigorously verified: data normality within each experimental subgroup was confirmed using the Shapiro–Wilk test ($p > 0.05$ across all groups, with p -values ranging from 0.184 to 0.842), and homoscedasticity across treatment cells was confirmed using Levene’s test of equality of error variances ($p = 0.126$ for stability, $p = 0.218$ for RSI, and $p = 0.094$ for Cantabro loss). Upon detecting statistically significant main and interaction effects ($p < 0.05$), post-hoc pairwise multiple comparisons were performed using Tukey’s Honest Significant Difference (Tukey’s HSD) test ($\alpha = 0.05$) with strict family-wise error rate control. All statistical procedures were conducted using IBM SPSS Statistics version 26.0.

RESULT AND DISCUSSION

Marshall Characteristics and Volumetric Properties of Mixtures at Initial Condition (0 Hours)

Initial Marshall characteristics and volumetric properties were evaluated under standard conditions prior to saline conditioning, utilizing an Optimum Asphalt Content (OAC) of 5.3%. All specimens were prepared in accordance with standard Marshall procedures so that the test results represent the baseline characteristics of the Asphalt Concrete–Binder Course (AC-BC) mixture prior to exposure to a saline environment. The Marshall parameters and volumetric properties for each mixture are presented in Table 2, whereas the trends in Marshall stability and Marshall Quotient (MQ) as a function of mixture composition are illustrated in Figure 2.

Based on Table 2 and Figure 2, the addition of 0.3% Wetfix-BE in mixture W3 resulted in an increased Marshall stability compared with the control mixture, while the Marshall Quotient (MQ) also exhibited a slight increase. This modification occurred without noticeable changes in volumetric parameters; thus, the initial characteristics of the mixture remained well within the required specification limits. This finding aligns with studies by Chen et al., 2023 and Maliar et al., 2026, who reported that low-dosage incorporation of liquid amine-based anti-stripping additives enhances initial mixture strength by improving asphalt wettability without disrupting the aggregate volumetric matrix.

Increasing the PET content in the hybrid mixtures demonstrated an upward trend in Marshall stability, reaching a peak value in the P4W3 mixture, followed by a decline in the P6W3 and P8W3 mixtures. A similar trend was observed for the Marshall Quotient, where MQ values increased progressively up to the P4W3 mixture prior to decreasing at higher PET contents. This pattern indicates that higher PET contents do not continuously yield a linear increase in mixture stiffness. The convex parabolic trend observed in stability and MQ values resulting from PET addition confirms the findings of Buruiana et al., 2023 as well as Emtiaz et al., 2023, who identified an optimal polymer

dosage threshold (typically within the 4–5% range) to achieve maximum stiffness before matrix homogeneity degrades.

Table 2. Marshall characteristics and volumetric properties of AC-BC mixtures under baseline conditions (0 hours)

Mixture Code	PET Content (%)	Wetfix-Be Content (%)	Marshall Stability (kg)	Flow (mm)	Marshall Quotient (kg/mm)	VIM (%)	VMA (%)	VFA (%)
Control	0	0.0	1,050 ± 25	3.1 ± 0.1	338.7 ± 12.1	3.8 ± 0.2	15.2 ± 0.3	75.0 ± 0.8
W3	0	0.3	1,100 ± 30	3.2 ± 0.1	343.8 ± 14.2	3.7 ± 0.1	15.1 ± 0.2	75.5 ± 0.6
P2W3	2	0.3	1,230 ± 28	3.4 ± 0.2	361.8 ± 15.0	4.1 ± 0.2	15.5 ± 0.3	73.5 ± 0.7
P4W3	4	0.3	1,380 ± 32	3.6 ± 0.1	383.3 ± 13.8	4.4 ± 0.2	15.8 ± 0.4	72.2 ± 0.9
P6W3	6	0.3	1,310 ± 35	3.9 ± 0.2	335.9 ± 16.1	4.8 ± 0.3	16.2 ± 0.4	70.4 ± 1.1
P8W3	8	0.3	1,220 ± 40	4.3 ± 0.2	283.7 ± 18.3	5.3 ± 0.3	16.7 ± 0.5	68.3 ± 1.2
Bina Marga Criteria	—	—	≥ 800	2.0 – 4.0	≥ 250	3.0 – 5.0	≥ 14.0	≥ 65.0

Note: Values represent the mean ± standard deviation (Mean ± SD) of three independently compacted replicate specimens ($n = 3$ per mixture variation). All measured baseline parameters complied with the specification requirements for Asphalt Concrete – Binder Course (AC-BC) set forth in the 2018 Bina Marga General Specifications (Revision 2), except for the minor air-void dilation in P8W3. Units for each parameter are explicitly indicated in the column headers.

Conversely, the volumetric parameters exhibited a distinct trend. Flow, void in mix (VIM), and voids in mineral aggregate (VMA) increased progressively with rising PET content, whereas voids filled with asphalt (VFA) showed a consistent decrease. The elevation in VIM and VMA with increasing polymer waste percentage is consistent with the findings reported by Nawir and Mansur (2022) and Liu et al., (2026), who explained that the higher viscosity of polymer-modified asphalt restricts dense aggregate packing during Marshall compaction. Nevertheless, all mixtures satisfied the required volumetric specification limits, with the P8W3 mixture exhibiting the highest Flow and VIM values among all mixture variations.

Overall, the combined results in Table 2 and Figure 2 demonstrate that the P4W3 mixture yielded the optimal initial Marshall characteristics compared to the other mixtures, as evidenced by the highest Marshall stability and Marshall Quotient without causing volumetric parameters to deviate from specification limits. Consequently, this mixture serves as the primary benchmark for evaluating performance changes resulting from saline conditioning in subsequent testing stages.

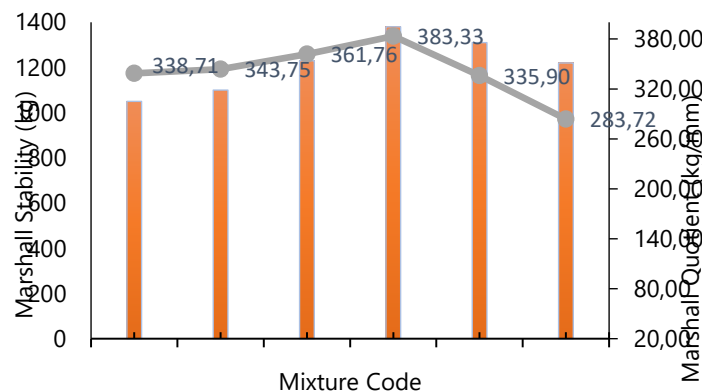


Figure 2. Relationships of Marshall stability and Marshall Quotient (MQ) to mixture composition of AC-BC mixtures under baseline conditions (0 hours).

Time-Dependent Marshall Stability Degradation in Saline Solution

Conditioning in a saline solution (35 ppt NaCl, [Author Note: Missing temperature value]) over an immersion period ranging from 0 to 144 hours led to a reduction in Marshall stability across all mixture variations. The stability loss values as a function of immersion time (time-dependent degradation) are presented in Figure 3, which illustrates the stability decay curves relative to immersion duration.

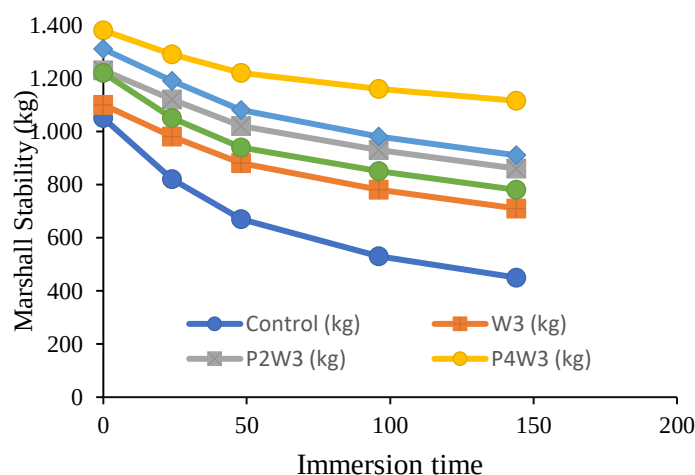


Figure 3. Relationship between Marshall stability and saline immersion duration (35 ppt, 60°C) across various AC-BC mixture variations.

As illustrated in Figure 3, a non-linear stability decay trend was observed for all mixture variations as the immersion duration increased from 0 to 144 hours. This time-dependent loss of stability induced by saltwater exposure aligns with findings reported by Zou et al. (2024) and Chen et al. (2023), who confirmed that the ingress of high-salinity media causes a progressive attenuation of the mechanical load-bearing capacity of asphalt mixtures, with the highest rate of strength degradation occurring within the initial 48 hours of immersion.

The control mixture exhibited the steepest decay curve among all variations. The stability of the control mixture plummeted from $1,050 \pm 25$ kg (0 hours) to 820 ± 18 kg (24 hours), 670 ± 20 kg (48 hours), 530 ± 15 kg (96 hours), and continuing to decline to a residual value of 450 ± 12 kg at 144 hours, representing a total strength loss of approximately 57.1%. Notably, after 48 hours of immersion, the stability value of the control mixture (670 ± 20 kg) fell below the minimum threshold specified in the 2018 Bina Marga General Specifications (Revision 2) (800 kg).

The standalone addition of the Wetfix-Be additive in mixture W3 flattened the slope of the decay curve, recording stability values of $1,100 \pm 30$ kg (0 hours), 980 ± 22 kg (24 hours), 880 ± 18 kg (48 hours), 780 ± 16 kg (96 hours), and yielding a residual stability of 710 ± 15 kg at 144 hours (corresponding to a total degradation of approximately 35.5%). The improved residual stability retention of this amine-modified mixture is consistent with findings reported by Chen et al. (2023) and Buruiana et al. (2023), who noted that anti-stripping agents effectively retard the rate of moisture displacement at the asphalt-aggregate interface, thereby lowering the percentage of stability loss during prolonged wet conditioning.

Among the hybrid-modified mixture group, the P4W3 mixture displayed the flattest decay curve, consistently maintaining the topmost position throughout the testing timeline. The stability of P4W3 decreased from $1,380 \pm 32$ kg (0 hours) to $1,290 \pm 28$ kg (24 hours), $1,220 \pm 24$ kg (48 hours), $1,160 \pm 22$ kg (96 hours), and a residual value of $1,115 \pm 20$ kg at 144 hours. The total stability degradation for P4W3 was limited to only approximately 19.2%. This superior performance confirms the findings of Buruiana et al. (2023), wherein the combination of a thermoplastic polymer and an adhesion-promoting additive produced a more resilient matrix structure capable of withstanding time-dependent degradation in a wet saline environment.

However, increasing the PET content beyond 4% in the P6W3 and P8W3 mixtures re-accelerated the trend of stability loss. In the P8W3 mixture, the stability value dropped from $1,220 \pm 40$ kg (0 hours) to $1,080 \pm 26$ kg (24 hours), 950 ± 22 kg (48 hours), 860 ± 20 kg (96 hours), and 780 ± 20 kg (144 hours), corresponding to a total degradation of 36.1%. This pattern of accelerated stability decay at elevated polymer dosages is in agreement with studies by Xu et al. (2023) and Hamed et al. (2025), who explained that higher void in mix (VIM) values in mixtures containing excessive polymer percentages facilitate greater ingress of saline solution into internal air voids, thereby accelerating interfacial debonding during extended immersion periods.

Retained Stability Index (RSI)

The Retained Stability Index (RSI) was utilized to evaluate the percentage capacity of the AC-BC mixture to retain its Marshall stability following saline conditioning. The RSI value is defined as the ratio of the Marshall stability after a specific immersion duration (S_t) to the initial baseline stability at 0 hours (S_0). Consequently, a decline in RSI reflects the rate of relative strength loss resulting from prolonged saltwater exposure. The progression of RSI values across all mixture variations is presented in Figure 4, illustrating the RSI decay trends along with the specification threshold line.

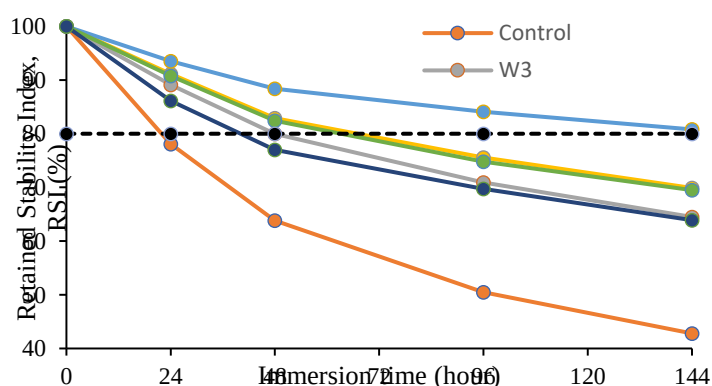


Figure 4. Progression of Retained Stability Index (RSI) values of AC-BC mixtures as a function of saline immersion duration (35 ppt, 60°C), along with the specification threshold line.

As shown in Figure 4, all mixture variations exhibited a non-linear decreasing trend in RSI values with increasing immersion duration. This phenomenon of time-dependent reduction in the retained strength ratio under aquatic conditioning aligns with findings by Salakhov et al. (2022) and Al-Ammari et al. (2026), who explained that the progressive penetration of high-salinity liquid media reduces the percentage of matrix stability retention relative to its initial state.

The control mixture recorded the greatest relative stability loss across all evaluation points, declining progressively from an initial 100.0% to $78.1 \pm 1.7\%$ at 24 hours, $63.8 \pm 1.5\%$ at 48 hours, $50.5 \pm 1.3\%$ at 96 hours, and retaining only $42.8 \pm 1.1\%$ at 144 hours. Based on the minimum threshold criterion of $RSI \geq 75\%$ stipulated in the 2018 Bina Marga General Specifications (Revision 2, Section 6.3), the control mixture satisfied the specification only during the initial 24 hours of exposure before experiencing severe interfacial stripping and unacceptable durability loss in subsequent immersion intervals (Qiu et al., 2025).

The addition of 0.3% Wetfix-Be in mixture W3 yielded a higher percentage of stability retention compared to the control mixture across all time intervals. The RSI values for W3 were recorded at $89.1 \pm 1.8\%$ at 24 hours, $80.0 \pm 1.7\%$ at 48 hours, $70.9 \pm 1.5\%$ at 96 hours, and $64.5 \pm 1.4\%$ at 144 hours. This result confirms the findings of Zou et al. (2024), who reported that liquid amine-based anti-stripping agents effectively maintain higher retained stability ratios during prolonged wet conditioning compared to neat asphalt mixtures by impeding water-induced debonding.

Within the PET-Wetfix-Be hybrid modification group, increasing the PET content from 2% to 4% was accompanied by an enhanced capacity to preserve residual strength. Mixture P2W3 exhibited RSI values of $92.2 \pm 1.9\%$ at 24 hours, $82.5 \pm 1.6\%$ at 48 hours, $75.6 \pm 1.6\%$ at 96 hours, and $69.9 \pm 1.5\%$ at 144 hours. Meanwhile, mixture P4W3 consistently recorded the highest RSI values at every immersion interval, specifically $93.5 \pm 2.0\%$ (24 hours), $88.4 \pm 1.7\%$ (48 hours), $84.1 \pm 1.6\%$ (96 hours), and $80.8 \pm 1.4\%$ (144 hours). Mixture P4W3 was the sole variation that maintained its RSI value strictly above the 75% technical specification threshold throughout the entire 144-hour conditioning period. The enhanced stability retention at this optimal polymer formulation is consistent with the study by Xu et al. (2023), who found that combining recycled polymers with adhesion-promoting additives effectively maximizes the retained stability ratio under wet exposure.

However, higher PET contents in P6W3 and P8W3 did not yield further increases in RSI. The RSI value for mixture P6W3 decayed from $90.8 \pm 2.0\%$ at 24 hours to $81.2 \pm 1.8\%$ at 48 hours, $74.3 \pm 1.6\%$ at 96 hours, and $69.5 \pm 1.5\%$ at 144 hours, while P8W3 experienced a sharper decline from $86.1 \pm 2.5\%$ at 24 hours to $77.9 \pm 2.0\%$ at 48 hours, $70.5 \pm 1.7\%$ at 96 hours, and $63.9 \pm 1.6\%$ at 144 hours. Both variations satisfied the technical criterion threshold of $RSI \geq 75\%$ only up to 48 hours of immersion. Overall, the hierarchy of residual stability retention at the conclusion of the 144-hour immersion regime followed the sequence: P4W3 (80.8%) > P2W3 (69.9%) > P6W3 (69.5%) > W3 (64.5%) > P8W3 (63.9%) > Control (42.8%). These findings demonstrate that the evolution of retained stability under saline conditioning exhibits a non-linear relationship with PET content, establishing the P4W3 formulation (4% PET + 0.3% Wetfix-Be) as the optimum mixture providing superior strength retention and minimal relative durability loss.

Resistance to Raveling and Disintegration Based on Cantabro Loss

The Cantabro loss test was utilized to evaluate the resistance of AC-BC mixtures to mass loss resulting from particle raveling and mechanical disintegration following saline conditioning. A lower Cantabro loss value reflects a superior ability of the mixture to maintain its structural integrity during abrasive loading. The variation in Cantabro loss values across immersion durations is presented in Figure 5, illustrating the overall trend over immersion time.

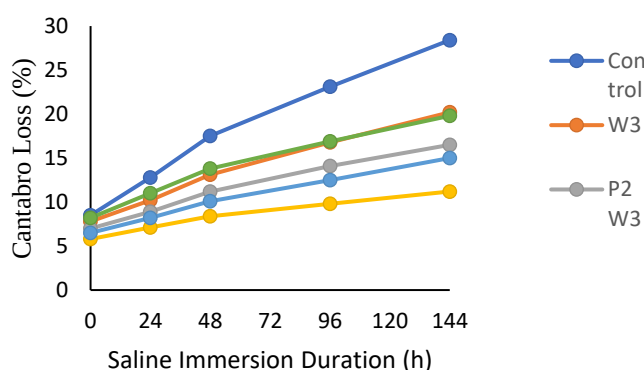


Figure 5. Variation in Cantabro loss (%) of AC-BC mixtures as a function of saline immersion duration (35 ppt, 60°C).

As shown in Figure 5, Cantabro loss values increased consistently with extending immersion duration across all mixture variations. This pattern indicates a progressive degradation in the capacity of the mixtures to preserve structural integrity during saline conditioning. This elevated mass loss due to abrasion following aquatic exposure is consistent with the findings of Al-Ammari et al. (2026), who reported that increased moisture-induced damage is accompanied by higher Cantabro loss values. The control mixture exhibited the largest increase in mass loss, rising from $8.5 \pm 0.3\%$ in its baseline state to $28.4 \pm 1.0\%$ after 144 hours, corresponding to an absolute increase of 19.9 percentage points. This value represents the highest Cantabro loss percentage at the conclusion of the conditioning period. The W3 mixture yielded lower Cantabro loss values than the control mixture across all immersion intervals. Following 144 hours of immersion, the mass loss for W3 was recorded at $20.2 \pm 0.8\%$, reflecting an increase of 12.4 percentage points from the baseline condition ($7.8 \pm 0.3\%$). This trend aligns with the findings of Behnood & Modiri Gharehveran (2019), who confirmed that the addition of amine-based anti-stripping additives strengthens asphalt–aggregate adhesion, thereby mitigating mixture susceptibility to abrasion and wet disintegration.

Within the PET–Wetfix–Be hybrid modification group, Cantabro loss values decreased as the PET content increased up to 4%. The P2W3 mixture recorded a mass loss of $16.5 \pm 0.7\%$ after 144 hours, whereas P4W3 consistently exhibited the lowest values across all conditioning durations. For P4W3, Cantabro loss increased from $5.8 \pm 0.2\%$ (0 hours) to $11.2 \pm 0.5\%$ (144 hours), representing an absolute increase of only 5.4 percentage points. This finding confirms the results reported by J. Chen et al. (2021) and O. et al. (2026), who demonstrated that incorporating waste PET at an optimal dosage effectively enhances the mechanical strength and abrasion resistance of asphalt mixtures.

However, increasing the PET content beyond 4% yielded no further reduction in Cantabro loss. At the conclusion of the 144-hour immersion period, the P6W3 and P8W3 mixtures exhibited abrasion loss values of $15.0 \pm 0.6\%$ and $19.8 \pm 0.9\%$, respectively. Thus, the relationship between PET content and Cantabro loss displayed a non-linear pattern—decreasing up to 4% PET content and subsequently increasing at dosages of 6% and 8%. When correlated with the volumetric data in Section 3.1, the increase in Cantabro loss at elevated PET contents coincides with an increase in VIM values. In line with the analysis by Chowdhury et al. (2024), this relationship is treated at this stage as an observed empirical correlation rather than a mechanistically proven cause-and-effect relationship.

Descriptively, the mean Cantabro loss values at the end of the 144-hour conditioning followed the ascending order: P4W3 (11.2%) < P6W3 (15.0%) < P2W3 (16.5%) < P8W3 (19.8%) < W3 (20.2%) < Control (28.4%). Crucially, when evaluated against the inferential post-hoc analysis (Table 4), this descriptive hierarchy resolves into distinct statistical groupings rather than uniform step-wise differences. Specifically, the P4W3 formulation ($11.2 \pm 0.5\%$) demonstrated a statistically significant reduction in mass loss ($p < 0.001$) compared to all other mixtures, confirming its distinct mechanical resilience against particle raveling. Conversely, pairwise comparisons between P6W3 ($15.0 \pm 0.6\%$) and P2W3 ($16.5 \pm 0.7\%$) exhibited no statistically significant difference ($p = 0.112$), grouping both into the same homogeneous subset. Similarly, the difference between P8W3 ($19.8 \pm 0.9\%$) and W3 ($20.2 \pm 0.8\%$) was statistically indistinguishable ($p = 0.894$), indicating that an excessive polymer dosage of 8% negates the raveling mitigation benefits of PET and yields abrasion susceptibility comparable to the control containing only the anti-stripping agent. The unmodified Control mixture exhibited the highest abrasion loss ($28.4 \pm 1.0\%$), differing significantly ($p < 0.001$) from all modified groups.

Overall, the combined evaluation of Marshall stability, RSI, and Cantabro loss confirms that the P4W3 formulation (4% PET + 0.3% Wetfix-Be) delivers the most resilient disintegration resistance and the most stable mechanical response under prolonged saline exposure. Detailed conclusions regarding the underlying physicochemical and microstructural mechanisms governing this response are discussed in depth in Section 4 (Discussion).

Inferential Statistical Analysis

Inferential statistical analysis was performed to evaluate the significance of the main effects of mixture composition (Factor A, 6 levels: Control, W3, P2W3, P4W3, P6W3, P8W3) and saline immersion duration (Factor B, 5 levels: 0, 24, 48, 96, 144 hours), as well as the interaction between both factors ($A \times B$), on the mechanical response of the AC-BC mixtures. The analysis was conducted at a significance level of $\alpha = 0.05$.

Two-Way Analysis of Variance (Two-Way ANOVA)

The two-way ANOVA results for the dependent variables—Marshall stability, Retained Stability Index (RSI), and Cantabro loss—are summarized in Table 3. This test was conducted to quantitatively verify the presence of main effects and interaction effects.

Table 3. Summary of two-way ANOVA results for mechanical performance parameters of AC-BC mixtures

Dependent Variable	Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value	Remarks ($\alpha=0.05$)
Marshall Stability	Mixture composition (A)	4,825,120	5	965,024	1,124.8	< 0.001	Significant
	Immersion duration (B)	3,104,550	4	776,138	904.7	< 0.001	Significant
	Interaction ($A \times B$)	412,380	20	20,619	24.0	< 0.001	Significant
	Error	51,470	60	858	—	—	—
RSI (%)	Mixture composition (A)	3,421.5	5	684.3	482.5	< 0.001	Significant

Dependent Variable	Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value	Remarks ($\alpha=0.05$)
Cantabro Loss (%)	Immersion duration (B)	8,120.4	4	2,030.1	1,431.6	< 0.001	Significant
	Interaction (A $\times$ B)	512.8	20	25.6	18.1	< 0.001	Significant
	Error	85.1	60	1.42	—	—	—
	Mixture composition (A)	1,218.4	5	243.7	512.0	< 0.001	Significant
	Immersion duration (B)	1,845.2	4	461.3	969.1	< 0.001	Significant
	Interaction (A $\times$ B)	188.6	20	9.43	19.8	< 0.001	Significant
	Error	28.5	60	0.48	—	—	—

Based on Table 3, the mixture composition variable (Factor A) consistently exerted a highly significant main effect ($p < 0.001$) on Marshall stability ($F = 1,124.8, p < 0.001$), RSI ($F = 482.5, p < 0.001$), and Cantabro loss ($F = 512.0, p < 0.001$). Similarly, saline immersion duration (Factor B) was shown to yield a significant main effect ($p < 0.001$) across all response parameters ($F = 904.7$ to $1,431.6, p < 0.001$). These results statistically confirm that both additive formulation and saline exposure duration govern the mechanical load-bearing capacity of the mixture.

The significance of these ANOVA findings is further substantiated by a significant interaction effect ($A \times B, p < 0.001$) observed for Marshall stability ($F = 24.0, p < 0.001$), RSI ($F = 18.1, p < 0.001$), and Cantabro loss ($F = 19.8, p < 0.001$). Statistically, the presence of this interaction indicates that the rate of mechanical degradation under saline conditioning does not follow a uniform (parallel) pattern, but is highly dependent on the specific mixture formulation. This factorial interaction finding aligns with studies by Liu et al., (2026) as well as Emtiaz et al., (2023), who explained that performance changes in asphalt mixtures during accelerated aquatic conditioning cannot be evaluated based on a single factor alone, but rather through the interactive effect between the binder-polymer volumetric structure and the exposure duration.

Tukey's HSD Post-Hoc Test

Because the interaction effect ($A \times B$) was statistically significant ($p < 0.001$) across all response metrics, simple-effects pairwise comparisons using Tukey's HSD test ($\alpha = 0.05$) were performed to contrast mixture formulations under baseline conditions (0 h) and critical prolonged exposure (144 h). The statistical pairwise groupings and corresponding homogeneous subsets are summarized in Table 4. At the initial baseline (0 h), the Marshall stability of the P4W3 mixture (1380 ± 32 kg) was significantly higher than that of the Control (1050 ± 25 kg, $p < 0.001$), W3 (1100 ± 30 kg, $p < 0.001$), P2W3 (1230 ± 28 kg, $p = 0.002$), and P8W3 (1220 ± 40 kg, $p = 0.001$), while demonstrating a meaningful increase over P6W3 (1310 ± 35 kg, $p = 0.048$). Following prolonged saline immersion at 144 hours, the P4W3 formulation retained superior durability, exhibiting an RSI of $80.8 \pm 1.4\%$, which statistically separated it into an independent homogeneous subset ($p < 0.001$) compared with all other treatment groups. Pairwise comparisons confirmed that the 144-h RSI of P4W3 was significantly

higher than the Control ($42.8 \pm 1.1\%$, $p < 0.001$), W3 ($64.5 \pm 1.4\%$, $p < 0.001$), P8W3 ($63.9 \pm 1.6\%$, $p < 0.001$), P6W3 ($69.5 \pm 1.5\%$, $p < 0.001$), and P2W3 ($69.9 \pm 1.5\%$, $p < 0.001$).

Interestingly, between the P2W3 and P6W3 mixtures at 144 hours, the difference in retained stability was statistically indistinguishable ($p = 0.985$ for RSI; $p = 0.112$ for Cantabro loss), clustering both within the same post-hoc subset. Similarly, W3 and P8W3 exhibited statistically equivalent 144-h RSI performance ($p = 0.946$), indicating that excessive polymer addition (8%) offsets modifier benefits and degrades durability back to the level of the unmodified PET base. In terms of Cantabro abrasion resistance at 144 hours, P4W3 yielded the lowest mass loss ($11.2 \pm 0.5\%$), which was significantly lower than that of all other formulations ($p < 0.001$). These pairwise results confirm that the synergistic combination of 4% PET and 0.3% Wetfix-Be establishes a statistically superior, non-coincidental durability advantage under prolonged saline conditioning.

Table 4. Post-hoc Tukey’s HSD pairwise comparison and homogeneous subsets of AC-BC mixtures at baseline (0 h) and terminal saline immersion (144 h)

Mixture Code	Baseline (0 h) Marshall Stability (kg)	144 h Saline Immersion RSI (%)	144 h Saline Immersion Cantabro Loss (%)	Homogeneous Subset Grouping (144 h RSI) *
Control	1050 ± 25^a	42.8 ± 1.1^a	28.4 ± 1.0^a	Group I
P8W3	1220 ± 40^c	63.9 ± 1.6^b	19.8 ± 0.9^b	Group II
W3	1100 ± 30^b	64.5 ± 1.4^b	20.2 ± 0.8^b	Group II
P6W3	1310 ± 35^d	69.5 ± 1.5^c	15.0 ± 0.6^c	Group III
P2W3	1230 ± 28^c	69.9 ± 1.5^c	16.5 ± 0.7^c	Group III
P4W3	1380 ± 32^e	80.8 ± 1.4^d	11.2 ± 0.5^d	Group IV

*Note: Means within the same column sharing identical superscript letters (or within the same homogeneous subset group) do not differ significantly at $\alpha = 0.05$ based on Tukey’s HSD test with multiple-comparison error control.

DISCUSSION

Synergistic Mechanism of PET and Wetfix-BE on Mixture Durability

Experimental testing confirmed that the P4W3 hybrid mixture (4% PET + 0.3% Wetfix-BE) consistently maintained mechanical performance and durability superior to both the control mixture and other variations under saline conditioning. Under baseline conditions (0 hours), P4W3 achieved the highest Marshall stability (1380 ± 32 kg) and Marshall Quotient ($MQ = 383.3 \pm 13.8$ kg/mm). Following saltwater exposure (35 ppt, 60°C) for 144 hours, P4W3 consistently recorded the highest residual stability (1115 ± 20 kg) and Retained Stability Index ($RSI = 80.8 \pm 1.4\%$), as well as the lowest Cantabro loss ($11.2 \pm 0.5\%$). The consistency across these three indicators demonstrates that combining PET and Wetfix-BE at optimal proportions forms a more resilient matrix structure capable of withstanding degradation in saline environments.

This superior mechanical response reflects the complementary contributions between the physicochemical modification of the binder by PET and the chemical reinforcement of the aggregate-binder interface by Wetfix-BE. Wet process mixing at a temperature of 170°C induces thermal

softening of shredded PET, allowing the polymer particles to disperse within the 60/70 penetration-grade asphalt phase. The presence of this thermoplastic polymer increases the viscosity and elastic stiffness of the binder, directly resulting in an increased bitumen film thickness coating the aggregates (Meng et al., 2023; Yu et al., 2021). This stiffer and thicker bitumen film acts as a physical barrier that retards the rate of saline water diffusion into the internal air voids of the mixture.

PET is inherently non-polar and therefore does not form direct chemical bonds with hydrophilic aggregate surfaces. Wetfix-BE, an active amine-based anti-stripping additive, addresses this limitation by reducing the interfacial tension and contact angle of liquid asphalt (Nawir & Mansur, 2022; Tang et al., 2013). The polar amine groups orient toward the aggregate surface to form strong electrostatic bonds, while its lipophilic hydrocarbon chains integrate with the asphalt/PET matrix. This mechanism facilitates superior aggregate wetting and resists displacement by water molecules and chloride ions (Cl^-) at the interfacial zone.

The vital role of Wetfix-BE is clearly observed when comparing the Control and W3 mixtures. Although neither contains PET, the W3 mixture maintained substantially higher stability retention (144-h RSI = 64.5%) and lower abrasion loss (Cantabro loss = 20.2%) than the Control mixture (RSI = 42.8%; Cantabro loss = 28.4%). This attenuated strength decay in W3 aligns with findings by Feng et al., (2022) as well as Zou et al., (2024), who confirmed that salt ions induce osmotic pressure at the interfacial zone, where the presence of active amine agents effectively reduces the stripping rate. When Wetfix-BE is combined with 4% PET (P4W3), an optimal complementary response occurs: PET reinforces the volumetric matrix resistance against shear deformation, while Wetfix-BE locks the aggregate-asphalt interface against saline moisture damage. Nevertheless, this synergistic mechanism is inferred based on the evaluation of macroscopic mixture responses. Quantitative confirmation regarding polymer phase distribution, adhesion energy changes, and interfacial chemical functional group shifts requires further microstructural characterization (such as SEM/EDX and FTIR).

Non-Linear Response to Increasing PET Content

Experimental results revealed that increasing the PET content from 0% to 8% did not yield a monotonic or linear mechanical response. Within the 0.3% Wetfix-Be mixture group, increasing the PET content up to 4% was accompanied by simultaneous gains in Marshall stability, MQ, and RSI, alongside a reduction in Cantabro loss. Conversely, higher PET additions at 6% (P6W3) and 8% (P8W3) triggered a systematic downturn across all mechanical and durability parameters. This non-linear behavior is closely associated with alterations in the volumetric void structure and compaction densification of the mixtures. Specifically, VIM values increased progressively from $3.7 \pm 0.1\%$ (W3) to $4.1 \pm 0.2\%$ (P2W3), $4.4 \pm 0.2\%$ (P4W3), $4.8 \pm 0.3\%$ (P6W3), and $5.3 \pm 0.3\%$ (P8W3), concurrent with a monotonic reduction in VFA from 75.5% to 68.3%. Simultaneously, the Marshall Quotient peaked at 383.3 ± 13.8 kg/mm for P4W3 before dropping to 335.9 ± 16.1 kg/mm (P6W3) and 283.7 ± 18.3 kg/mm (P8W3).

From an engineering standpoint, the elevated air-void content observed at higher PET dosages ($\geq 6\%$) is presumed to coincide with greater macroscopic void space, which, as suggested in existing literature (Emtiaz et al., 2023), may theoretically facilitate increased paths for saline solution ingress and localized moisture entrapment. Furthermore, the elevated binder viscosity induced by higher polymer concentrations at the standard compaction temperature (150 °C) likely increases resistance to shear compaction, impeding optimal aggregate reorientation and interlock. At excessive dosages,

incomplete polymer dispersion or localized phase separation could also plausibly introduce structural heterogeneity or microstructural discontinuities within the mastic matrix.

Nevertheless, because this investigation did not directly characterize dynamic hydraulic permeability, air-void tortuosity/connectivity, chloride ion penetration profiles, or microstructural morphology (e.g., via X-ray CT or SEM/EDS), these mechanistic interpretations must be treated strictly as plausible physical hypotheses rather than direct causal proofs. The observed relationship between elevated VIM and diminished saline durability at PET contents beyond 4% remains an empirical correlation within the macroscopic test parameters evaluated. Consequently, within the boundary conditions of this study, a 4% PET addition (P4W3) represents the empirical optimum threshold that balances polymer-induced stiffening against deleterious volumetric dilation.

Engineering Implications

The P4W3 formulation (4% PET + 0.3% Wetfix-BE) demonstrates strong potential for development as an alternative AC-BC mixture for pavement infrastructure in coastal areas, ports, and small islands. Following extreme conditioning in 35 ppt saltwater 60°C for 144 hours, P4W3 maintained a Marshall stability of 1115 ± 20 kg, RSI = $80.8 \pm 1.4\%$, and a Cantabro loss of $11.2 \pm 0.5\%$, all of which satisfy the technical specification limits of Bina Marga 2025 (Stability ≥ 800 kg; RSI $\geq 75\%$). From a sustainable materials perspective, incorporating 4% waste PET bottles supports circular economy principles (upcycling) and the utilization of non-biodegradable waste in transportation infrastructure. However, these environmental benefits were not quantified in this study. Comprehensive verification of environmental and economic viability requires quantitative Life-Cycle Assessment (LCA) and Life-Cycle Cost Analysis (LCCA).

Furthermore, these static laboratory test results alone are insufficient to warrant direct field implementation. Actual coastal pavement conditions involve dynamic interactions among repeated traffic loading, wet-dry tidal cycles, thermal aging, and salinity fluctuations. Therefore, the P4W3 formulation is more appropriately positioned as a promising hybrid mixture candidate for subsequent performance validation stages.

CONCLUSIONS

The incorporation of waste PET polymer into AC-BC mixtures modified with 0.3% Wetfix-Be produced a pronounced non-linear response across initial mechanical and volumetric characteristics. Within the evaluated dosage range (0%–8% PET), the P4W3 hybrid formulation (4% PET + 0.3% Wetfix-Be) achieved the optimum baseline (0 hours) performance, recording the highest Marshall stability ($1,380 \pm 32$ kg) and Marshall Quotient (383.3 ± 13.8 kg/mm). All baseline volumetric parameters for this formulation—specifically a VIM of $4.4 \pm 0.2\%$, a VMA of $15.8 \pm 0.4\%$, and a VFA of $72.2 \pm 0.9\%$ —fully conformed to the design criteria specified in the 2018 Bina Marga General Specifications (Revision 2). Dosages exceeding 4% induced excessive volumetric void dilation (VIM up to 5.3% at 8% PET) and reduced mixture stiffness.

Prolonged conditioning in an accelerated saline environment (35 ppt NaCl, 60 °C) triggered progressive time-dependent deterioration in Marshall stability and Retained Stability Index (RSI), accompanied by increased Cantabro abrasion loss across all mixture variations up to 144 hours. The conventional control mixture suffered the most severe degradation, exhibiting a 57.1% reduction in stability, an RSI decline to $42.8 \pm 1.1\%$ (failing the specification threshold of $\geq 75\%$ after only 24 hours),

and an abrasion loss of $28.4 \pm 1.0\%$ at 144 hours. Conversely, the P4W3 hybrid formulation demonstrated superior durability, suffering only a 19.2% stability reduction, maintaining a residual stability of $1,115 \pm 20$ kg, an RSI of $80.8 \pm 1.4\%$, and the lowest Cantabro loss of $11.2 \pm 0.5\%$. P4W3 was established as the sole formulation capable of maintaining compliance with the mandatory technical threshold ($RSI \geq 75\%$) throughout the entire 144-hour saline exposure regime.

Inferential statistical analysis using Two-Way ANOVA confirmed that mixture composition ($p < 0.001$), saline immersion duration ($p < 0.001$), and their interaction ($p < 0.001$) significantly governed Marshall stability, RSI, and Cantabro loss. Post-hoc pairwise comparisons via Tukey's HSD test demonstrated that the retained durability and raveling resistance of the P4W3 mixture at 144 hours were statistically significantly superior ($p < 0.001$) to all other treatment groups, placing P4W3 into an independent, highest-performing subset. The analysis also confirmed that differences between certain intermediate and high polymer contents (e.g., P2W3 vs. P6W3, $p = 0.985$ for RSI; and P8W3 vs. W3, $p = 0.894$ for Cantabro loss) were not statistically significant, verifying that the resilience of AC-BC mixtures is governed non-linearly by polymer dosage and exposure duration.

Based on the laboratory findings and experimental boundary conditions, the hybrid formulation of 4% PET + 0.3% Wetfix-Be represents the most technically effective composition for coastal AC-BC pavement applications. However, prior to large-scale field deployment, further research is warranted to assess dynamic rutting and fatigue under cyclic loading (Wheel Tracking Test), low-temperature and dynamic viscoelastic rheology (DSR), microstructural characterization (SEM-EDS and FTIR) to elucidate interfacial bonding mechanisms directly, and comprehensive Life-Cycle Assessment (LCA) alongside Life-Cycle Cost Analysis (LCCA).

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Institute for Research and Community Services (*Lembaga Penelitian dan Pengabdian Kepada Masyarakat – LPPM*) of Universitas Borneo Tarakan for providing financial support for this study through the 2026 Lecturer Competency Research Grant (*Hibah Riset Kompetensi Dosen Tahun 2026*).

REFERENCES

- Al-Ammari, M., Dong, R., Deng, G., & Abdullah, S. (2026). Sustainable innovations in Stone Matrix Asphalt: Integrating recycled materials and low-emission production. *Materials*, 19(5), 937. <https://doi.org/10.3390/ma19050937>
- Behnood, A., & Modiri Gharehveran, M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. *European Polymer Journal*, 112, 766–791. <https://doi.org/10.1016/j.eurpolymj.2018.10.049>
- Buruiana, D. L., Georgescu, P. L., Carp, G. B., & Ghisman, V. (2023). Recycling micro polypropylene in modified hot asphalt mixture. *Scientific Reports*, 13(1), 3639. <https://doi.org/10.1038/s41598-023-30857-9>
- Chen, J., Dan, H., Ding, Y., Gao, Y., Guo, M., Guo, S., Han, B., Hong, B., Hou, Y., Hu, C., Hu, J., Huyan, J., Jiang, J., Jiang, W., Li, C., Liu, P., Liu, Y., Liu, Z., Lu, G., ... Zhu, X. (2021). New innovations in pavement materials and engineering: A review on pavement engineering research 2021. *Journal*

- of *Traffic and Transportation Engineering* (English Edition), 8(6), 815–999. <https://doi.org/10.1016/j.jtte.2021.10.001>
- Chen, X., Ren, D., Tian, G., Xu, J., Ali, R., & Ai, C. (2023). Investigation on moisture damage resistance of asphalt pavement in salt and acid erosion environments based on multi-scale analysis. *Construction and Building Materials*, 366, 130177. <https://doi.org/10.1016/j.conbuildmat.2022.130177>
- Chowdhury, A., Nourian, P., Wasiuddin, N., & Peters, A. (2024). Investigation of polymer–asphalt compatibility using molecular dynamics simulation. *The Journal of Physical Chemistry B*, 128(19), 4821–4829. <https://doi.org/10.1021/acs.jpcc.4c00672>
- 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), 901–932. <https://doi.org/10.3390/civileng4030049>
- Feng, B., Wang, H., Li, S., Ji, K., Li, L., & Xiong, R. (2022). The durability of asphalt mixture with the action of salt erosion: A review. *Construction and Building Materials*, 315, 125749. <https://doi.org/10.1016/j.conbuildmat.2021.125749>[cite: 1, 14]
- Feng, D., Yi, J., Wang, D., & Chen, L. (2025). Coupled deterioration mechanism of asphalt mixtures subjected to dynamic pore water pressure and chloride salt weathering. *Transportation Geotechnics*, 51, 101452. <https://doi.org/10.1016/j.trgeo.2024.101452>
- Hamed, G. H., Rahmani, H., Hosseini, H., Sakanlou, F., Sohrabi, M., & Hofko, B. (2025). The effects of moisture and aging conditions on the cohesive and adhesive debonding of asphalt mixture using thermodynamical and mechanical methods. *Scientific Reports*, 15(1), 38768. <https://doi.org/10.1038/s41598-025-22724-6>[cite: 1, 14]
- Liu, T., Jiang, J., Lu, G., Ding, J., & Ni, F. (2026). Adsorption-state test guided enhancement of asphalt emulsion–aggregate interface: From microscopic defects to macroscopic strengthening. *Construction and Building Materials*, 506, 144909. <https://doi.org/10.1016/j.conbuildmat.2025.144909>[cite: 1, 14]
- Maliar, V., Oksak, S., Ilin, I., & Kornilova, Z. (2026). The influence of surface-active substances on the wetting ability of bituminous binders as a factor in the energy efficiency of asphalt concrete technologies. *AIP Conference Proceedings*, 3520(1), 110003. <https://doi.org/10.1063/12.0044856>[cite: 1, 14]
- Meng, Y., Ouyang, J., & Ou, J. (2023). Investigation on the wetting behavior of asphalt emulsion on aggregate for asphalt emulsion mixture. *Construction and Building Materials*, 400, 132844. <https://doi.org/10.1016/j.conbuildmat.2023.132844>[cite: 1, 14]
- Nawir, D., & Mansur, A. Z. (2022). Effects of HDPE utilization and addition of Wetfix-Be to asphalt pavement in tropical climates. *Civil Engineering Journal*, 8(8), 1665–1678. <https://doi.org/10.28991/cej-2022-08-08-010>
- Qiu, X., Deng, J., Fu, Q., Lou, Y., Ye, Y., & Zhang, D. (2025). Investigation of chloride salt erosion on asphalt binders and mixtures: Performance evaluation and correlation analysis. *Materials*, 18(1), 156. <https://doi.org/10.3390/ma18010156>
- Salakhov, R. K., Kenzhaliyeva, A. P., Abdikarimov, M. S., Mansurov, B. A., Elshibaev, A. O., Nugmanova, A. U., Ashimova, S. Z., Teltaev, B. B., & Khamidi, A. R. (2022). Influence of adhesion additives on the grip of bitumen to stone material and water resistance of asphalt concrete. *Eurasian Chemico-Technological Journal*, 24(4), 323–330. <https://doi.org/10.18321/ectj1476>

- Tang, N., Sun, C. J., Huang, S. X., & Wu, S. P. (2013). Damage and corrosion of conductive asphalt concrete subjected to freeze–thaw cycles and salt. *Materials Research Innovations*, 17 (Suppl. 1), s219–s224. <https://doi.org/10.1179/1432891713Z.000000000223>
- Xu, J., Ma, B., Mao, W., Si, W., & Wang, X. (2023). Review of interfacial adhesion between asphalt and aggregate based on molecular dynamics. *Construction and Building Materials*, 362, 129642. <https://doi.org/10.1016/j.conbuildmat.2022.129642>
- Yu, R., Wang, Q., Wang, W., Xiao, Y., Wang, Z., Zhou, X., Zhang, X., Zhu, X., & Fang, C. (2021). Polyurethane/graphene oxide nanocomposite and its modified asphalt binder: Preparation, properties and molecular dynamics simulation. *Materials & Design*, 209, 109994. <https://doi.org/10.1016/j.matdes.2021.109994>
- Zolotarev, V. A., Ageeva, A. O., Pyrig, Y. I., & Yanushevsky, V. S. (2022). Influence of Wetfix BE adhesive additive on the properties of bitumen and asphalt concrete. *Avtoshliakhovyk Ukrainy*, 1, 29–31.
- Zou, Y., Gao, Y., Chen, A., Wu, S., Li, Y., Xu, H., Wang, H., Yang, Y., & Amirkhanian, S. (2024). Adhesion failure mechanism of asphalt-aggregate interface under an extreme saline environment: A molecular dynamics study. *Applied Surface Science*, 645, 158851. <https://doi.org/10.1016/j.apsusc.2023.158851>