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Tensile Strength of AC-BC (Asphalt Concrete – Binder Course) Asphalt Mixture Using Low-Density Polyethylene (LDPE) Plastic as an Additive: A Marshall and SEM Microstructural Study

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Abstract: *Flexible pavement, particularly the Asphalt Concrete–Binder Course (AC-BC) layer, plays an important role in distributing traffic loads and therefore requires an asphalt mixture with good tensile strength. Meanwhile, Low-Density Polyethylene (LDPE) plastic waste remains a significant environmental problem in Indonesia. This study analyzes the effect of adding LDPE plastic as an additive on the Indirect Tensile Strength (ITS) of AC-BC asphalt mixtures and observes the resulting microstructural changes through Scanning Electron Microscope (SEM) testing. LDPE was added using the dry process at variations of 0%, 2%, 3%, 4%, and 5% of the coarse aggregate weight, at the optimum bitumen content (5.80%) obtained from Marshall testing. Specimens were evaluated through Marshall and indirect tensile strength testing. Results show that the ITS value increased with increasing LDPE content up to 4%, reaching a maximum of 0.108 kg/mm², before decreasing at 5% content. A quadratic regression analysis ($y = -0.0038x^2 + 0.0261x + 0.637$; $R^2 = 0.9957$) produced a theoretical optimum point at 3.434% LDPE content with a maximum ITS value of 0.107 kg/mm², closely matching the experimental result. SEM observations supported these findings: the 4% LDPE content produced the most homogeneous surface morphology, with better interfacial bonding among aggregate, bitumen, and LDPE, and fewer voids and microcracks, whereas the 5% content exhibited LDPE particle agglomeration that reduced mixture compatibility. Based on the combined results of Marshall, ITS, and SEM testing, an LDPE content of 4% is recommended as the optimum level for improving the resistance of AC-BC mixtures to cracking under indirect tensile loading.*

Keywords: *Tensile Strength; LDPE; AC-BC; SEM; Asphalt Mixture; Marshall Test.*

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I. INTRODUCTION

Flexible pavement, particularly the Asphalt Concrete–Binder Course (AC-BC) layer, plays an important role in resisting and distributing traffic loads to the underlying layers. An asphalt mixture with good strength and resistance to water and repeated loading is therefore required, one indicator of which is the tensile strength of the mixture.

At the same time, plastic waste remains a significant environmental problem in Indonesia. One widely generated type is Low-Density Polyethylene (LDPE). Utilizing plastic waste as an additive in asphalt mixtures is an alternative solution that can simultaneously improve pavement performance and reduce environmental impact. The addition of LDPE plastic to asphalt mixtures is known to increase stability and resistance to deformation; however, studies specifically addressing the tensile strength of AC-BC mixtures with LDPE addition remain limited. This study therefore analyzes the effect of LDPE plastic, added using the dry process, on the Indirect Tensile Strength (ITS) of AC-BC asphalt mixtures, with the aim of improving pavement quality while supporting the sustainable use of plastic waste.

The specific objectives of this study are: (1) to determine the effect of LDPE plastic waste addition on the indirect tensile strength of AC-BC asphalt mixtures; and (2) to characterize the microstructure of AC-BC mixtures containing LDPE through Scanning Electron Microscope (SEM) testing, and to relate the observed microstructure to the heating temperature of the asphalt and the resulting tensile strength.

ITS testing quantifies the ability of the mixture to withstand tensile stress generated by traffic loading and temperature changes, while SEM observation reveals the distribution of LDPE particles, the interfacial bonding among aggregate, bitumen, and LDPE, and the presence of microvoids or microcracks that may reduce tensile strength. Correlating the mechanical (ITS) and microstructural (SEM) results provides a more complete understanding of the behavior of LDPE-modified asphalt mixtures, which is important for the development of sustainable, plastic-waste-based asphalt mixtures with optimal structural performance.

II. MATERIALS AND METHODS

2.1 Materials

Coarse and fine aggregates were obtained from a stone-crushing plant (AMP) belonging to PT. Sapta Unggul, sourced from the Watusampu quarry, Ulujadi Sub-district, Palu, Central Sulawesi. The bitumen used was Pen 60/70 penetration-grade bitumen produced by PT. Pertamina. LDPE plastic waste was collected from household plastic-bag (kresek) waste, which was sorted, washed, dried, and shredded into particles smaller than 5 mm using a plastic-crushing machine before use. Mix design followed the AC-BC gradation limits of the Indonesian Directorate General of Highways (Bina Marga) General Specification 2025, using the mid-point (ideal) gradation obtained by the by-sieve method, with proportions of 48% coarse aggregate, 40% fine aggregate (stone dust), and 12% sand.

2.2 Mix Design and Marshall Testing

The estimated optimum bitumen content (Pb) was first calculated using Pb = 0.035(%CA) + 0.045(%FA) + 0.18(%Filler) + K, where CA, FA, and Filler are the percentages of aggregate retained on sieve No. 4, passing sieve No. 4 and retained on No. 200, and passing sieve No. 200, respectively, and K is a constant (0.5–1 for laston). This yielded an estimated bitumen content of about 6%. Specimens were then prepared at five trial bitumen contents (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%), two specimens per content, and evaluated using the Marshall method (SNI 06-2489-1991) to determine density, stability, flow, VIM (voids in mix), VMA (voids in mineral aggregate), and VFB (voids filled with bitumen). The optimum bitumen content (OBC) was determined graphically as the value satisfying all Bina Marga 2025 specification limits simultaneously, and was confirmed with additional Marshall and Marshall-immersion specimens.

At the OBC, LDPE plastic was added to the mixture by the dry process at contents of 0%, 2%, 3%, 4%, and 5% of the coarse aggregate weight (the 0% content served as the control). In this method, shredded LDPE was not blended directly into the bitumen; instead, heated coarse aggregate (heated above the LDPE melting range of approximately 200°C) was coated with the molten plastic in 3–7 successive additions with continuous mixing, forming a thin polymer film on the aggregate surface prior to mixing with bitumen. Six specimens were prepared for each LDPE content for Marshall and volumetric testing, compacted manually with 2×75 blows per specimen.

2.3 Indirect Tensile Strength (ITS) Testing

The Indirect Tensile Strength (ITS) test was conducted in accordance with ASTM D6931-12 to evaluate the resistance of the AC-BC mixture to cracking under indirect tensile loading. Cylindrical specimens (101.6 mm diameter) compacted with 75 blows per side were loaded diametrically at a constant rate until failure (splitting) occurred. Two horizontal LVDTs measured horizontal elongation and two vertical LVDTs measured vertical shortening during loading. Three replicate specimens were tested for each LDPE content (0%, 2%, 3%, 4%, and 5%) at the optimum bitumen content of 5.80%, giving 15 specimens in total. The percentage mortality-style ITS value (kg/mm²) was computed from the maximum load recorded at failure, the specimen thickness, and the specimen diameter.

2.4 Scanning Electron Microscope (SEM) Testing

SEM observation was performed to examine the surface morphology and the distribution of LDPE particles within the asphalt matrix. Cubic specimens (1 cm × 1 cm) were prepared from mixtures at the optimum bitumen content (5.80%) for LDPE contents of 2%, 3%, 4%, and 5%, following Marshall testing. Each specimen was examined at four magnifications (500×, 1000–1500×, 2000×, and 3500×) to progressively resolve the coating continuity, interfacial bonding among aggregate, bitumen, and LDPE, and the presence of microvoids or microcracks. Testing was carried out at the UPA Integrated Laboratory, Universitas Tadulako.

III. RESULTS AND DISCUSSION

3.1 Material Characterization

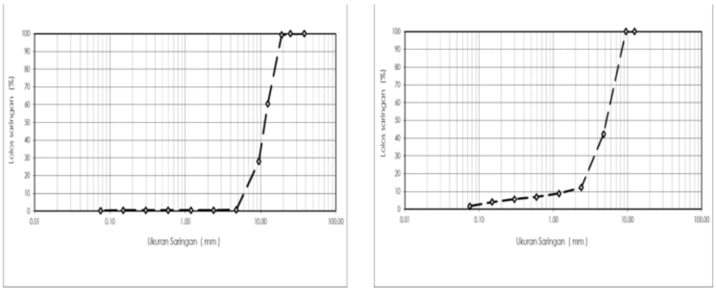
Physical testing of the coarse and fine aggregate (specific gravity, absorption, sieve analysis, abrasion, and material passing sieve No. 200) confirmed that all fractions met the Bina Marga 2025 specification. The bulk specific gravity of the 3/4-inch and 3/8-inch coarse-aggregate fractions was 2.78 and 2.68, respectively, with absorption of 0.58% and 0.52%; the fine-aggregate (stone dust and sand) bulk specific gravity was 2.61 and 2.50, with absorption of 1.26% and 1.57%. The Los Angeles abrasion loss was 20%, well below the 30% maximum limit. The Pen 60/70 bitumen met all specification requirements, as summarized in Table 1.

Table 1. Physical properties of the Pen 60/70 bitumen used in the mixture

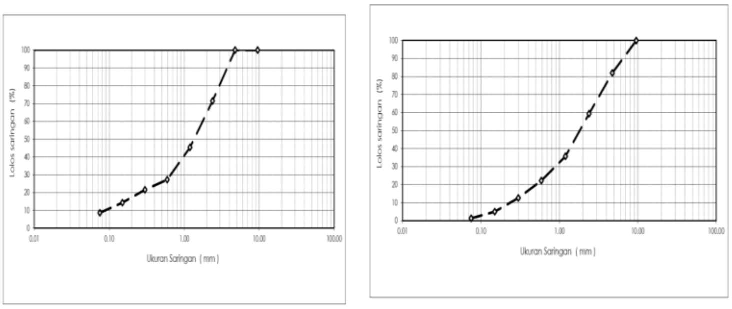
No.	Property	Unit	Result	Specification	Remark
1	Penetration at 25°C	0.1 mm	64	60–70	Meets spec.

No.	Property	Unit	Result	Specification	Remark
2	Softening point	°C	52.43	≥ 48	Meets spec.
3	Ductility at 25°C	cm	140	≥ 100	Meets spec.
4	Specific gravity	–	1.033	≥ 1	Meets spec.

The LDPE plastic waste used was sieved and shredded so that at least 90% passed both the 3/8-inch and No. 4 sieves, satisfying the requirements of Pd-09-2019-B (Hot-Mix Asphalt Specification Using Plastic Waste). A melting-point test showed that the LDPE began to change shape at approximately 130–134.7°C, and had still not fully melted at 190°C, indicating that the true melting point exceeds 200°C — the reference used to set the aggregate-heating temperature during the dry-process coating stage.



a. Grafik Gradasi Analisa Saringan Fraksi ¾" b.Grafik Gradasi Analisa Saringan Fraksi 3/8"



c. Grafik Gradasi Analisa Saringan Fraksi AbuBatu d.Grafik Gradasi Analisa Saringan Fraksi Pasir

Figure 1. Sieve-analysis gradation curves for (a) 3/4-inch, (b) 3/8-inch, (c) stone-dust, and (d) sand aggregate fractions.

The combined aggregate gradation (48% coarse aggregate, 40% stone dust, 12% sand) fell within the Bina Marga 2025 gradation envelope for AC-BC at every sieve size, confirming the mixture design used the mid-point ("ideal") gradation.

3.2 Optimum Bitumen Content (OBC)

Following the estimated Pb of approximately 6%, Marshall specimens at 4.5–6.5% bitumen content were tested; the resulting density, stability, flow, VIM, VMA, and VFB values were plotted against bitumen content and compared with the Bina Marga 2025 specification bands to obtain the range of bitumen contents satisfying all parameters simultaneously. This analysis yielded an Optimum Bitumen Content (OBC) of 5.80%, which was subsequently confirmed with dedicated Marshall and Marshall-immersion (retained stability) specimens, giving a retained stability of 92.4% — well above the 90% minimum requirement. All subsequent LDPE-modified specimens were therefore prepared at 5.80% bitumen content.

3.3 Aggregate Coating and Effect of LDPE Content on Marshall Properties

Visual inspection of the coated coarse aggregate (Figure 2) showed a clear, progressive change with increasing LDPE content. At 2% LDPE the surface remained relatively rough and dry, with patches of bare aggregate still visible, indicating an incomplete polymer film. At 3% the coating was darker and more even, although small uncoated gaps remained. At 4% the aggregate surface was the darkest, glossiest, and most uniformly coated of all variations, with the natural aggregate texture almost entirely concealed, while individual particles remained discrete (no clumping). At 5%, however, an excess-polymer (over-coating) condition appeared: several particles began to adhere to one another, forming clusters bridged by surplus LDPE. These qualitative observations already suggested 4% as the coating optimum, consistent with the quantitative Marshall results discussed below.

Figure 2. Coated coarse aggregate at LDPE contents of (from left) 2%, 3%, 4%, and 5%.

Table 2. Marshall properties of the AC-BC mixture at OBC = 5.80% with varying LDPE content

Property	0%	2%	3%	4%	5%	Spec.
Density (gr/cc)	2.309	2.311	2.332	2.372	2.394	Min. 2.0
VIM (%)	5.7	5.6	4.8	3.2	2.2	3–5
VMA (%)	18.1	18.0	17.3	15.9	15.1	Min. 15
VFB (%)	68.4	68.7	72.3	80.1	85.1	Min. 65
Stability (kg)	1174.2	1239.4	1294.6	1324.7	1214.4	Min. 800
Flow (mm)	2.5	3.5	3.7	3.4	3.5	2–4

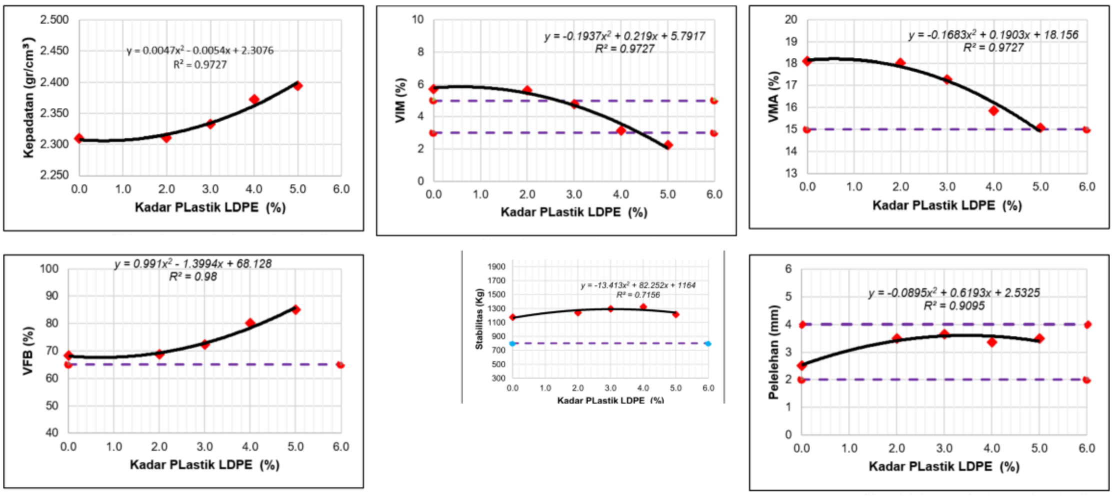


Figure 3. Relationship between LDPE content and (a) density, (b) VIM, (c) VMA, (d) VFB, (e) stability, and (f) flow, each fitted with a second-order polynomial regression.

Density increased almost monotonically with LDPE content, as molten plastic filled part of the inter-aggregate voids, producing a denser, more uniform structure — consistent with Sukobar et al. (2021) and Hidayati et al. (2021), who reported similar densification effects of dry-process LDPE modification. VIM decreased and VFB increased with LDPE content for the same reason, while VMA decreased slightly but remained within specification up to 5%. Stability and flow both followed a parabolic (rise-then-fall) trend, increasing from 0% to a peak near 3–4% before declining at higher content — stability rose from 1174.2 kg (0%) to a maximum of 1324.7 kg (4%), then fell to 1214.4 kg (5%). This pattern is consistent with LDPE first filling voids and strengthening interparticle bonding (increasing stability), then, beyond the optimum, acting as a stiff, inelastic phase that creates new weak points and reduces load-carrying capacity, a behavior also reported by Ramadhani (2023) and Awwad and Shbeeb (2007).

Overlaying the LDPE ranges that individually satisfy the Bina Marga 2025 specification for stability, flow, VMA, VIM, and VFB (Figure 4) identifies a common (overlap) range of 3.0–4.0%, giving an Optimum Plastic Content (OPC) of 3.5% as the midpoint. This result is corroborated by the qualitative coating assessment (Section 3.3), in which 4% produced the most uniform, homogeneous film without particle clumping while 5% clearly over-coated. Combining the quantitative Marshall analysis with the qualitative visual coating assessment therefore reinforces the conclusion that an LDPE content in the 3.5–4% range yields the best overall Marshall performance.

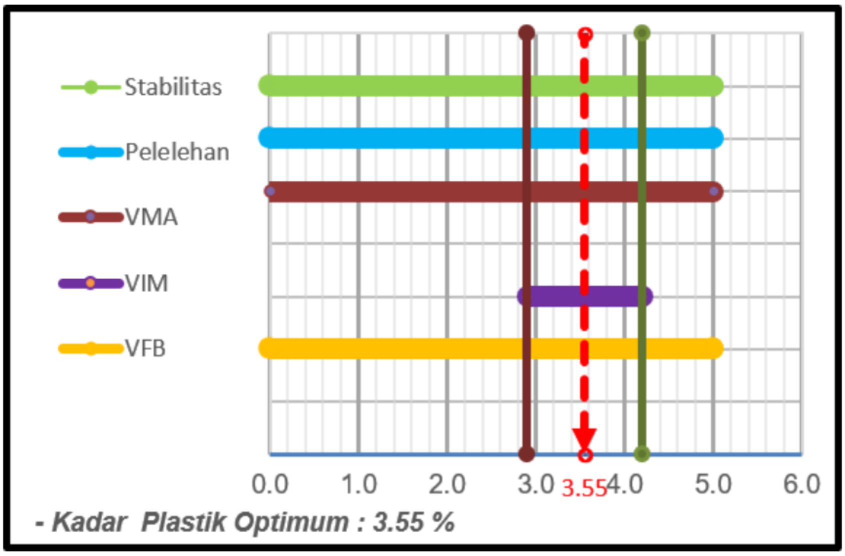


Figure 4. Overlay of LDPE content ranges satisfying the Bina Marga 2025 specification for stability, flow, VMA, VIM, and VFB, giving an optimum plastic content of 3.55%.

3.4 Indirect Tensile Strength (ITS)

ITS testing was carried out on three replicate specimens for each LDPE content (0%, 2%, 3%, 4%, and 5%) at the optimum bitumen content of 5.80%. The average ITS values, summarized in Table 3, increased consistently from 0.063 kg/mm² at 0% LDPE (control) to a maximum of 0.108 kg/mm² at 4% LDPE — an increase of approximately 68.9% — before declining to 0.100 kg/mm² at 5% LDPE.

Table 3. Average Indirect Tensile Strength (ITS) of the AC-BC mixture at OBC = 5.80% with varying LDPE content

LDPE content (%)	Average ITS (kg/mm²)	Remark
0	0.063	Control (no LDPE)
2	0.103	Increase
3	0.106	Increase
4	0.108	Highest (maximum)
5	0.100	Begins to decrease

The relationship between LDPE content and ITS forms a downward-opening parabola, indicating a single maximum. Fitting a second-order (quadratic) polynomial regression to the data (Figure 5) gave:

$$\mathbf{ITS = -0.0038(LDPE)^2 + 0.0261(LDPE) + 0.637 \quad (R^2 = 0.9957)}$$

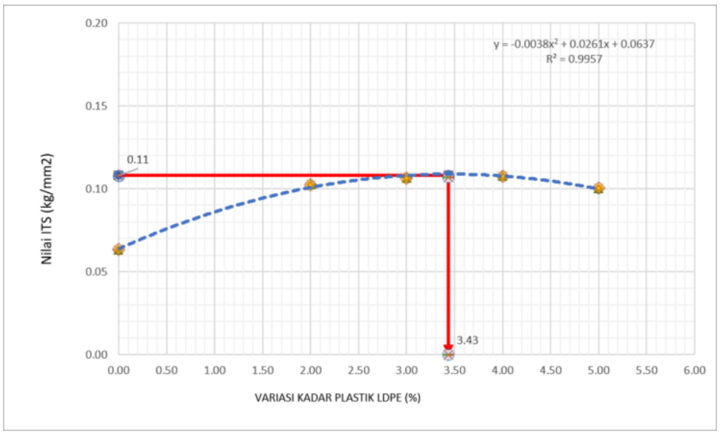


Figure 5. Relationship between LDPE content and ITS value, with second-order polynomial regression fit; the theoretical optimum (3.43%, 0.11 kg/mm²) is highlighted.

Setting the first derivative of the regression equation to zero (d(ITS)/d(LDPE) = 2ax + b = 0) gives a theoretical optimum LDPE content of x = −b/2a = −0.0261 / (2 × −0.0038) = 3.434%, at which the predicted maximum ITS is 0.107 kg/mm². This theoretical value is remarkably close to the experimental maximum of 0.108 kg/mm² recorded at 4% LDPE (a difference of only about 0.001 kg/mm², or roughly 0.99%), and the very high coefficient of determination ($R^2 = 0.9957$) confirms that the quadratic model explains about 99.6% of the variation in ITS due to LDPE content. Because laboratory testing was performed only at the discrete contents of 0%, 2%, 3%, 4%, and 5%, the theoretical optimum of 3.434% could not be tested directly; the experimentally verified content of 4% is therefore adopted as the practical, recommended optimum.

The increase in ITS from 0% to 4% LDPE is attributed to the ability of molten LDPE to fill voids within the mixture and strengthen the bond between aggregate particles and bitumen, increasing the mixture's resistance to indirect tensile stress. The subsequent decrease at 5% is attributed to excess plastic causing uneven (non-homogeneous) distribution within the mixture, which weakens interparticle bonding and can make the mixture excessively stiff and brittle, making it more prone to cracking under tensile load — consistent with the crack-pattern observations described below and with prior findings by Awwad and Shbeeb (2007).

Examination of the fractured ITS specimens showed a vertical dominant crack through the specimen center in every case, consistent with the diametral-loading failure mechanism of the ITS test. At 0% LDPE, the main crack was relatively straight with several minor branch cracks, indicating limited resistance to crack propagation. At 2% LDPE, branching decreased, indicating that LDPE addition had begun to increase the bonding capacity of the mixture. At 3% LDPE, the crack path narrowed and became more concentrated on a single fracture plane, indicating a more even stress distribution. At 4% LDPE, the crack pattern was the most regular with the fewest branches, showing that the mixture had the greatest capacity to resist crack propagation — consistent with the peak ITS value recorded at this content. At 5% LDPE, cracks widened and again showed irregular branching, consistent with a non-homogeneous plastic distribution creating localized weak zones.

3.5 Relationship between ITS and Marshall Stability

Both ITS and Marshall stability represent the capacity of the mixture to resist, respectively, indirect tensile stress and compressive/shear loading from traffic. As shown in Table 4 and Figure 6, the two parameters follow an essentially identical trend with respect to LDPE content: both increase from 0% to a peak at 4% LDPE (ITS: 0.063 → 0.108 kg/mm²; stability: 1174.2 → 1324.7 kg) and then decline at 5% (ITS: 0.100 kg/mm²; stability: 1214.4 kg).

Table 4. Relationship between ITS and Marshall stability of the AC-BC mixture with varying LDPE content

LDPE content (%)	ITS (kg/mm²)	Stability (kg)
0	0.063	1174.2
2	0.103	1239.4
3	0.106	1294.6
4	0.108	1324.7
5	0.100	1214.4

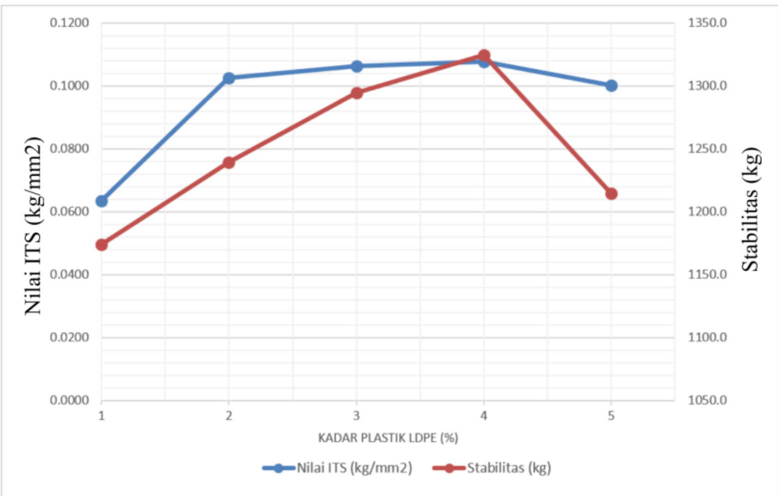


Figure 6. Comparison of ITS and Marshall stability values across LDPE contents, showing the identical peak at 4% LDPE.

The parallel trend indicates that LDPE, as a bitumen/aggregate modifier, simultaneously increases stiffness and viscosity up to about 4% content, strengthening interparticle bonds and improving resistance to both compressive and tensile loading. Beyond 4%, excess, non-homogeneous LDPE tends to agglomerate and form localized weak spots that impair adhesion between bitumen and aggregate, making the mixture excessively stiff and brittle and reducing both parameters. This agreement between two independent mechanical tests strengthens confidence that 4% LDPE is the genuine optimum content, a conclusion consistent with the parabolic stability–LDPE relationship reported by Antoni and Rita (2018) for LDPE-modified AC-WC mixtures.

3.6 SEM Microstructural Analysis

Scanning Electron Microscope (SEM) imaging was performed on 1 cm × 1 cm cubic specimens taken from mixtures at the optimum bitumen content (5.80%) for LDPE contents of 2%, 3%, 4%, and 5%, at magnifications of 500×, 1000–1500×, 2000×, and 3500×, to progressively resolve coating continuity, interfacial bonding, and the presence of microvoids or microcracks.

LDPE 2% (ITS = 0.103 kg/mm²). At this content, LDPE particles remained largely discrete, with limited dispersion and low aggregate coverage; the bitumen matrix was still dominant. At 1000–2000×, LDPE appeared as flake-like fragments with sharp edges scattered non-uniformly through the matrix, some showing signs of incomplete melting. At the highest magnification (3500×), visible surface roughness, microvoids, and gaps at the LDPE–bitumen interface indicated that diffusion of bitumen into the polymer surface, and melting of the LDPE itself, had not yet occurred completely, leaving the interfacial bond relatively weak — consistent with the comparatively modest ITS improvement recorded at this content.

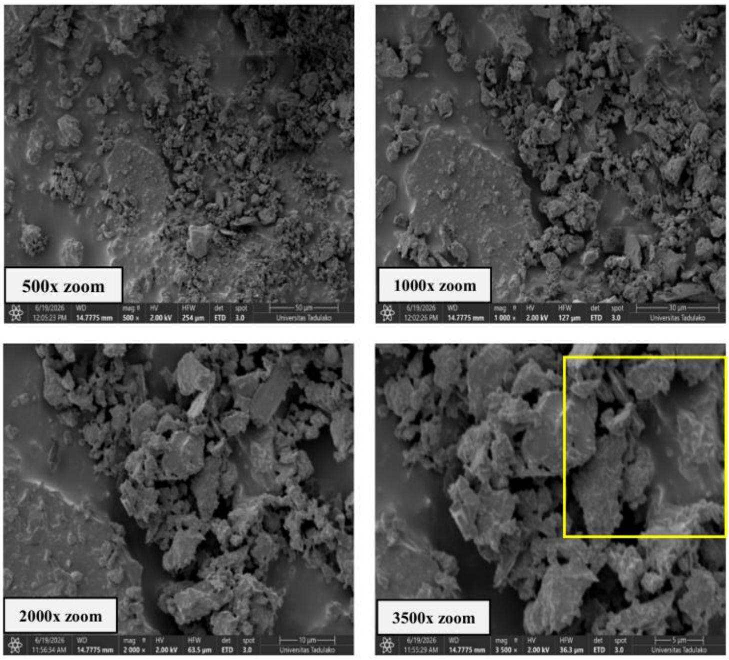


Figure 7. SEM micrographs of the AC-BC mixture with 2% LDPE at 500×, 1000×, 2000×, and 3500× magnification.

LDPE 3% (ITS = 0.106 kg/mm²). Increasing the LDPE content increased the amount of polymer dispersed in the matrix and expanded the coated area, although the film remained locally discontinuous. At 1500×, particles were more closely spaced, forming local coating zones on the aggregate surface. At 2000×, the density of coating points increased further, though gaps and uncoated patches were still present, indicating that interfacial bonding among aggregate, bitumen, and LDPE had begun to form but had not yet reached an optimal state. At 3500×, LDPE was seen beginning to fill small spaces around the aggregate surface, improving contact compared with 2%, although microvoids and interfacial gaps — potential stress-concentration sites under repeated loading — were still present.

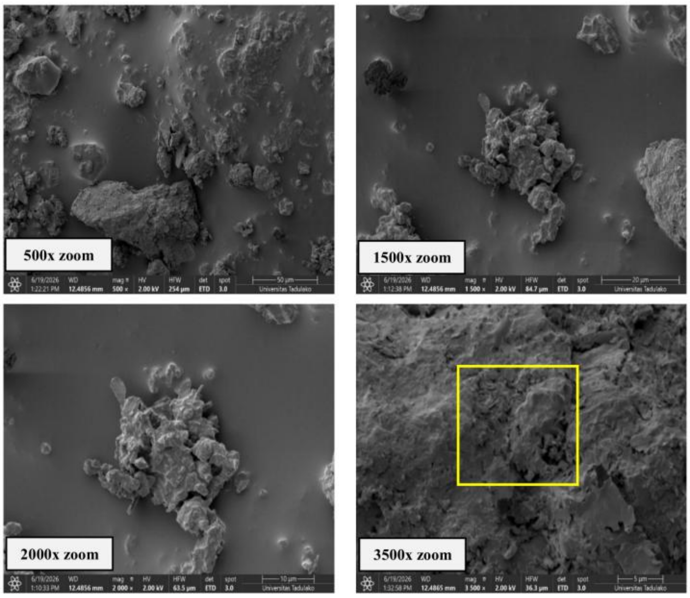


Figure 8. SEM micrographs of the AC-BC mixture with 3% LDPE at 500×, 1500×, 2000×, and 3500× magnification.

LDPE 4% (ITS = 0.108 kg/mm², peak). This content showed the most favorable morphology of all variations examined: a relatively continuous coating that followed the contours of the aggregate and bitumen with no large uncoated areas. At 500×, material distribution was fairly uniform across the observation field, with only a few larger clumps among the finer particles and no dominant empty regions. At 1000×, a laminar (layered) texture with fine surface cracking began to appear, indicating that the LDPE had melted and spread effectively, forming a layered structure that followed the aggregate contour. At the highest magnification (3500×), a wrinkled, fibrous film covered nearly the entire observation field continuously, with the fewest residual microvoids among all contents tested — indicating the best interfacial bonding among aggregate, bitumen, and LDPE, and directly explaining why the tensile strength peaked at this content: the most homogeneous, least-defective microstructure corresponds to the highest capacity to resist tensile stress.

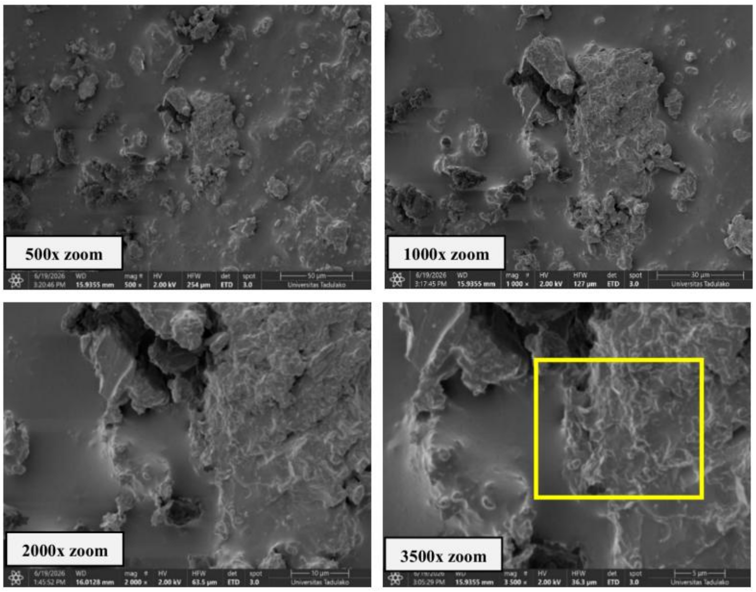


Figure 9. SEM micrographs of the AC-BC mixture with 4% LDPE (optimum) at 500×, 1000×, 2000×, and 3500× magnification.

LDPE 5% (ITS = 0.100 kg/mm², decreasing). Beyond the optimum content, morphology changed markedly for the worse: rather than a continuous film, LDPE tended to agglomerate into clusters, producing a coarser, more granular, and less uniform surface texture. At 500×, some regions remained relatively smooth while others showed local accumulations of small particles forming clusters, indicating loss of distribution homogeneity.

At 1000– 2000×, rounded-to-irregular particles were seen grouping into local agglomerations rather than spreading evenly as at 4%, with voids and gaps surrounding the clusters, indicating incomplete melting and spreading. At 3500×, the clustered LDPE surface was rough, folded, and irregular, with a distinct, sharply defined boundary between the polymer clusters and the surrounding bitumen matrix — clear evidence of reduced interfacial bonding caused by excess polymer content. This microstructural degradation directly explains the drop in ITS at 5% LDPE: excess, non-homogeneous plastic no longer disperses effectively and instead becomes a source of stress concentration.

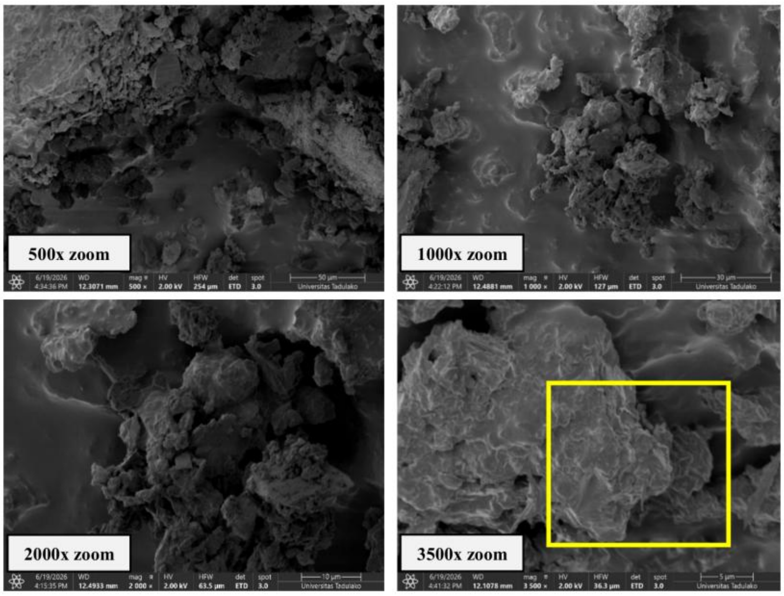


Figure 10. SEM micrographs of the AC-BC mixture with 5% LDPE at 500×, 1000×, 2000×, and 3500× magnification, showing LDPE particle agglomeration.

3.7 Correlation between ITS and SEM Findings

Table 5 summarizes how the SEM-observed microstructure at each LDPE content corresponds to the measured ITS value, providing microstructural justification — not merely confirmation — for the mechanical trend.

Table 5. Correlation between LDPE content, ITS value, and SEM-observed microstructure

LDPE (%)	ITS (kg/mm²)	Key SEM observation
2	0.103	Discrete LDPE particles, low aggregate coverage, matrix dominated by bitumen, microvoids present at interface
3	0.106	Denser particle distribution, local coating zones forming, but gaps and uncoated areas still present
4	0.108 (max.)	Continuous, uniform coating; wrinkled but fused LDPE film; fewest voids/microcracks; best interfacial bonding
5	0.100	LDPE agglomeration (clustering); coarse, granular texture; voids and microcracks reappear; distinct polymer–bitumen boundary

The progression is consistent across both methods: from 2% to 4% LDPE, coating becomes more complete, voids decrease, and interfacial bonding strengthens in step with the rising ITS; at 4% the coating is homogeneous and continuous, coinciding with the ITS maximum; and at 5% the coating reverts to agglomeration, with voids and microcracks reappearing, coinciding with the ITS decline. This agreement between an independent quantitative mechanical test (ITS) and qualitative microstructural observation (SEM) reinforces the conclusion that 4% LDPE is the optimum content — supported not only by statistical/regression evidence but also by direct physical evidence of the mixture's internal microstructure. This is further consistent with the broader literature: Sukobar et al. (2021) and Hidayati et al. (2021) both reported that LDPE modification via the dry process improves volumetric and mechanical properties up to an optimum content, Al-Hadidy and Tan (2009) confirmed a similar non-monotonic (rise-then-fall) trend in Marshall stability for pyrolyzed-LDPE-modified bitumen using comparative micrographs, and Ramadhani (2023) likewise used SEM to relate heating temperature and LDPE content to the resulting Marshall characteristics of asphalt mixtures, supporting the value of combining mechanical testing with direct microstructural observation.

IV. CONCLUSION

1. The highest Indirect Tensile Strength (ITS) of the AC-BC mixture, 0.108 kg/mm², was obtained at an LDPE plastic content of 4%. This finding is supported by a quadratic regression analysis ($y = -0.0038x^2 + 0.0261x + 0.637$; $R^2 = 0.9957$), which gives a theoretical optimum at 3.434% LDPE with a predicted maximum ITS of 0.107 kg/mm². The close agreement between the theoretical and experimental optima, together with the very high coefficient of determination, confirms that 4% LDPE can be recommended as the optimum additive content for improving the resistance of asphalt mixtures to cracking under indirect tensile loading.

2. SEM observation showed that an increase in Marshall stability is not always accompanied by improved microstructural quality. The mixture with 4% LDPE exhibited the most homogeneous surface morphology, characterized by more uniform aggregate coating, better interfacial bonding among aggregate, bitumen, and LDPE, and fewer voids and microcracks — indicating a more stable microstructure with the potential for improved resistance to traffic loading and environmental effects. At 5% LDPE, although Marshall stability still exceeded the specification minimum, SEM revealed a less homogeneous microstructure marked by LDPE particle agglomeration, voids, and microcracks at the interfacial region, indicating that the LDPE content had exceeded the compatibility limit with the bitumen matrix, potentially reducing internal bond quality and long-term durability. Combining Marshall and SEM results, 4% LDPE represents the most optimum content in this study, offering the best balance between improved mechanical characteristics and microstructural quality, and is recommended for pavement applications requiring long-term stability, resistance, and durability.

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