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RESEARCH ARTICLE

Enhancing road stability with plastic waste in asphalt mixtures: a comparative study of dry and wet mixing methods

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Abstract: The incorporation of plastic into asphalt mixtures has gained attention as a potential approach to improving pavement performance. However, the comparative effects of plastic characteristics and mixing methods on asphalt mixture performance remain unclear. This study evaluates the influence of polyethylene terephthalate (PET) and low-density polyethylene (LDPE) as partial asphalt replacements through dry and wet mixing methods. Marshall testing was conducted to determine the optimum asphalt content (OAC) and assess mixture stability, flow, and volumetric properties, supported by polynomial regression and analysis of variance (ANOVA). Both SNI 2489:2018 and ASTM D6927-22 procedures yielded an OAC of 5.5%. PET achieved a maximum stability of 2286.50 kg at 5% substitution using wet mixing, while LDPE reached 2759.78 kg at 9% substitution using dry mixing, representing improvements of 28.42% and 55%, respectively. Statistical analysis revealed distinct effects on mechanical and volumetric properties depending on plastic type and mixing conditions. These findings demonstrate that asphalt modification effectiveness depends not only on plastic content but also on the interaction between material characteristics and incorporation methods, providing a comparative basis for optimizing plastic-modified asphalt mixtures.

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1. Introduction

Indonesia is among the largest contributors to global waste generation, producing millions of tonnes of waste annually. According to data from the National Waste Management Information System (SIPSN) by the Ministry of Environment and Forestry (KLHK), total national waste generation reached 27,8 million tonnes in 2025, of which only 3% was properly managed, while the remaining 97% remained untreated [1]. A significant portion of this waste consists of plastic, which has become a major environmental concern due to its non-biodegradable nature and its origin from petroleum-based materials [1]. Various approaches have been developed to manage plastic waste, including mechanical recycling methods such as sorting, washing, and reprocessing [2]−[3], as well as chemical recycling techniques like pyrolysis and depolymerization [4]. However, mechanical recycling is often limited by contamination issues, while chemical recycling requires high energy input and may contribute to greenhouse gas emissions [5]−[6]. Therefore, alternative strategies for plastic waste utilization are increasingly being explored to reduce environmental impact.

In recent decades, various approaches have been explored to utilize plastic and polymer waste in engineering applications [7]. One promising approach is the incorporation of such materials into asphalt mixtures as modifiers for pavement construction. During its service life, asphalt pavement is subjected to repeated traffic loading, which can lead to common distresses such as fatigue cracking and permanent deformation, particularly in the surface layer [8]. To address these issues, several studies have investigated the use of additives, including polymers and fibers, to enhance the mechanical performance of asphalt mixtures [9]−[11]. Most of these studies report improvements in properties such as stability, stiffness, and resistance to deformation. Since both asphalt binder and plastic materials are hydrocarbon-based, their incorporation can potentially enhance the overall performance of the mixture through improved material interaction [12]−[13].

Extensive research has been conducted to investigate methods for improving pavement performance through the incorporation of plastic waste [6]. Thermoplastics, in particular, are widely utilized due to their ability to soften under heat, facilitating improved interaction with asphalt mixtures [14]−[15]. Common thermoplastic materials include polyethylene terephthalate (PET) and low-density polyethylene (LDPE), which are extensively used in products such as plastic bottles and plastic bags [16].

Among these materials, PET has attracted significant attention due to its availability and favorable mechanical properties. PET, a polyester commonly used in beverage bottles and packaging, is known for its high stiffness and high melting temperature [17], which contribute to enhanced resistance to deformation at elevated temperatures [18]. Previous studies from Modarres et al. [19], Baradaran et.al [20], and Wadu et al. [21] have reported that the incorporation of PET can significantly improve the mechanical performance of asphalt mixtures, including increased stability, stiffness, and resilient modulus, as well as improved resistance to rutting. For instance, Mashaan et al. [22] using the wet method, the study found that adding 6–8% PET improved the binder's modulus, elasticity, and rutting resistance. RTFOT and PAV results showed reduced aging and better fatigue performance, with 8% PET giving the lowest fatigue factor. These

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findings indicate that waste PET can function effectively as a value-added asphalt modifier. Similarly, Li et al. [23] employed FTIR and SEM analyses and found that the interaction between PET and asphalt is primarily physical rather than chemical, although changes in functional group intensity indicate improved thermal stability. In addition, studies have shown that the use of PET can enhance mixture performance in Stone Mastic Asphalt (SMA), particularly in terms of stiffness and deformation resistance, although excessive PET content may increase air voids and reduce workability [24]−[25]. Overall, these findings suggest that PET is a promising additive for improving the performance of asphalt mixtures.

In contrast to PET, low-density polyethylene (LDPE) is another widely used thermoplastic polymer characterized by its lower density, semi-crystalline structure, and relatively low melting temperature, typically around 115 °C [26]. Due to these properties, LDPE is more flexible and can be more easily blended with asphalt during the mixing process. Previous studies have shown that the incorporation of LDPE can improve the mechanical performance of asphalt mixtures, particularly in terms of Marshall stability and viscoelastic behavior [27]. For example, Cardoso et al. [28] reported an increase in stability and stiffness modulus, accompanied by a reduction in phase angle, indicating enhanced viscoelastic properties. Similarly, Genet et al. [29] found that LDPE-modified mixtures exhibit improved resistance to permanent deformation, with optimal performance observed at certain plastic contents before declining at higher dosages. In addition, the effectiveness of LDPE has been shown to depend on its physical form, where pellet-shaped LDPE provides better performance compared to shredded or powdered forms in dry mixing applications [30]. From a mechanistic perspective, study from Ghani et al. [31] using FTIR and SEM analyses suggest that LDPE interacts with asphalt primarily through physical blending, with limited chemical modification. SEM observations also indicate a non-uniform distribution and the presence of micro-cracks, which explain why the improvements are more pronounced in strength-related properties rather than volumetric characteristics. Overall, LDPE is considered an effective modifier for enhancing high-temperature performance, particularly in improving rutting resistance, although its effectiveness is influenced by dosage, form, and mixing conditions.

In addition to material type, the method of incorporating plastic into asphalt mixtures plays a crucial role in determining performance. Two commonly used approaches are the dry and wet methods [32]−[33]. In the dry process, plastic is added to the aggregates in solid form before the binder is introduced, whereas in the wet process, plastic is blended with the asphalt binder at elevated temperatures prior to mixing with aggregates [34]−[36]. The effectiveness of these methods is influenced by several factors, including the melting temperature of the plastic, mixing temperature, and mixing time [37]. Thermoplastics with lower melting points, such as polyethylene-based materials, tend to exhibit better dispersion and interaction with the binder, particularly in the wet process [38]. These differences in mixing approach can significantly affect the distribution of plastic within the mixture, the interaction mechanism with the binder, and ultimately the overall mechanical performance of the asphalt mixture [39]. Therefore, comparing dry and wet mixing methods is important to determine how the incorporation process influences the dispersion and interaction of different plastic types within the asphalt mixture and, consequently, their mechanical performance.

The performance of plastic-modified asphalt mixtures is influenced by multiple factors, including the type of polymer used and the method of incorporation [40]. Previous studies have reported varying and sometimes conflicting results regarding the effectiveness of plastic modification, for instance, a study has shown that the incorporation of PET or LDPE can enhance mixture stability and stiffness [24], [41], while others have reported negligible or even adverse effects on certain performance parameters [42]−[44]. These inconsistencies suggest that the influence of plastic modification is not solely dependent on material type, but also on other factors such as mixing conditions and methodology. However, most existing studies have been conducted separately, focusing on individual materials or specific mixing techniques [32], [45]−[49]. Consequently, it remains unclear how PET and LDPE respond to dry and wet mixing when evaluated within a common experimental framework. In particular, it is not well established whether the differences in mixture performance are primarily associated with the characteristics of the plastic itself, the mixing method, or the interaction between these two factors.

To address this gap, this study compares PET and LDPE under both dry and wet mixing methods using a common asphalt mixture and consistent mixing, compaction, and Marshall testing procedures. The comparison is intended to distinguish the influence of plastic type and mixing method on the resulting mixture performance. Different substitution levels were employed for PET and LDPE based on the experimental design, while the same base mixture and testing framework were maintained. The objective of this study is therefore to investigate the effects of PET and LDPE incorporation through dry and wet mixing methods on the mechanical and volumetric properties of asphalt mixtures and to identify the differences in their performance under each incorporation method.

2. Materials and Methods

2.1 Asphalt

The asphalt used in this study was 60/70 penetration asphalt purchased from PT. Pertamina. The asphalt was further evaluated at the Bitumen Laboratory of Sampoerna University, as listed in Table 1. The results revealed that the asphalt met the minimum criteria, with the temperatures for mixing and compacting the samples being 158°C and 145°C, respectively.

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Table 1. Asphalt testing result

Testing	Testing Method	Asphalt Pen 60/70 (Standard)	Testing Result
Penetration, 25°C (0,1 mm)	SNI 06-2456-1991	60-70	63.70
Flash point (°C)	SNI-06-2433-2011	≥ 232	334
Viscosity 135°C (cSt)	SNI 06-6441-2000	≥ 300	420
	Mixing Temperature	-	158
	Compaction Temperature	-	145

2.2 Aggregate Gradation

In this study, continuous gradation, often referred to as Asphalt Concrete Wearing Course (AC-WC), was used. Figure 1 shows the evaluation results by gradation graph, revealing it is a continuous gradation with a complete range of coarse, medium, and fine aggregates, resulting in strong interlocking, stiffer, and more stable pavement.

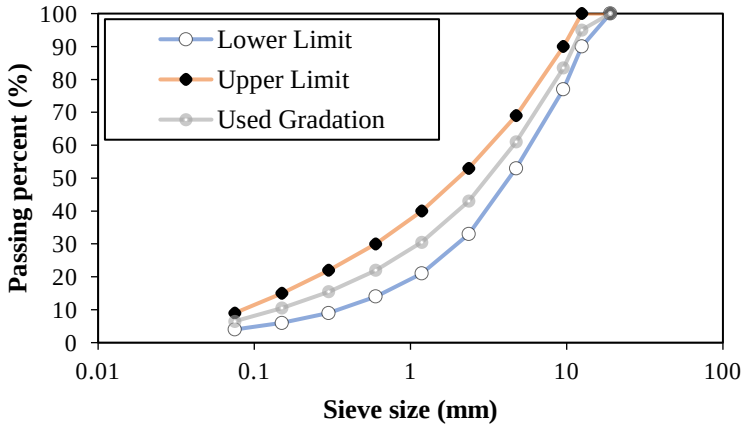


Figure 1. Aggregate gradation and specification limits

2.3 Plastic Materials

Two types of plastic waste with different physical forms and thermal characteristics were selected in this study, namely polyethylene terephthalate (PET) and low-density polyethylene (LDPE). PET was obtained from post-consumer plastic bottles and was processed before being incorporated into the asphalt mixture. The bottles were first shredded and subsequently reduced into smaller particles using a grinder. The processed PET was then sieved to obtain particles smaller than 5 mm. LDPE, in contrast, was obtained in the form of commercially available pellets and was used without further size reduction. The physical appearance and form of the plastic materials used in this study are shown in Figure 2.



(a) (b)

Figure 2. Physical appearance of the plastic materials: **(a)** LDPE **(b)** PET

As illustrated in Figure 2, the two materials differ considerably in their physical form. LDPE consists of relatively uniform pellets, whereas PET exhibits irregular particles resulting from the shredding and grinding of waste bottles. These differences in physical form are relevant to the subsequent mixing process, as the size and morphology of the plastic particles can affect their distribution within the asphalt mixture. The particle size information and other reported physical properties of PET and LDPE are summarized in Table 2.

Table 2. Typical Physical Properties of PET and LDPE Additives

Properties	PET	LDPE	References
Density (g/cm3)	1.4	0.8 – 0.9	[28], [50]
Specific Gravity	1.3 – 1.4	1.014 – 1.042	[51]−[52]
Melting Temperature (°C)	240 – 255	110 – 120	[29], [53]

The reported properties in Table 2 further demonstrate the differences between the two plastic materials. PET generally exhibits a higher melting temperature, approximately 250 °C [53], whereas LDPE melts at a substantially lower temperature of approximately 110 – 120 °C [29]. The density and specific gravity values reported in previous studies also indicate differences in their physical characteristics. Such differences are expected to influence the softening behavior, dispersion, and interaction of each plastic with the asphalt binder during the mixing process.

2.4 Mix Design and Asphalt Content Determination

In creating the Marshall sample, the material composition of the mixture depends on the asphalt content. Various asphalt contents were tested through the Marshall test to determine the optimum asphalt content. The initial estimated asphalt content (Pb) was calculated using the empirical formula specified in the Indonesian technical guideline for hot mix asphalt pavement implementation, issued in accordance with Ministerial Regulation No. 28/PRT/M/2007 [54]. The formula is presented below:

$$\mathrm{Pb} = 0.035\ (\%\mathrm{CA}) + 0.045\ (\%\mathrm{FA}) + 0.18\ (\%\mathrm{FF}) + \mathrm{constant} \quad (1)$$

Symbol description:

Pb = Estimated asphalt content value (Percentage of total mixture weight)

CA = Coarse aggregate (Percentage of aggregate retained on No.4 sieve)

FA = Fine aggregate (Percentage of aggregate passed No.4 sieve)

FF = Filler material (Percentage of aggregate passed o.200 sieve with not less than 75% of its weight)

Constant = Ranging from 0.5 to 1 for AC-WC

In this study, it was found that Pb is 5.49%. It is necessary to validate the formula calculation with experimental results obtained through the Marshall Test by employing five variations of asphalt content, each incremented by 0.5% with at least two lower and two higher contents surrounding the estimated optimum. Subsequently, Marshall testing was conducted on test specimens with asphalt content variations of 4%, 4.5%, 5%, 5.5%, and 6%. The optimum asphalt content is determined based on the analysis of the Marshall characteristic graph, which includes parameters such as VMA (Void in Mineral Aggregate), VIM (Void in Mixture), Void Filled with Asphalt (VFA), Marshall Stability and Marshall flow the graph indicates the range of asphalt content that meets the mixture specifications using the Narrow Range method.

Furthermore, asphalt substitution with plastic was based on the optimum asphalt content. In this study, asphalt substitution with PET ranged from 2%, 5%, 6%, to 8% of the asphalt weight, while LDPE ranged from 5%, 8%, 9%, to 11% of the asphalt weight. The substitution rate varied, as adjustments were made to account for the possibility of reaching higher or lower values throughout the experiment.

2.5 Mixing Method

Two mixing methods, namely dry and wet processes, were employed to investigate the influence of plastic incorporation on the performance of asphalt mixtures. In the wet process, the plastic was introduced into the heated asphalt binder prior to mixing with the aggregates. In the dry process, the plastic was added directly to the heated aggregates before the asphalt binder was introduced. For both methods, the mixing temperature was maintained at 158–160 °C, while compaction was conducted at approximately 145 – 150 °C.

For the wet process, PET was introduced into the heated asphalt binder at 158–160 °C. Since this temperature is substantially lower than the reported melting temperature of PET (approximately 250 °C), PET did not fully melt during mixing [55]−[56]. Instead, the PET particles were manually dispersed within the heated binder through continuous stirring. Similar observations have been reported in previous studies, indicating that achieving a fully homogeneous mixture with PET through the wet process is challenging [19], [57]. In contrast, LDPE, with a melting temperature of approximately 110–120 °C, could melt within the applied mixing temperature range. Therefore, PET and LDPE were incorporated under the same temperature condition but with different physical states during mixing.

The optimum bitumen content (OBC) of the control mixture was determined using binder contents ranging from 4% to 6%, with three replicate specimens prepared for each binder content according to the SNI and ASTM procedures resulting in 30 control specimens. The selected OBC was subsequently used as the basis for preparing the plastic-modified mixtures. PET was incorporated at four substitution levels (2%, 5%, 6%, and 8% by weight of bitumen), while LDPE was incorporated at four levels (5%, 8%, 9%, and 11%). For each plastic type, content, and mixing method, three replicate specimens were prepared. Both dry and wet mixing methods were applied, resulting in 48 modified-mixture specimens.

The mixing process was conducted manually using a metal pan for approximately 5 – 7 min. Since no mechanical mixer was used, a fixed mixing speed was not applicable. To maintain consistency and repeatability, the same equipment,

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material addition sequence, mixing temperature, mixing duration, and manual stirring procedure were applied to all specimens. The mixture was continuously stirred until the aggregates were adequately coated with asphalt and the plastic particles were visually distributed throughout the mixture. Three replicate specimens were prepared for each mixture condition to evaluate the consistency of the measured results.

2.6 Sample Conditioning

In preparing the samples, both SNI 2489:2018 [58] and ASTM D6927-22 [59] standards generally follow similar procedures, including the application of 75 compaction blows per face for AC-WC Marshall specimens. Minor variations are observed in the conditioning stage prior to testing. In the SNI procedure, specimens are removed from the mold and immersed in water at room temperature for approximately 24 hours before being conditioned in a water bath at 60 °C for 30 minutes. In contrast, the ASTM procedure allows the specimens to cool within the mold without immersion for up to 24 hours, followed by conditioning in a water bath at 60 °C for 30 minutes prior to testing.

2.7 Marshall Test

In this study, all 78 prepared Marshall samples with varied contents and mixing methods were subjected to shear load through a Marshall Test machine, as depicted in Figure 3. Prior to the test, sufficient petroleum jelly was applied to the machine's module to minimize friction during testing. In the Marshall test, several parameters are obtained, namely stability, flow, VIM (Void in Mixture), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). Using this testing machine, stability and flow values were extracted by utilizing the two dial gauges.



Figure 3. Marshall testing machine

3. Results and Discussion

3.1 Analysis of Optimum Asphalt Content

The data from the Marshall Test results and other component results related to the existence of voids in the sample, such as VIM, VMA, and VFA, are presented in this section. These results form the foundation for selecting the optimum asphalt content (OAC). However, a sample with the highest stability result is much preferred as it ensures the overall quality and safety of the asphalt pavement [60]. Moreover, stability and other component results are compared to the criteria established by the government, specifically Bina Marga (Indonesia) [61] , for this study. All results must meet the minimum or maximum values specified by the criteria, which are applied uniformly to all samples in this study, including those conditioned based on ASTM D6927-22 standards. In accordance with the applicable Bina Marga 2025 specifications, the minimum Marshall stability requirement was set at 800 kg for conventional asphalt mixtures and 1000 kg for polymer-modified asphalt mixtures. Accordingly, the conventional control mixtures were evaluated against the 800 kg criterion, while the PET- and LDPE-modified mixtures were assessed using the 1000 kg criterion.

According to Table 3, based on the conducted Marshall Test, the highest stability, according to the SNI 2489:2018 conditioning standard, was achieved at 5.5% asphalt content with 1780.5 kg. A mixture with higher asphalt content tends to increase the stability value as it provides a stronger bond between the aggregates [62]. However, if the optimum point is surpassed, the mix becomes saturated and can lead to weaker aggregate interlocking, resulting in lower stability [63]. The oversaturated mixture also has low shear resistance and makes it more susceptible to deformation, leading to a higher flow value. An example of both conditions is the 6.0% asphalt content, which had lower stability than the 5.5% asphalt content, with the flow exceeding the criteria, while the remaining asphalt contents succeeded.

Prior to the Marshall Test, the samples underwent weighing in several conditions to obtain their VIM, VMA, and VFA. Table 3 lists the VIM, VMA, and VFA of samples that were immersed for 24 hours, as regulated by SNI 2489:2018 Standard, for conditioning. The results revealed that asphalt contents of 4.0%, 4.5%, and 5.0% failed to fulfill the VIM and VFA requirements set by Bina Marga, as their results had higher voids than allowed. This condition was caused by insufficient asphalt content to fill the voids in the mixture [64]. However, for VMA, all asphalt contents from 4.0% to 6.0% fulfilled the regulated minimum value of 15%. The existence of voids is important to address as it depicts the interior

features of the sample. Samples with void percentages that are not in accordance with the regulations are more likely to be susceptible to oxidation, leading to the degradation of asphalt pavement quality [65].

Table 3. Analysis of OAC using SNI 2489:2018 method

Asphalt Content	Stability (Min. 800 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
4.00	1775.58	3.45	7.80	15.65	50.58
4.50	1524.34	3.03	6.43	15.48	58.90
5.00	1766.29	3.43	5.73	15.92	64.52
5.50	1780.50	3.70	3.96	15.42	74.44
6.00	1563.75	4.23	3.41	16.00	79.33

Overall, for the samples conditioned based on SNI 2489:2018 Standard, all of them exhibited stability much higher than 800 kg, which is the minimum requirement. Concerning flow, only the sample with 6.0% asphalt content exceeded the allowable limit. In terms of voids, all samples met the VMA criteria, but the samples with asphalt contents of 4.0%, 4.5%, and 5.0% did not meet the VIM and VFA criteria. As summarized in Figure 4, using the narrow range graph, the sample with 5.5% asphalt content was determined to be the optimum one for samples conditioned with SNI 2489:2018 Standard.

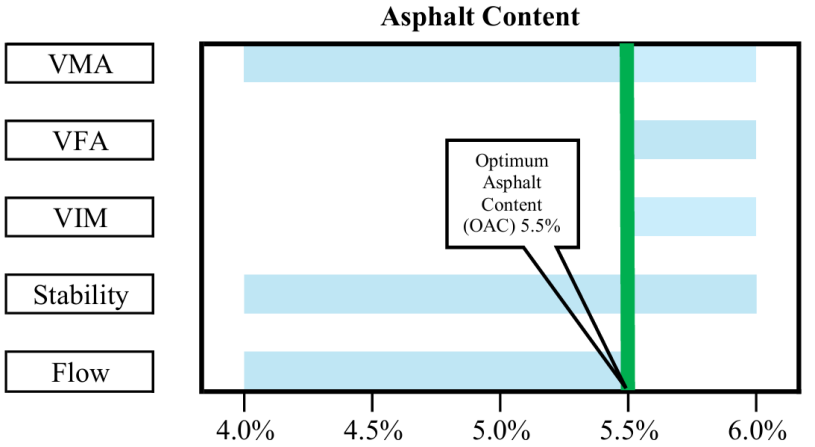


Figure 4. OAC using SNI 2489:2018 method

Moreover, Marshall Test results of samples conditioned according to ASTM D6927-22 Standard are presented in Table 4. All samples met the minimum 800 kg stability requirement, with the highest stability recorded at 5.5% asphalt content, reaching 1895.36 kg. Conversely, concerning flow, only the sample with 6.0% asphalt content exceeded the maximum regulation by 0.23 mm. This observation mirrors the findings of the SNI 2489:2018, where the sample with 6.0% asphalt content exhibited lower stability than that with 5.5% asphalt content, despite its higher asphalt content, consequently resulting in increased flow.

Table 4 also presents the void characteristics of samples conditioned according to ASTM D6927-22 Standard. The findings indicate that the sample with 4.0% asphalt did not meet the VIM, VMA, and VFA regulations. Samples with 4.5% asphalt content only met the VMA requirement. Conversely, samples with 5.0% and 6.0% asphalt content only fell short of the maximum VIM value, with a deviation of 0.05% higher and 0.08% lower, respectively. Notably, the sample with 5.5% asphalt content was the only one that met all void criteria.

Table 4. Analysis of OAC using ASTM D6927-22 method

Asphalt Content	Stability (Min. 800 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
4.00	1651.36	3.05	6.90	14.83	53.56
4.50	1845.67	3.10	6.38	15.44	58.83
5.00	1749.96	3.60	5.05	15.31	67.42
5.50	1895.36	3.90	3.74	15.22	75.65
6.00	1784.37	4.23	2.92	15.57	81.88

While opting for 4.5% asphalt content may seem enticing due to its stability being only 49.69 kg less and its cost-effectiveness on a larger scale, its VIM and VFA results still fail to meet the requirements. As mentioned earlier, VIM, VMA, and VFA signify the internal characteristics of the pavement. Higher void counts are likely to expedite the oxidation process, leading to quicker stability degradation and ultimately resulting in higher maintenance expenses [66]. Therefore, 4.5% asphalt content should be avoided, and 5.5% proved to be a much more suitable option compared to the

others. Utilizing the narrow range graph as shown in Figure 5, it was determined that 5.5% asphalt content was the optimal.

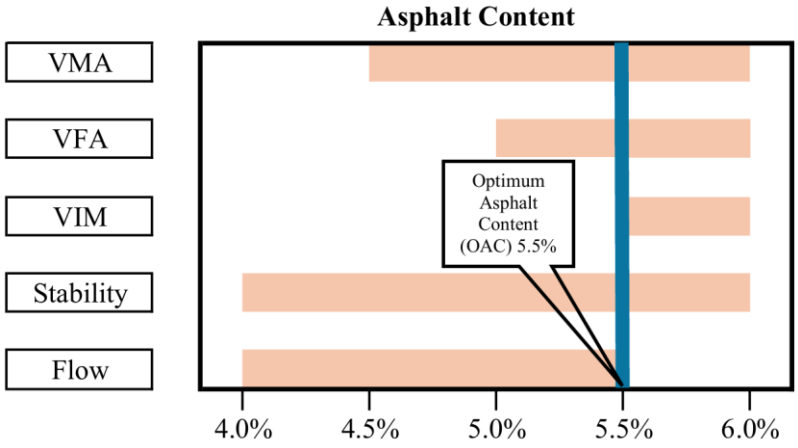
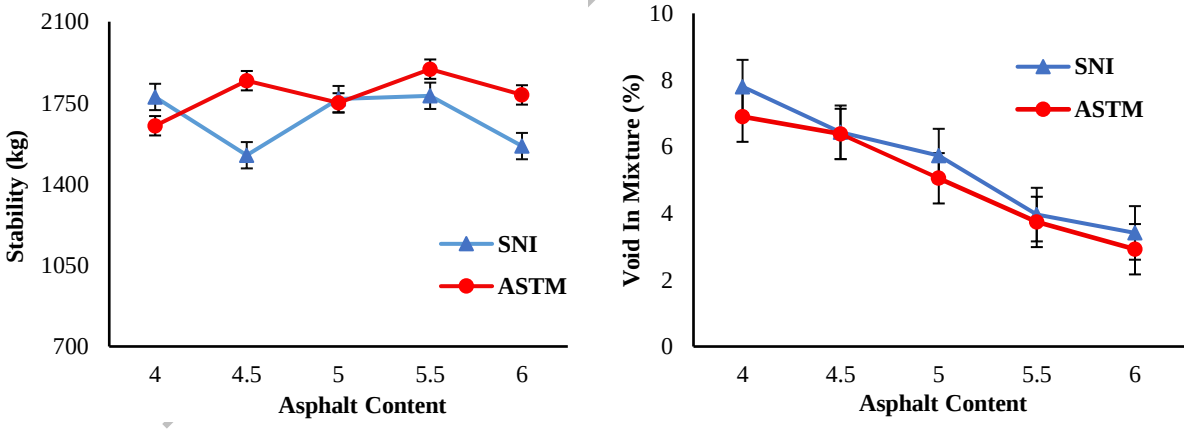


Figure 5. OAC using ASTM D6927-22 method

In summary, both SNI 2489:2018 and ASTM D6927-22 conditioning standards indicated that the optimum asphalt content was 5.5%. Interestingly, differences in flow, VIM, VMA, and VFA between the two sets of samples were found to be insignificant. However, there was a tendency for ASTM D6927-22 samples to display superior void characteristics, with lower VIM, VMA, and higher VFA [67]. Additionally, ASTM D6927-22 samples showed higher stability at asphalt contents of 4.5%, 5.5%, and 6.0%, as illustrated in Figure 6. Even at 5.0% asphalt content, where SNI 2489:2018 indicated slightly higher stability, the difference was marginal, only 16.33 kg. These findings are consistent with the study reported by Indriani and Utomo [68], which demonstrated that immersion conditioning can influence Marshall parameters and the strength characteristics of asphalt mixtures. The higher stability observed in the ASTM D6927-22 specimens may therefore be associated with the differences in conditioning procedures between the two standards. In the SNI 2489:2018 procedure, specimens are immersed in water at room temperature for approximately 24 hours before being conditioned in a 60 °C water bath for 30 minutes. In contrast, the ASTM D6927-22 procedure does not require the initial 24-hour water immersion; the specimens are conditioned directly in a 60 °C water bath for 30 minutes prior to testing. Prolonged exposure to water may promote moisture-induced damage by interacting with the polar components of the asphalt binder and weakening the cohesive strength of the binder phase, while moisture reaching the asphalt–aggregate interface may reduce the adhesion between the binder and aggregate [69]−[70]. Consequently, the longer water exposure in the SNI conditioning procedure may have contributed to the lower Marshall stability observed compared with the ASTM-conditioned specimens in this study.



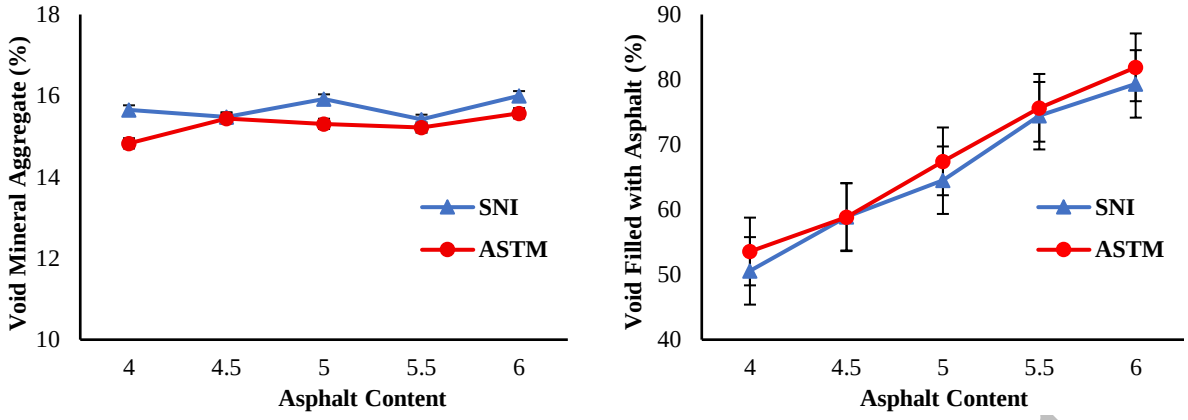


Figure 6. Marshall stability and volumetric properties at different asphalt contents under SNI 2489:2018 and ASTM D6927-22 conditioning procedures

3.2 Dry vs Wet Mixing for Asphalt Substitution with Shredded PET

The asphalt mixture was substituted by replacing a portion of the asphalt with plastic. The substitution rate was determined based on the optimum asphalt content specified by the SNI 2489:2018, which was 5.5%. The 5.5% asphalt content was replaced with various weight ratios of plastic using both dry and wet mixing methods. Subsequently, the outcomes were juxtaposed with the results obtained from the OAC and aligned with Bina Marga regulations for comparison.

In the substitution of asphalt with PET using the dry mixing method, all varied percentages met the minimum 1000 kg standard stability requirement and demonstrated higher stability compared to the OAC's result, which stood at 1780.5 kg. The peak stability was attained with a 5% asphalt substitution, yielding 2071.86 kg, representing a 16.36% increase over the OAC's figure. Nevertheless, escalating asphalt substitution percentages led to a saturated mixture and decreased stability, evident in the cases of 6% and 8% asphalt substitution with PET, as indicated in Table 5. Similar outcomes were noted with higher asphalt content that was mentioned in the previous section. Concerning flow, all asphalt substitution percentages with PET using dry mixing methods fell within the permissible flow range, as shown in Table 5. Notably, the 8% asphalt substitution, yielding a 4 mm flow, hovered precisely at the upper limit. Furthermore, Table 5 illustrates that augmenting asphalt substitution with PET led to escalated flow rates, suggesting that PET enhanced the mixture's flexibility.

Moreover, as illustrated in Table 5, among the four asphalt substitution variations, only the 6% and 8% substitutions with PET plastic via dry mixing failed to meet void requirements. Specifically, the 6% substitution fell short of fulfilling the maximum VIM value, while the 8% substitution failed to meet both VIM and VFA regulations. Substituting asphalt with larger amounts of PET resulted in increased void presence in the mixture, evident in the VIM and VMA values. Furthermore, PET, when used as an asphalt substitute, failed to adequately occupy the voids within the mixture, as indicated by Table 5, wherein the VFA decreased with escalating asphalt substitution with PET. This outcome was likely attributable to the viscosity disparity between PET and asphalt, with PET being more viscous [71]. Additionally, this condition may also be influenced by unmelted PET, given its relatively high melting point, ranging from 250°C to 270°C [72].

Table 5. Marshall Test result of asphalt substitution with shredded PET waste by dry mixing method

PET Content	Stability (Min. 1000 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
0%	1780.50	3.70	3.96	15.42	74.44
2%	1972.84	3.60	4.60	15.95	71.40
5%	2071.86	3.73	4.80	16.20	70.50
6%	2013.80	3.82	5.50	16.77	67.30
8%	1735.89	4.00	8.90	19.74	55.50

When employing the wet mixing method to substitute asphalt with PET, the outcomes depicted in Table 6 mirrored those of Table 5, where the dry mixing method was utilized. Void content analyses revealed that the 6% and 8% substitutions exhibited elevated VIMs surpassing the maximum limit, while the 8% substitution's VFA fell below the minimum threshold. Conversely, for VMA, every percentage of asphalt substitution in Table 5 successfully met the minimum requirement. Flow characteristics resembled those observed with the dry mixing method, wherein higher substitution rates corresponded to increased flow. However, in this instance, the 6% and 8% substitutions using the wet method demonstrated slightly higher flow, surpassing the maximum 4 mm limit. Lastly, the highest stability was attained with a 5% substitution using the wet mixing method, yielding 2286.5 kg, marking a 28.42% increase compared to the OAC's stability.

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Table 6. Marshall Test result of asphalt substitution with shredded PET waste by wet mixing method

PET Content	Stability (Min. 1000 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
0%	1780.50	3.70	3.96	15.42	74.44
2%	2161.94	3.73	4.50	15.90	71.50
5%	2286.50	3.80	4.90	16.30	70.00
6%	2139.07	4.03	5.40	16.68	67.70
8%	1945.53	4.17	8.70	19.60	55.70

Overall, Tables 5 and 6 demonstrate that substituting asphalt with PET, whether through dry or wet mixing methods, yielded increased stability but compromised the interior structure, as evidenced by VIM, VMA, and VFA values. While asphalt-PET substitution enhanced mixture adhesiveness and cohesiveness, it concurrently elevated void content, increasing susceptibility to oxidation. Notably, higher stability was achieved through the wet mixing method, as depicted in Figure 7. Examination of the wet mixing process revealed that before aggregate addition, most melted plastics settled at the bottom of the pan, overlaid by asphalt. This sequence most likely facilitated early interaction between asphalt and aggregate, resulting in asphalt-coated aggregate. Through the stirring process, melted plastic in contact with the asphalt-coated aggregate strengthened bond integrity and enhanced stability. Conversely, the dry mixing method led to shredded plastic entangling with fine aggregate, impeding its attachment to coarse aggregate. Subsequent asphalt addition covered coarse aggregate, while plastic agglomerates formed with fine aggregate, creating a flexible coarse-sized aggregate substitute, which still contributed to a tougher mixture. However, it is essential to note that these conclusions necessitate further investigation.

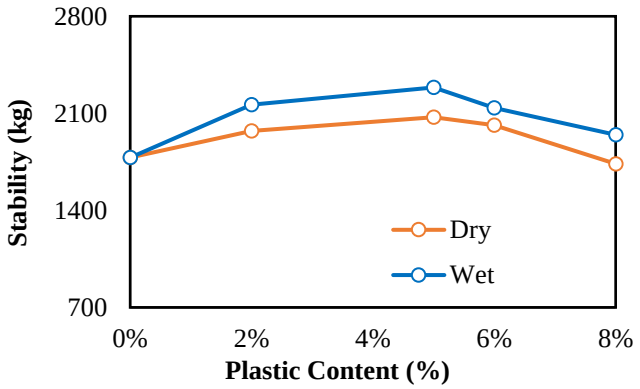


Figure 7. Stability comparison of dry vs. wet mixing methods for PET

3.3 Dry vs Wet Mixing for Asphalt Substitution with LDPE Pellet

Table 7 shows the Marshall Test results and the void components of samples using LDPE pellets as an asphalt substitute with the dry mixing method. It was found that the highest stability was obtained at 9% substitution with 2759.78 kg, 55% higher than that of the OAC's. At 11% substitution, the stability decreased by 391.22 kg. Thus, the 9% substitution was the saturation point or the limit for increasing stability by substituting more asphalt with plastic. Moreover, it was found that increasing the substitution rate did not always increase the flow, which was uncertain in this case. By 9% substitution, the highest flow of 3.77 mm was achieved, only 0.07 mm higher than that of the OAC's. Regarding the void components, except for the VIM of 11% substitution, the remaining void components: VIM, VMA, and VFA fulfilled the regulated value by Bina Marga. Thus, 9% substitution was the optimum rate for substituting asphalt with LDPE through dry mixing method. Despite its impact on improving the stability of the mixture, substituting asphalt with LDPE decreased the interior condition. This finding was like the result of substituting asphalt with PET, which increased both the VIM and VMA while decreasing the VFA.

Table 7. Marshall Test result of asphalt substitution with virgin LDPE pellet by dry mixing method

Asphalt Content	Stability (Min. 1000 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
0%	1780.50	3.70	3.96	15.42	74.44
5%	2145.89	3.55	4.10	15.56	74.00
8%	2547.25	3.67	4.56	15.95	71.40
9%	2759.78	3.77	4.63	16.01	71.10
11%	2368.56	3.73	5.56	16.83	67.00

Table 8 presents the results of asphalt substitution with LDPE using the wet mixing method. The highest stability, at 2640.14 kg, was achieved with 11% substitution, representing the highest substitution rate. Consequently, there is still a possibility to achieve a higher stability. Regarding the flow of the samples, findings were akin to those of the dry mixing method, showing no tendency for an increase in flow with higher substitution rates. In this scenario, the highest flow, at 3.87 mm, was observed for 11% substitution, slightly surpassing the flow observed for asphalt substitution with LDPE using the dry mixing method but remaining within the permissible range. Furthermore, concerning void contents, 9% substitution exceeded the maximum limit of VIM, while 11% substitution failed to meet requirements for both VIM and VFA values. Thus, the optimum substitution rate with LDPE using the wet mixing method was 8% with a stability of 2487.71 kg. The concern of void mirrors results from other substitutions, where plastics inadequately replaced asphalt in filling the voids within the mixture, leading to elevated VIM and VMA values and a reduced VFA.

Table 8. Marshall Test result of asphalt substitution with virgin LDPE pellet by wet mixing method

Asphalt Content	Stability (Min. 1000 kg)	Flow (2-4 mm)	VIM (3-5%)	VMA (Min. 15%)	VFA (Min. 65%)
0%	1780.50	3.70	3.96	15.42	74.44
5%	2368.70	3.60	3.70	15.20	76.00
8%	2487.71	3.80	4.95	16.30	69.70
9%	2494.46	3.67	5.10	16.46	68.80
11%	2640.14	3.87	7.00	18.10	62.00

Unlike substitution with PET, where the wet mixing method showed better performance, substitution with LDPE demonstrated superior performance using the dry mixing method. Specifically, compared with the wet method, the dry mixing method achieved higher stability values at 8% and 9% LDPE content, with increases of 59.54 kg and 265.32 kg, respectively, as shown in Figure 8. The higher stability observed for LDPE can be attributed to its lower melting temperature compared with PET. Under the mixing and compaction temperatures applied in this study, LDPE could soften and redistribute within the mixture, allowing better contact with the surrounding aggregate and asphalt binder [29]. In contrast, PET remained predominantly in particulate form because its melting temperature was substantially higher than the temperatures applied during mixing and compaction [73]–[74]. This difference in physical state have allowed LDPE to achieve better distribution within the mixture and contribute more effectively to load transfer, resulting in higher stability compared with PET.

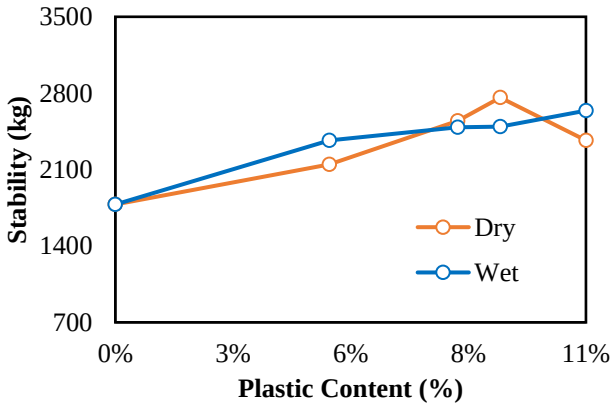


Figure 8. Stability comparison of dry vs. wet mixing methods for LDPE

3.4 Stability Comparison: Shredded PET Waste vs. LDPE Pellet

The results presented in Figure 9 clearly highlight the contrasting performance of PET and LDPE in asphalt mixtures. LDPE generally exhibited higher stability values than PET across the investigated mixing methods and substitution ranges, while PET showed a noticeable decline in stability at higher contents, particularly at 8% in the dry mixing method. This reduction indicates that PET may have exceeded its optimum dosage, leading to a loss of mixture integrity.

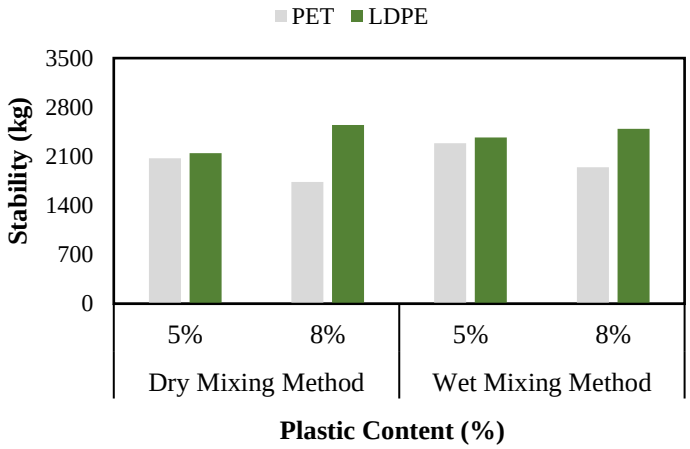


Figure 9. Stability comparison of PET vs. LDPE through dry and wet mixing methods

The addition of plastic waste resulted in an increase in Marshall stability compared with the control mixture, which recorded 1780.50 kg. For the dry mixing method, the highest stability for PET was obtained at 5% substitution, reaching 2071.86 kg or 16.36% higher than the control. In comparison, 9% LDPE resulted in the highest stability of 2759.78 kg, representing a 55% increase. A similar trend was observed for the wet mixing method, where 5% PET increased the stability to 2286.50 kg (28.4%), while 8% LDPE increased the stability to 2487.71 kg (39.7%). Overall, LDPE provided a greater improvement in stability than PET for both mixing methods, with the dry method showing the highest increase.

Previous studies have also reported that LDPE can improve the Marshall stability of asphalt mixtures up to a certain plastic content, beyond which the stability tends to decrease. Almeida et al. [44] reported improved Marshall performance with the incorporation of LDPE flakes into asphalt concrete. In their study, 6% LDPE by weight of bitumen was selected based on the Marshall and volumetric properties, with the modified mixture showing higher stability and lower flow than the reference mixture. Similarly, Lubis et al. [75] observed an increase in Marshall stability up to 8% LDPE, after which the stability decreased. In the present study, LDPE showed a comparable increasing trend, with the highest stability obtained at 9% for dry mixing. For the wet mixing method, stability continued to increase up to 11%; however, this content did not satisfy the required volumetric properties. Therefore, considering both stability and volumetric requirements, 8% was selected as the optimum LDPE content for the wet method. The difference in the stability peak between the present study and previous investigations may be related to differences in plastic form, mixture composition, and mixing procedure.

Previous studies have also reported that the performance of PET-modified asphalt does not continuously increase with increasing PET content. Mashaan et al. [76] reported that waste PET increased Marshall stability compared with the unmodified mixture, with the modified mixture showing improved performance up to 8% PET. Similarly, a recent study on PET-modified asphalt mixtures identified 4% PET as the optimum content based on the balance of stability, flow, and density [77]. In the present study, 5% PET provided the highest stability under both dry and wet mixing conditions. Although the optimum contents differed among studies, these results indicate that the effect of PET is dependent on the plastic content and mixture characteristics.

The superior performance of LDPE compared to PET can be primarily attributed to differences in their thermal and physical properties, which significantly influence their interaction with the asphalt binder. LDPE has a relatively low melting temperature, allowing it to melt and disperse effectively within the typical asphalt mixing temperature range [40]. This enables LDPE to form a more homogeneous blend with the binder, improving coating, adhesion, and the overall viscoelastic behavior of the mixture [78]. Previous studies have reported that polyethylene-based modifiers can enhance the stiffness and deformation resistance of asphalt mixtures due to their ability to integrate well within the binder matrix [79]−[80].

In contrast, PET possesses a much higher melting temperature, which is not achieved under conventional mixing conditions. As a result, PET does not fully melt but remains in a semi-rigid or particulate form within the mixture. This may limit PET dispersion and interfacial interaction with the binder under certain mixing conditions, causing PET to act predominantly as a particulate modifier rather than forming a fully homogeneous polymer–binder blend. Several studies have also indicated that PET–asphalt interaction is predominantly physical, with limited compatibility and bonding at the interface, especially under standard mixing temperatures [13], [23], [79]. Fourier Transform Infrared Spectroscopy (FTIR) analysis has shown no significant formation of new functional groups, suggesting that the interaction between PET and asphalt binder is mainly physical rather than chemical in nature [23].

Additionally, the difference in dispersion and compatibility affects the internal structure of the mixture. LDPE, in its molten state, can distribute more uniformly and enhance stress transfer across the matrix [81]−[82], resulting in higher stability [29]. On the other hand, PET particles may create localized stress concentrations and weaker interfacial bonding, which can reduce the overall mechanical performance. These findings are consistent with previous research highlighting the importance of polymer melting behavior and compatibility in determining the effectiveness of asphalt modification [83].

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While the qualitative trends provide initial insight into the performance differences, a more quantitative assessment is required to better define the relationship between plastic content and stability. To further quantify the observed trends in Marshall stability, polynomial regression analysis was conducted for all mixtures. The relationship between plastic content and stability can be expressed using second-order polynomial equations, as presented in Figure 10. The regression models showed strong correlations, with coefficients of determination (R^2) ranging from 0.892 to 0.967, indicating that the models adequately represent the experimental data.

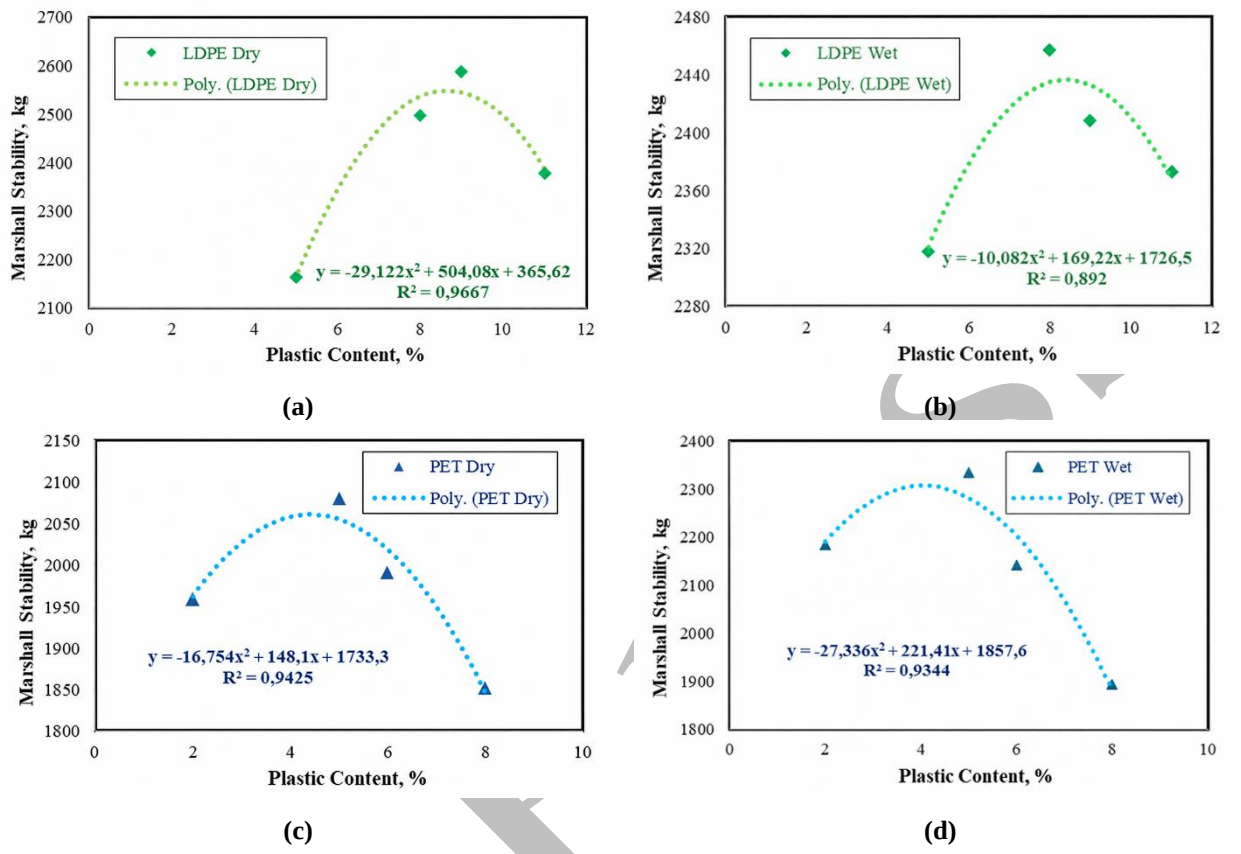


Figure 10. Modeled relationship between plastic content and Marshall stability using polynomial regression for PET and LDPE mixtures under dry and wet mixing conditions **(a)** LDPE Dry **(b)** LDPE Wet **(c)** PET Dry **(d)** PET Wet

The regression results further indicate that the effect of plastic content was not linear and that excessive plastic addition could reduce mixture stability. The optimum content for LDPE was observed at approximately 8–9%, while PET reached its optimum at a lower range of around 4–5%. Beyond these values, a decline in stability was observed, particularly for PET, indicating a higher sensitivity to excessive plastic content. In addition, LDPE showed a smoother curve and less pronounced reduction after the optimum point, suggesting better tolerance to variations in plastic content compared to PET.

The observed differences between dry and wet mixing methods further support the role of interaction mechanisms in determining mixture performance. In general, the wet method allows better dispersion of low-melting polymers such as LDPE, while the dry method tends to rely on physical coating, particularly for high-melting materials like PET. This difference contributes to the variation in stability observed in this study.

3.5 Mechanism of Plastic Asphalt Interaction

To better understand the differences observed between PET- and LDPE-modified mixtures, particularly in terms of stability and overall performance, it is important to consider how these materials interact with the asphalt binder. For LDPE, its relatively low melting temperature allows it to melt and disperse within the asphalt matrix during the mixing process, particularly at the mixing temperature of 158–160 °C used in this study. From a molecular perspective, polymer chains can interact with the lighter maltene fractions of bitumen at elevated temperatures, promoting the formation of a more homogeneous polymer–binder system. The compatibility between the polymer and bitumen is also influenced by the difference in solubility parameters ($\Delta\delta$), where a smaller difference generally indicates better compatibility. As a result, the molten LDPE can become more uniformly distributed within the binder and contribute to better interfacial contact and stress transfer. This mechanism provides a possible explanation for the higher stability observed in LDPE-modified mixtures in the present study. However, previous SEM observations have also revealed localized surface microcracks and discontinuities in the LDPE matrix, as illustrated in Figure 11 [31], [84], indicating that the degree of polymer dispersion and compatibility may vary depending on material composition and processing conditions.

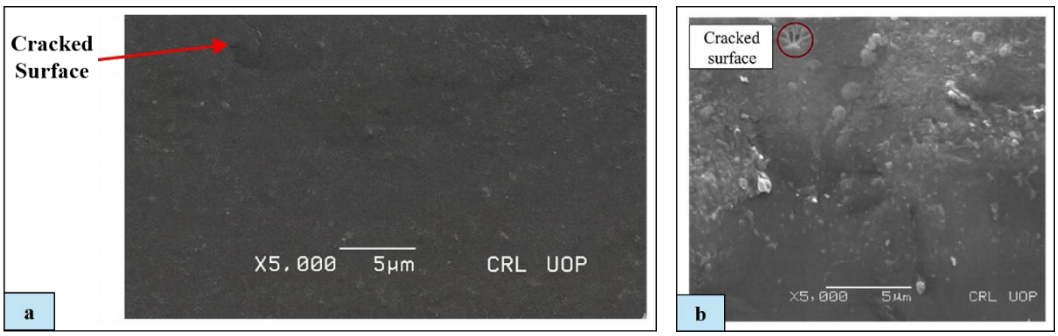


Figure 11. SEM micrographs of 6% LDPE-modified bitumen from previous studies: **(a)** 6% LDPE-modified bitumen exhibiting localized surface microcracks [84] ; **(b)** 6% LDPE-modified bitumen showing surface microcracks and a discontinuous LDPE matrix [31]

In contrast, PET behaves differently due to its substantially higher melting temperature (approximately 250 °C), which is not reached under the mixing temperature of 158–160 °C applied in this study. Consequently, PET particles did not fully melt and remained predominantly in solid form during mixing. Nevertheless, previous studies have demonstrated that PET can physically interact with asphalt despite this temperature limitation. Li et al. [23] reported that waste PET particles could swell within the asphalt binder, forming a network-like structure and reducing the distinction between the PET and asphalt phases. Such morphological characteristics suggest physical interaction and closer contact between PET and the surrounding bitumen. Furthermore, Fahmy et al. [52] investigated PET-modified hot mix asphalt using scanning electron microscopy (SEM) and reported that PET was well distributed throughout the asphalt mixture. These findings suggest that PET incorporation can influence asphalt microstructure through physical dispersion and interaction, although the resulting morphology depends on the material composition and processing conditions.

As illustrated in Figure 12(a), the SEM micrograph reported by Li et al. [23] shows a network-like structure associated with the swelling of waste PET within the asphalt binder. The less distinct interface between PET and asphalt suggests physical interaction between the two phases. Meanwhile, Figures 12(b) and 12(c), obtained from Fahmy et al. [52], illustrate the microstructure of PET-modified hot mix asphalt at magnifications of ×1,500 and ×500, respectively. The micrographs provide observations of the mixture morphology at different scales, while the original study reported a relatively uniform distribution of PET within the asphalt mixture. These findings highlight the role of physical interaction and particle distribution in the microstructural characteristics of PET-modified asphalt materials.

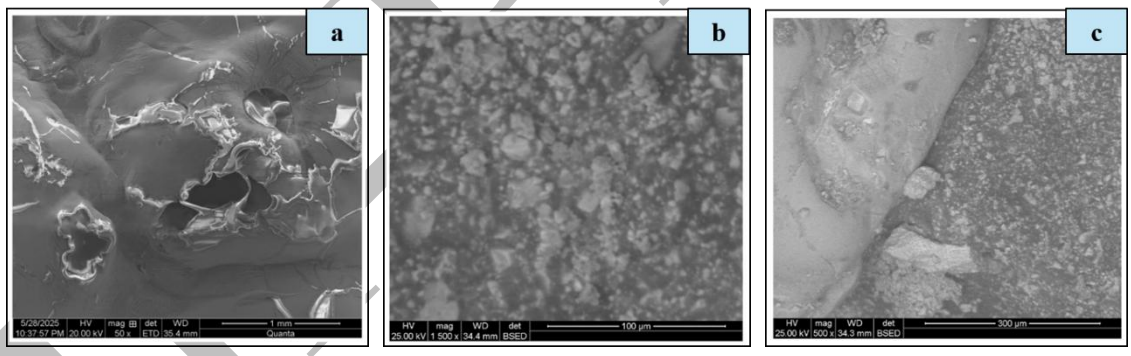


Figure 12. SEM micrographs of PET-modified asphalt materials from previous studies: **(a)** Waste PET-modified asphalt exhibiting a swollen PET network structure and tighter PET–asphalt interfacial contact [23]; **(b)** PET-modified hot mix asphalt at ×1,500 magnification [52]; **(c)** PET-modified hot mix asphalt at ×500 magnification [52]

These differences in melting behavior and dispersion can lead to distinct internal structures within the asphalt mixtures. LDPE, due to its ability to melt and blend with the binder, can promote a more uniform and cohesive matrix, contributing to improved stability. On the other hand, PET tends to remain as a more rigid dispersed phase, which may introduce localized stress concentrations and reduce the effectiveness of load distribution, particularly at higher substitution levels. These differences in material behavior and phase interaction provide a possible explanation for the higher stability obtained with LDPE compared with PET under both dry and wet mixing conditions in the present study.

3.6 Statistical Analysis of Marshall Parameters

To further examine the influence of plastic content on the Marshall characteristics, a one-way analysis of variance (ANOVA) was conducted for each parameter. This analysis was intended to determine whether the observed variations in stability, flow, and volumetric properties (VIM, VMA, and VFA) were statistically significant across different plastic contents. The null hypothesis assumes that changes in plastic content do not affect the measured parameters, while the alternative hypothesis suggests that at least one variation produces a significant difference. In this study, a significance level of 0.05 was adopted, meaning that a p-value below 0.05 indicates that the differences are unlikely to have occurred

by chance. In addition to statistical significance, the effect size (η^2) was also considered to evaluate the magnitude of the influence of plastic content on each parameter. The results of the ANOVA analysis are presented in Table 9.

Table 9. Summary of ANOVA results for Marshall parameters

Plastic	Mixing Method	Parameter	ANOVA Result			Interpretation
			F	P-Value	η^2	
PET	Dry	Stability	3.395	0.053	0.576	*Moderate, not significant*
		Flow	0.695	0.612	0.218	*Weak, not significant*
		VIM	41.628	0.000	0.943	*Strong, significant*
		VMA	92.272	0.000	0.974	*Strong, significant*
		VFA	7.607	0.004	0.753	*Strong, significant*
	Wet	Stability	31.339	0.000	0.926	*Strong, significant*
		Flow	0.828	0.537	0.249	*Weak, not significant*
		VIM	11.040	0.001	0.815	*Strong, significant*
		VMA	0.998	0.453	0.285	*Weak, not significant*
		VFA	9.081	0.002	0.784	*Strong, significant*
LDPE	Dry	Stability	11.223	0.001	0.818	*Strong, significant*
		Flow	0.134	0.966	0.051	*Negligible*
		VIM	1.528	0.267	0.379	*Moderate, not significant*
		VMA	1.539	0.264	0.381	*Moderate, not significant*
		VFA	1.354	0.317	0.351	*Moderate, not significant*
	Wet	Stability	2.053	0.162	0.451	*Moderate, not significant*
		Flow	0.344	0.842	0.121	*Weak*
		VIM	2.733	0.090	0.522	*Moderate, strong*
		VMA	2.721	0.091	0.521	*Moderate, strong*
		VFA	2.894	0.079	0.537	*Moderate, strong*

As shown in Table 9, the statistical results reveal distinct patterns depending on the type of plastic and mixing method. For PET-modified mixtures, significant differences are observed in several parameters, particularly VIM ($F = 41.628$, $p < 0.001$, $\eta^2 = 0.943$), VMA ($F = 92.272$, $p < 0.001$, $\eta^2 = 0.974$), and VFA ($F = 7.607$, $p = 0.004$, $\eta^2 = 0.753$), all indicating strong effect sizes. This suggests that PET has a substantial influence on the internal structure of the asphalt mixture. In terms of mechanical performance, stability shows a significant improvement under the wet mixing method ($F = 31.339$, $p < 0.001$, $\eta^2 = 0.926$), confirming that PET interacts more effectively with asphalt when pre-blended prior to aggregate addition.

In contrast, LDPE-modified mixtures display a more limited statistical response. A significant effect is only observed in stability for the dry mixing method ($F = 11.223$, $p = 0.001$, $\eta^2 = 0.818$), while other parameters such as flow, VIM, VMA, and VFA show no statistically significant differences ($p > 0.05$). This indicates that LDPE primarily enhances the strength of the mixture without significantly altering its volumetric properties. Furthermore, the wet mixing method for LDPE shows no significant effect across all parameters ($p > 0.05$), suggesting that this method may not provide sufficient interaction between LDPE and asphalt.

These findings indicate that PET exhibits a broader and more consistent influence across both mechanical and volumetric properties, whereas LDPE shows a more selective effect, primarily improving stability under dry mixing conditions.

4. Conclusions

Indonesia is one of the largest contributors to plastic waste in the world. Incorporating plastic waste into asphalt mixtures offers an innovative approach to enhance mechanical properties such as durability and crack resistance. In this study, Optimum Asphalt Content (OAC) was determined following ASTM D6927-22 and SNI 2489:2018 standards, yielding a uniform OAC of 5.5%. ASTM-conditioned samples generally showed higher stability, likely due to better asphalt adhesion after immersion. Shredded PET and LDPE pellets were used as partial asphalt replacements through dry and wet mixing methods. Both plastics improved mixture stability, surpassing the minimum 1000 kg requirement by Bina Marga. PET exhibited the highest influence on mixture performance, particularly in VIM, VMA, and VFA, as confirmed by one-way ANOVA (e.g., VIM $F = 41.628$, $p < 0.001$, $\eta^2 = 0.943$), indicating strong effect sizes across both volumetric and mechanical properties. PET substitution achieved maximum stability at 5.0% for both mixing methods, with wet mixing yielding the highest stability (2286.5 kg, 28.42% above OAC). LDPE showed a more selective effect, significantly improving stability under dry mixing (2759.78 kg, 55% above OAC) but with non-significant changes in other parameters (flow, VIM, VMA, VFA), highlighting a moderate effect size. Both substitutions increased void content, suggesting

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enhanced adhesiveness and cohesiveness but insufficient void filling, which may affect long-term oxidation resistance. Overall, ANOVA results confirm that PET has a broader and more consistent impact on asphalt mixture properties than LDPE, and the choice of mixing method further influences the effectiveness of plastic incorporation. Further investigation into the interaction between plastic type, substitution rate, and mixing method is recommended to optimize high-performance asphalt mixtures.

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Declaration of Competing Interests
All authors certify that they have no affiliations with any organisation with a financial or non-financial interest in the subject matter of this manuscript'

CRediT Author Contribution Statement
Ravlesya Dian Elaiza Wibowo (Formal analysis; Revision; Writing—original draft preparation; Editing)
Kushendarsyah Saptaji (Conceptualisation; Validation; Supervision)
Farid Triawan (Data curation; Resources)
Rindu Twidi Bethary (Project administration; Validation; Data curation)
Wan Noor Hin Mior Sani (Writing – review; Editing)

Availability of Data and Materials
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Disclosure
No generative artificial intelligence tools were used in the preparation of this manuscript. All intellectual content is original and solely attributable to the authors.

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