

SUSTAINABLE PAVEMENT DEVELOPMENT THROUGH PLASTIC BOTTLE WASTE UTILIZATION: A PERFORMANCE AND COST ANALYSIS

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Abstract

Indonesia is ranked among the top eight countries contributing the largest amount of plastic waste globally, producing approximately 3.4 million tons annually. One potential strategy to address this issue is the utilization of plastic waste in asphalt mixtures, which can enhance road infrastructure performance. This study employs mineral water bottle waste made of Polyethylene Terephthalate (PET), which is abundantly available but remains underutilized. In this research, PET was substituted into AC-WC asphalt mixtures using the wet mixing method with variations of 0%, 2%, 5%, 6%, and 8%. Each variation was tested using the Marshall method at the optimum asphalt content (OAC) to evaluate the mixture characteristics. Unlike previous studies that mainly emphasized technical aspects, this research also considers cost efficiency. The findings indicate that the optimum level was achieved at 5% PET, which increased the mixture strength by up to 28.44% compared to conventional asphalt, while reducing construction costs by as much as 2.02%. These results demonstrate that incorporating mineral water bottle waste not only improves pavement strength but also offers economic benefits and supports efforts to reduce plastic waste.

Keywords: asphalt modification; cost efficiency; mineral water bottle waste; pavement strength; Polyethylene Terephthalate (PET).

1. INTRODUCTION

Plastic pollution has become an urgent global issue over the past few decades. Indonesia is currently ranked as the eighth-largest contributor to global plastic waste, generating approximately 3.4 million tons per year (World Population Review, 2022). A significant portion of this waste—particularly Polyethylene Terephthalate (PET) plastic bottles, which are known for their low biodegradability—ends up in landfills without proper treatment. This situation not only contaminates the environment but also creates health and social problems, highlighting the need for innovative approaches to recycle plastic waste into value-added materials. One promising solution is the utilization of plastic waste as a modifier in asphalt mixtures for road construction. This approach not only helps reduce environmental pollution but is also expected to enhance pavement performance.

The use of PET in asphalt mixtures has shown technical, economic, and environmental benefits. Alwi, Sudibyo, and Herni (2020), reported that adding PET to asphalt increases Marshall stability, with an optimum PET content of 2% by asphalt weight. Modarres and Hamedi (2014), further demonstrated that PET-modified mixtures exhibit improved moisture resistance and longer pavement service life. Additionally, the incorporation of plastic supports sustainability programs in road infrastructure development (Mikhailenko et al. 2021). More specifically, PET

particles within the size range of 2.36–1.18 mm have been shown to improve volumetric properties, Marshall parameters, and resistance to moisture-induced damage (Choudhary, Kumar, and Murkute 2018). Other studies observed that substituting 6–8% of asphalt with PET increased resistance to rutting, aging, and fatigue cracking (Mashaan et al. 2021) as well as enhancing fatigue life and moisture damage resistance (Li et al. 2021).

Two common approaches are used when incorporating plastic waste into asphalt mixtures: the wet mixing method and the dry mixing method (Saputro Dedy, Suparma Budi, and Satyarno Iman 2022). The wet mixing method blends shredded or melted plastic directly into the asphalt binder before combining it with aggregates. In this method, PET acts as a binder modifier that alters the rheological properties of asphalt, such as increasing its viscosity, stiffness, and bonding performance (Duarte and Faxina, 2021). In contrast, the dry mixing method introduces plastic particles into heated aggregates before adding the binder, where the PET functions more as a fine-aggregate substitute, filling voids and enhancing particle interlocking. Although dry mixing is simpler, does not require specialized equipment, and is easier to implement in the field, the resulting mixture tends to be less homogeneous compared to wet mixing, leading to lower resistance to moisture damage and fatigue cracking (Nur et al. 2021).

Despite these promising findings, many previous studies have focused primarily on plastic shapes, sizes, and mixing techniques, while economic feasibility—an equally important aspect of sustainable infrastructure—remains underexplored. Sustainable pavement development should be evaluated not only based on technical performance but also cost efficiency (Ayu S. E and Yulcherlina, 2020). The novelty of this research, therefore, lies in assessing both the mechanical improvements and the potential construction cost savings associated with using PET in asphalt mixtures.

This study aims to determine the extent to which PET bottle waste can enhance the strength of asphalt mixtures and whether PET-modified mixtures offer cost advantages over conventional asphalt. The proposed hypothesis is that an optimum PET content exists that can significantly improve mechanical performance while reducing overall construction costs. Accordingly, the objectives of this study are to evaluate the mechanical properties and economic efficiency of PET-modified asphalt mixtures and to determine the most effective PET content from both technical and economic perspectives. In this research, PET waste derived from shredded percentage that provided the highest performance improvements while maintaining compliance with AC–WC specifications.

2. MATERIALS AND METHODS

This study employed an experimental laboratory approach using the wet mixing method to investigate the influence of Polyethylene Terephthalate (PET) waste on the performance of asphalt mixtures. The primary materials consisted of 60/70 penetration asphalt binder and aggregates designed for Asphalt Concrete–Wearing Course (AC–WC) gradation. The plastic waste used in this research was sourced from discarded PET mineral water bottles, which were processed to serve as a partial replacement for the asphalt binder.

2.1. DETERMINATION OF OPTIMUM ASPHALT CONTENT (OAC)

The first stage of the research focused on determining the Optimum Asphalt Content (OAC). Marshall tests were conducted at several asphalt content variations to evaluate key performance parameters, including:

- Marshall Stability
- Flow value
- Voids in Mineral Aggregate (VMA)
- Voids in the Mix (VIM)
- Voids Filled with Asphalt (VFA)
- Marshall Quotient (MQ)

These parameters were analyzed collectively to determine the asphalt content that met the AC–WC specification requirements and provided the best balance between strength and flexibility. The selected OAC was then used as the baseline asphalt content for subsequent modification with PET.

2.2. PREPARATION OF PET WASTE MATERIAL

PET bottles were collected, cleaned thoroughly, and air-dried to remove impurities that could affect the bonding and homogeneity of the asphalt mixture. The bottles were then shredded into particles smaller than 0.5 cm to facilitate melting during mixing.

The PET particles were heated to approximately 250 °C, near their melting temperature, to ensure that they softened adequately and could blend uniformly with the hot asphalt binder. This step is critical for preventing clumping, improving dispersion, and enhancing the interaction between PET and the asphalt matrix.

2.3. WET MIXING PROCESS

The wet mixing method was used because it allows PET to act as a binder modifier rather than merely a filler. The process involved:

1. Heating PET particles to ~250 °C until they reached a semi-molten state.
2. Introducing the melted or softened PET into hot asphalt binder under continuous mechanical stirring.
3. Mixing the PET–asphalt blend until a homogeneous modifier-binder mixture was achieved.
4. Adding preheated AC–WC aggregates into the PET-modified asphalt binder.
5. Continuing the mixing process until all components were evenly coated and blended.

This method enhances binder rheology, increases viscosity and stiffness, and ensures better adhesion between binder and aggregate.

2.4. SPECIMEN PREPARATION

Test specimens were prepared in cylindrical form following the Marshall Standard Method. The PET modification levels used in this study were:

- 0% (control mix)
- 2% PET
- 5% PET
- 6% PET
- 8% PET

The percentages refer to the weight of asphalt binder.

In accordance with the Marshall mix design standard, three specimens were prepared for each PET content level to obtain representative average values.

Replicates were produced to enhance statistical reliability and allow the calculation of mean values and variability (e.g., standard deviation) for each performance parameter.

2.5. MARSHALL TESTING PROCEDURE

The prepared specimens were tested according to the Marshall method to assess the mechanical and volumetric properties of the mixtures. The parameters evaluated included:

- Marshall Stability (load-bearing capacity)
- Flow (deformation at failure)
- VIM (air voids in the mix)
- VFA (percentage of voids filled with asphalt)
- VMA (voids in mineral aggregate)
- Marshall Quotient (stability-to-flow ratio)

The analysis focused on identifying trends in strength, stiffness, and deformation characteristics as PET content increased. Special attention was given to determining the optimum PET percentage that provided the highest performance improvements while maintaining compliance with AC–WC specifications.

2.6. COST EFFICIENCY ANALYSIS

After identifying the optimum PET content, an economic evaluation was performed to quantify the potential cost savings associated with substituting a portion of asphalt binder with PET waste.

The cost analysis included:

- Comparison of material costs between conventional asphalt mix and PET-modified mix
- Reduction in asphalt binder consumption due to partial substitution with PET
- Economic implications for large-scale pavement construction
- Assessment of feasibility and sustainability from a cost–benefit perspective

This stage aimed to support a comprehensive evaluation of PET-modified asphalt not only in terms of mechanical performance but also in economic and environmental value.

3. RESULTS AND DISCUSSION

3.1. ASPHALT BINDER PROPERTIES

The asphalt binder used in this research was 60/70 penetration grade asphalt. A series of laboratory tests were conducted to determine its physical properties, including penetration (Standar Nasional Indonesia, 1991), flash and fire point (Badan Standarisasi Nasional, 2011), and viscosity (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2002).

The results, summarized in Table 1, indicate that the penetration value is within the required range of 60–70 (0.1 mm), with a measured value of 64.50 (0.1 mm). The flash and fire points were recorded at 336°C, significantly higher than the minimum requirement of $\geq 232^\circ\text{C}$, demonstrating adequate safety against ignition during mixing. The viscosity at 135°C was 426 cSt, exceeding the minimum specification of ≥ 300 cSt, indicating sufficient thickness and resistance to flow at elevated temperatures.

Overall, these results confirm that the asphalt binder meets the technical specifications for hot mix asphalt production and is suitable for blending with aggregates and PET plastic waste. In the mixing process, PET plastic was first heated to approximately 250°C to allow it to melt. After the PET had melted, the asphalt binder, which had been heated to approximately 155°C

(mixing temperature), was gradually added and mixed with the molten PET to obtain a more homogeneous binder before being blended with the aggregates.

Table 1. Asphalt binder properties

Test	Standard Method	Specification	Result
Penetration, 25°C (0.1 mm)	SNI 06-2456-1991	60–70	64.50
Flash & fire point (°C)	SNI 06-2433-2011	≥ 232	336
Viscosity at 135°C (cSt)	SNI 06-6441-2000	≥ 300	426
Mixing temperature (°C)	Mixing Temperature		155
Compaction temperature (°C)	Compaction Temperature		146

3.2. AGGREGATE TESTING

To ensure the quality and durability of the aggregates used in the asphalt mixture, several laboratory tests were conducted according to Indonesian and international standards. These tests evaluated physical and mechanical characteristics such as sulfate soundness, abrasion resistance, adhesion with asphalt, and impact resistance. The results are listed in Table 2.

Table 2. Aggregate test results

Test	Standard	Specification	Result
Soundness (Na ₂ SO ₄ & MgSO ₄)	SNI 3407:2008	Max.18%	0.18%
Los Angeles Abrasion (500 revolutions)	SNI 2417-2008	Max. 30%	17.70%
Adhesion to asphalt	SNI 2439-2011	Min. 95%	98%
Aggregate Impact Value (AIV)	BS EN 1097 – 2:2010	Max. 30%	8.95%

3.2.1. Sulfate Soundness

The soundness test result showed a weight loss of only 0.18%, far below the maximum allowable limit of 18%. This indicates excellent resistance to disintegration and weathering in the presence of sodium and magnesium sulfate solutions. The aggregates are therefore highly durable under repeated wet–dry cycles.

3.2.2. Abrasion Resistance

Abrasion testing using the Los Angeles machine with 500 revolutions in accordance with SNI 2417:2008 (Standar Nasional Indonesia, 2008). Resulted in a value of 17.70%, which is still below the specified maximum limit of 30%. This result indicates that the aggregate has good strength and wear resistance against traffic loads.

3.2.3. Adhesion Test

The aggregate–asphalt adhesion test based on SNI 2439:2011 (Standar Nasional Indonesia, 2011), showed a value of 98%, which is higher than the minimum requirement of 95%. This indicates that the aggregate has excellent adhesion capability to asphalt, thereby potentially improving the durability of the mixture.

3.2.4. Impact Resistance

The Aggregate Impact Value (AIV) was recorded at 8.95%, significantly below the maximum limit of 30% (British Standard 1990). This low AIV value reflects high aggregate toughness and excellent resistance to sudden impact loads, ensuring stability under dynamic traffic stresses.

Overall Evaluation, all aggregate tests produced results that not only meet but exceed the required specifications. This confirms that the aggregates are of high quality and suitable for producing AC–WC asphalt mixtures with enhanced stability and durability.

3.2.5. Aggregate Gradation

In this study, a continuously graded aggregate structure, commonly referred to as Asphalt Concrete Wearing Course (AC-WC), was employed. Figure 1 illustrates the gradation evaluation, demonstrating that the mixture conforms to a dense and continuous gradation pattern encompassing a full spectrum of coarse, intermediate, and fine aggregate fractions. Such a distribution ensures an optimal packing condition that enhances interparticle contact and mechanical interlock.

The presence of well-integrated aggregate fractions contributes to the formation of a strong internal structure, resulting in a stiffer pavement layer with superior resistance to deformation. This structural arrangement leads to improved stability under traffic loading, as the aggregates form a robust skeleton with reduced reliance on the asphalt binder for load support. Moreover, the minimized void spaces within the mixture help lower permeability, thereby reducing the potential for moisture-related damage.

Given these characteristics, the AC-WC gradation is highly suitable for wearing course applications, where high durability, rutting resistance, and structural integrity are essential.

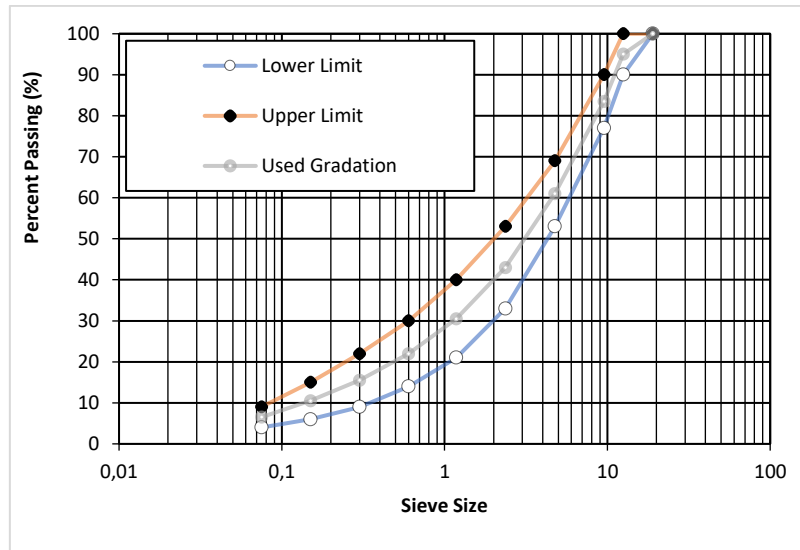


Figure 1. Aggregate gradation

3.3. OPTIMUM ASPHALT CONTENT

In the preparation of Marshall test specimens, the mixture composition is determined by the asphalt binder content. To obtain the optimum asphalt content, a series of Marshall tests is conducted using several asphalt content variations. As an initial estimate, the asphalt content can be predicted using Equation 1:

$$Pb = 0.035(\%CA) + 0.045(\%FA) + 0.18(\%FF) + C \quad (1)$$

Description:

- **Pb** = estimated asphalt content (percent by total weight of the mixture)
- **CA** = coarse aggregate (percent retained on No. 4 sieve)
- **FA** = fine aggregate (percent passing No. 4 sieve)
- **FF** = filler material (percent passing No. 200 sieve, with at least 75% meeting filler criteria)
- **C** = correction factor ranging from 0.5–1.0 for AC-WC mixtures

Based on this formula, the estimated asphalt content (Pb) obtained in this study was 5.49%. This predicted value was then validated experimentally through a series of Marshall tests using five asphalt content variations at increments of 0.5%, covering two values below and two values above the initial estimate. The asphalt contents tested were 4%, 4.5%, 5%, 5.5%, and 6%.

The optimum asphalt content (OAC) was determined through graphical analysis of the Marshall characteristics, which include Void in Mineral Aggregate (VMA), Void in Mixture (VIM), Void Filled with Asphalt (VFA), Marshall Stability, and Marshall Flow. The plotted graphs help

identify the range of asphalt contents that meet standard specifications, applying the Narrow Range Method to ensure consistency between all required parameters.

Based on the obtained optimum asphalt content, partial substitution of asphalt with plastic was conducted. In this study, PET plastic was incorporated at substitution levels of 0%, 2%, 5%, 6%, and 8% of asphalt weight. The selected variation range was designed to accommodate the potential need for both lower and higher substitution levels during experimental evaluation.

Marshall test results for the asphalt–plastic mixtures are presented in Table 3, while Figure 2 illustrates the procedure for selecting the optimum asphalt content (OAC), which was determined to be 5.5%. At this asphalt content, the mixture satisfies all standard requirements based on Marshall criteria, including stability, flow, VIM, VMA, and VFA, indicating that 5.5% is the most appropriate binder content for achieving balanced performance in terms of strength and durability.

Table 3. Summary of marshall test results for asphalt mixtures

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

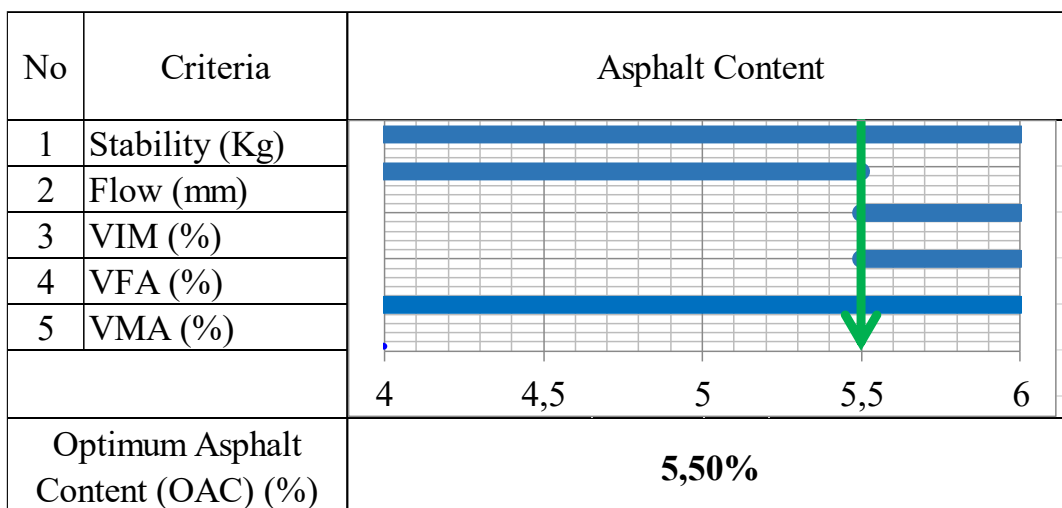


Figure 2. Narrow range graph for determining optimum asphalt content

3.4. MODIFICATION OF ASPHALT MIXTURES USING WASTE PLASTIC BOTTLES

The asphalt mixtures in this study were modified by replacing a portion of the asphalt binder with plastic waste. The substitution levels were determined based on the optimum asphalt content obtained following SNI 2489:2018 (Badan Standarisasi Nasional 2018). Experimental results showed that the Optimum Asphalt Content (OAC) for the control mixture was 5.5%. This optimum binder content was then partially replaced with various percentages of PET plastic using the wet mixing method, in which the plastic is blended into the hot asphalt binder before being mixed with aggregates.

The performance of each modified mixture was subsequently evaluated and compared with both the OAC mixture (without plastic) and the specifications set by Bina Marga (Indonesian Highway Agency) as performance benchmarks. The results of the Marshall tests for asphalt mixtures containing PET are presented in Table 4, while Figure 3 illustrates the trend and helps identify the optimum PET content, which was found to be 5%.

Table 4. Summary of marshall test results for asphalt mixtures with PET addition

PET Content	Stability (Min. 800 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

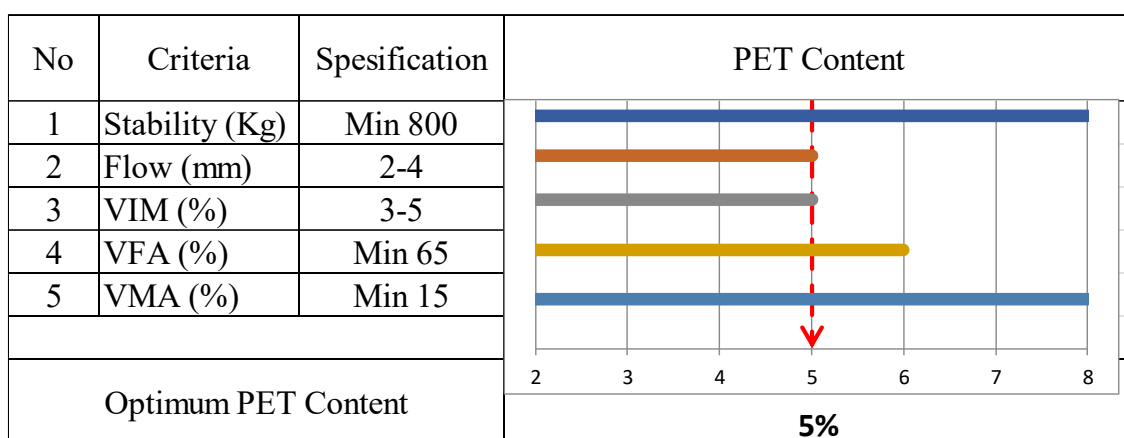


Figure 3. Narrow range graph of asphalt modified with PET

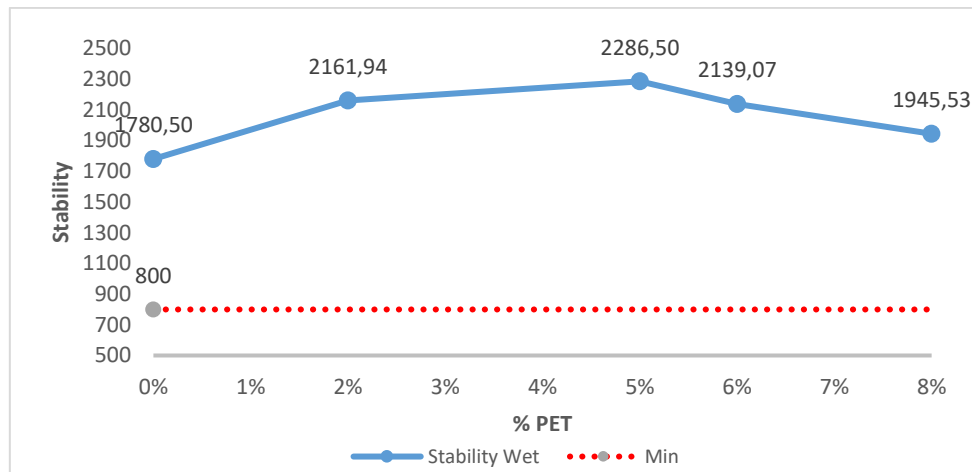


Figure 4. Graph of the relationship between PET addition and marshall stability

The results obtained using the wet mixing method show that the stability pattern of the mixture forms a parabolic curve, with the optimum point occurring at 5% PET content (Figure 4). Stability tends to increase as the asphalt and PET content increase, until it reaches a saturation point where stability begins to decline.

During the increasing phase, the melted plastic is able to fill the voids between aggregates while simultaneously strengthening the interparticle bonding through additional adhesion. This mechanism leads to an increase in stability of up to 28.44% compared with the conventional asphalt mixture, achieving a value of 2286.50 kg.

However, when PET content is increased to 6% and 8%, a portion of the plastic does not fully blend with the asphalt. This results in the formation of plastic layers or agglomerates that reduce the ability of the asphalt binder to coat the aggregates effectively, causing the stability to decrease again. This phenomenon is consistent with the corresponding changes in the void characteristics within the mixture.

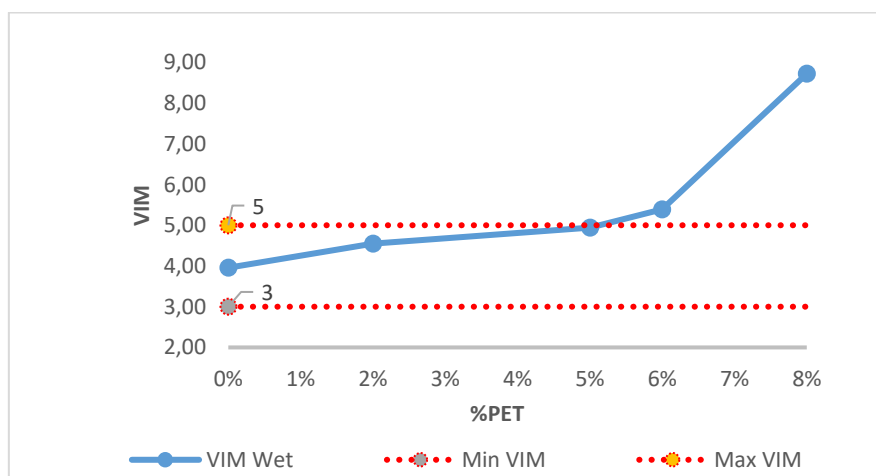


Figure 5. Relationship between PET content and VIM values

The Void in Mix (VIM) value represents the proportion of air voids contained within the asphalt mixture after compaction. Based on the test results, VIM increases as the PET content in the mixture rises. This phenomenon occurs because some plastic particles, especially at higher contents, do not melt completely during the mixing and compaction processes. As a result, these plastic particles act as solid inclusions that do not fully bond with the asphalt matrix or aggregate. This condition leaves empty spaces around the plastic particles, thereby increasing the total void volume in the mixture. In addition, the presence of plastic reduces the amount of effective asphalt that should fill the voids between aggregates, as part of the asphalt volume is replaced by plastic material. Consequently, the increase in VIM becomes more significant at higher plastic contents (Figure 5).

The increase in VIM directly leads to a reduction in the Void Filled with Asphalt (VFA) value, which represents the percentage of aggregate voids filled with asphalt. When the effective asphalt content decreases due to being replaced by plastic, the ability of asphalt to fill the voids becomes increasingly limited. This results in a lower proportion of voids being filled with asphalt, thereby decreasing the VFA value. The reduction becomes more pronounced at higher PET contents, and at 8% PET, the VFA value falls below the minimum requirement specified by the standards (Figure 6). This condition indicates that at excessively high plastic contents, the mixture loses its optimal ability to maintain cohesion between aggregate particles, which may ultimately reduce the stability and durability of the pavement.

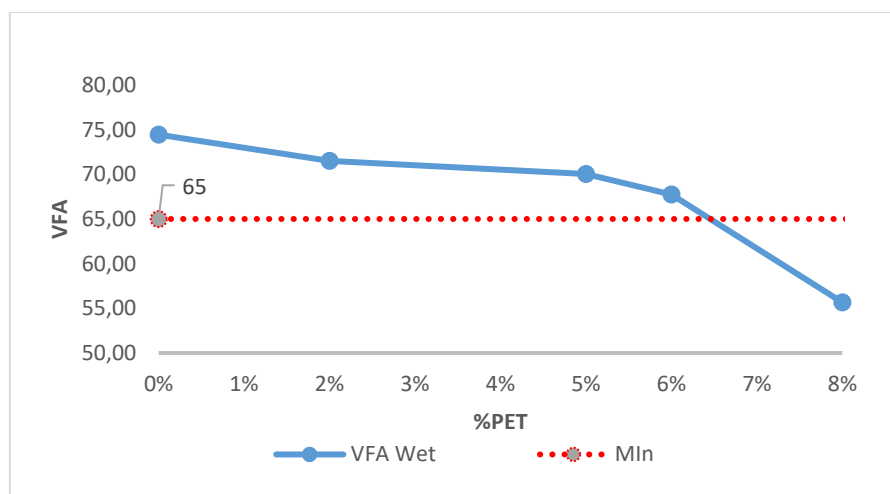


Figure 6. Relationship between PET content and VFA values

On the other hand, the Void in Mineral Aggregate (VMA) values at all substitution levels still meet the minimum requirements, as the aggregate gradation structure does not change

significantly. However, at higher PET contents, VMA tends to increase slightly due to the formation of additional voids resulting from plastic agglomeration (Figure 6).

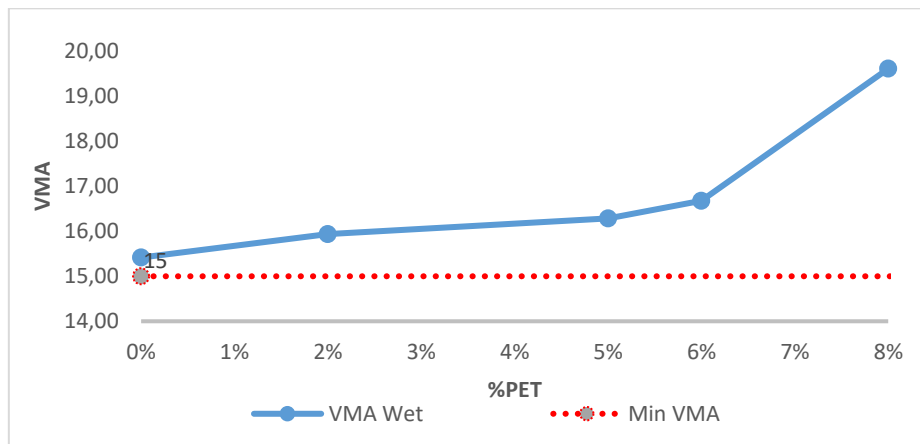


Figure 7. Relationship between PET content and VMA values

Meanwhile, the flow values show an increasing trend with the addition of PET (Figure 8). This occurs because plastic materials are more flexible than pure asphalt, making the mixture more plastic and more susceptible to deformation. At lower PET contents, this flexibility provides a positive effect by helping the mixture absorb stress. However, at 6% and 8% PET, the excessive amount of plastic makes the mixture too soft, causing the flow values to exceed the maximum limit of 4 mm. Thus, while the addition of PET can improve stability at its optimum content, using it in excessive quantities may reduce the internal structural quality of the mixture.

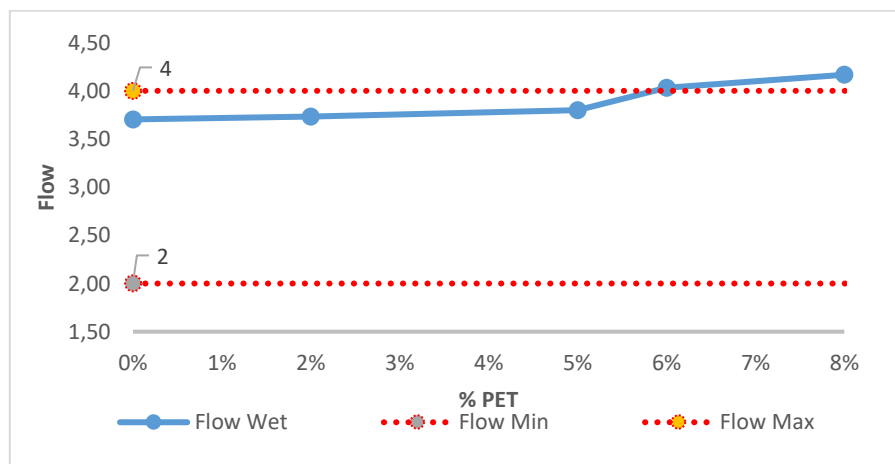


Figure 8. Relationship between PET content and flow values

3.5. COST EFFICIENCY ANALYSIS

The calculation of the mixture composition was carried out under the following assumptions:

- The total mass of the mixture is 2400 kg per 1 m³.
- The density of the mixture is 2.4 t/m³.

- The Optimum Asphalt Content (OAC) used is 5.5%, based on the narrow range graph from the Marshall test results.
- The total mass of asphalt is therefore $5.5\% \times 2400 \text{ kg} = 132 \text{ kg}$.
- For mixtures with PET, a 5% substitution of asphalt mass was applied:
 $0.05 \times 132 = 6.6 \text{ kg}$ of PET.
- Thus, the binder in the modified mixture consists of 125.4 kg of pure asphalt + 6.6 kg of PET.

Mixture Composition

In the conventional mixture (without PET), the material composition is as follows:

- Total mixture mass = 2400 kg
- Asphalt = 132.0 kg
- Coarse aggregate (39%) = 884.52 kg
- Medium and fine aggregate (54.5%) = 1236.06 kg
- Filler (6.5%) = 147.42 kg

Meanwhile, in the mixture with 5% PET substitution:

- Asphalt mass = 125.4 kg
- PET mass = 6.6 kg
- The aggregate composition remains unchanged:
 - Coarse aggregate (39%) = 884.52 kg
 - Medium and fine aggregate (54.5%) = 1236.06 kg
 - Filler (6.5%) = 147.42 kg
- The total mixture mass remains 2400 kg, indicating that modification occurs only in the binder, without altering the aggregate proportions.

Cost Analysis

The cost analysis was conducted to compare the material cost between the conventional asphalt mixture and the mixture incorporating 5% PET as a partial substitute for asphalt binder. The unit price of asphalt binder was assumed to be Rp 15,000 per kg.

Material Cost Calculation

For the conventional mixture, the asphalt binder requirement was 132 kg per unit mixture.

Therefore, the asphalt cost can be calculated as follows:

Pure asphalt mixture:

$$132 \text{ kg} \times \text{Rp } 15,000 = \text{Rp } 1,980,000$$

For the modified mixture containing 5% PET, the asphalt requirement decreased to 125.4 kg, resulting in the following cost:

Asphalt + PET mixture:

$$125.4 \text{ kg} \times \text{Rp } 15,000 = \text{Rp } 1,881,000$$

This substitution reduces asphalt consumption by 6.6 kg per unit mixture, which corresponds to a material cost saving of Rp 99,000 per m³.

Project Scenario Assumption

To illustrate the economic implication at the project level, a simplified road construction scenario was assumed with the following parameters:

- Pavement thickness = 5 cm
- Lane width = 3.5 m
- Road length = 1 km

The pavement volume can be calculated as:

$$Volume = thickness \times width \times length \quad (2)$$

$$Volume = 0.05 \times 3.5 \times 1000 = 175 \text{ m}^3$$

Based on this volume, the total construction cost can be estimated for both mixtures.

Table 5. Construction Cost Comparison Without PET Processing Costs

Type of Mixture	Cost per m ³ (Rp)	Volume (m ³)	Total Cost (Rp)	Cost Difference (Rp)
Conventional Asphalt	1,980,000	175	346,500,000	–
Asphalt + PET (5%)	1,940,400	175	339,500,000	7,000,000

The results show that using 5% PET in a one-lane road section of 1 km produces a cost saving of Rp 7,000,000, equivalent to 2.02% compared with the conventional asphalt mixture.

Although the percentage of savings appears relatively small, the economic benefit may become significant when applied to large-scale road construction projects.

PET Material Requirement

The reduction of asphalt binder by 6.6 kg per m³ implies that the same amount of PET is required as a substitute. For a pavement volume of 175 m³, the total PET requirement can be estimated as:

$$PET = 6.6 \times 175 \quad (3)$$

$$PET = 1,155 \text{ kg}$$

Thus, approximately 1.15 tons of PET waste are required for a 1 km road segment.

Additional Processing Cost Consideration

In the initial calculation, PET waste was assumed to have negligible material cost. However, in practical implementation several additional cost components may arise, including:

- collection and transportation of PET waste
- cleaning and drying processes
- shredding or size reduction
- additional energy required to heat PET to approximately 250°C
- potential increase in production time due to the wet modification process
- possible changes in workability affecting mixing and compaction efficiency

To illustrate a more realistic scenario, a simplified simulation was conducted by assuming an average processing cost of Rp 3,000 per kg of PET, which includes collection, cleaning, shredding, and heating energy.

A realistic assumption of plastic waste processing costs in Indonesia was applied in this analysis.

Table 6. Processing Cost of PET

Component	Estimated Cost
Collection and transportation	Rp 1,000/kg
Cleaning and drying	Rp 500/kg
Plastic shredding	Rp 700/kg
Heating energy up to 250°C	Rp 800/kg

The total PET processing cost is therefore:

$$1,000 + 500 + 700 + 800 = \text{Rp } 3,000/\text{kg} \quad (4)$$

Based on the PET requirement of 1,155 kg, the additional processing cost can be estimated as:

$$1,155 \times 3,000 = 3,465,000 \quad (5)$$

When the PET processing cost is included, the net cost saving becomes:

$$7,000,000 - 3,465,000 = 3,535,000 \quad (6)$$

Therefore, the total cost of the modified mixture becomes approximately:

Table 7. Construction Cost Comparison Including PET Processing Costs

Type of Mixture	Total Cost (Rp)
Conventional Asphalt	346,500,000
Asphalt + PET (including processing cost)	342,965,000

Under this scenario, the net cost saving decreases to approximately Rp 3,535,000, or about 1.02% compared with the conventional mixture.

The calculation results show that the use of 5% PET in a 1 km single-lane road segment produces a cost saving of IDR 7,000,000, which is equivalent to 2.02% compared with the conventional mixture. Although the percentage of savings is relatively small, the implication can become significant when applied to large-scale road construction projects. In addition, the use of PET also supports sustainability by reducing the consumption of virgin asphalt and providing an alternative approach for utilizing plastic waste in pavement infrastructure.

To strengthen the economic evaluation, an additional estimation of PET processing costs was also conducted. In practical implementation, PET waste requires several processing stages, including collection and transportation, cleaning and drying, material shredding, and heating prior to the mixing process. In this study, a simple processing cost of approximately IDR 3,000 per kg of PET was assumed. Based on an estimated PET requirement of approximately 1,155 kg for a 1 km road segment, the additional PET processing cost is estimated at IDR 3,465,000. Under this scenario, the net cost saving decreases from IDR 7,000,000 to approximately IDR 3,535,000, which is equivalent to about 1.02% of the total construction cost.

A sensitivity analysis was also conducted to evaluate the effect of variations in PET processing costs (Figure 9). If the processing cost increases to IDR 5,000 per kg, the additional cost would reach IDR 5,775,000, reducing the net saving to approximately IDR 1,225,000. Conversely, if the processing cost can be reduced to IDR 2,000 per kg through a more efficient recycling system, the net saving could increase to approximately IDR 4,690,000.

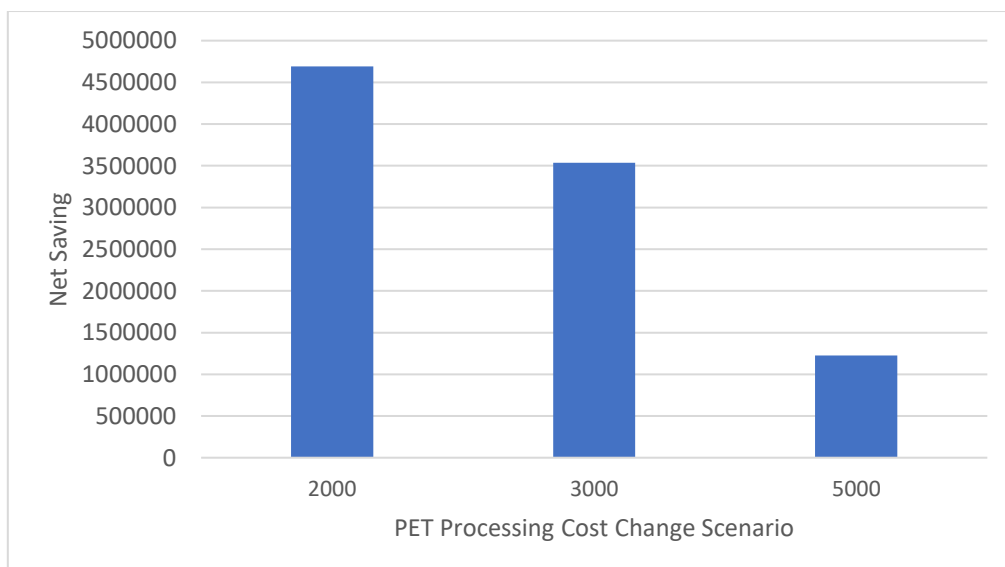


Figure 9. A Sensitivity Analysis Was Also Conducted to Evaluate the Effect of Variations in PET Processing Costs

Based on these scenarios, the break-even analysis (Figure 10) indicates that asphalt modification using PET still provides an economic benefit as long as the processing cost does not exceed approximately IDR 6,060 per kg of PET. If the processing cost exceeds this threshold, the total production cost of PET-modified asphalt mixtures would become equal to or even higher than that of conventional mixtures. Therefore, the economic feasibility of using PET in asphalt mixtures strongly depends on the efficiency of the plastic waste processing system as well as the energy consumption involved in the production process.

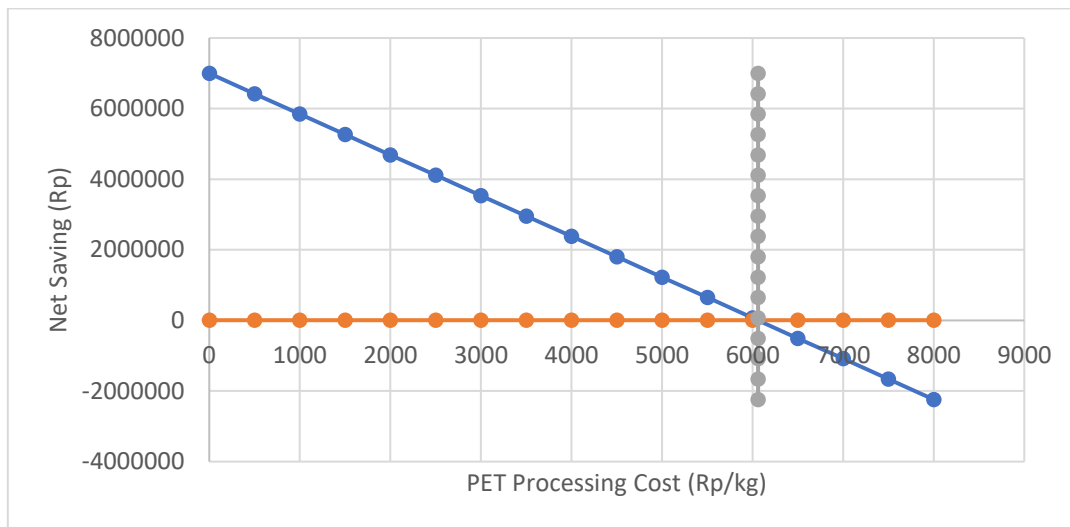


Figure 10. Break Even Analysis of PET Processing Cost

4. CONCLUSION

This study demonstrates that incorporating PET plastic bottle waste into asphalt mixtures using the wet mixing method can enhance pavement performance while also providing construction cost savings. At the optimum PET content of 5%, the mixture strength increased by 28.44% compared to conventional asphalt, while construction costs decreased by up to 2.02%. These findings offer a scientific contribution by presenting an environmentally friendly alternative for utilizing plastic waste as an additive material in road infrastructure. Future research may focus on evaluating long-term field performance and conducting a comprehensive environmental impact assessment, enabling wider and more sustainable implementation of PET in pavement applications.

5. ACKNOWLEDGEMENTS

The authors express their highest appreciation and gratitude to Sampoerna University and Universitas Jenderal Soedirman for their support in enabling this research to be carried out

successfully. The support in the form of laboratory facilities, collaborative opportunities, and a conducive academic environment greatly facilitated the research process. The authors also thank all parties who contributed, directly or indirectly, to the completion of this study.

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