Research in Education, Technology, and Multiculture

ISSN: 3025-6763 | Journal's DOI: 10.61436/rietm

Homepage: https://imrecsjournal.com/journals/index.php/rietm

Influence of Multilayer Plastic Waste Content and Mixing Process on the Marshall Stability of Asphalt Concrete Binder Course

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ARTICLE INFO

Article History:

Received: 26 October 2026

Accepted: 23 November 2026

Published: 29 November 2026

Keywords:

Asphalt Concrete–Binder Course;
Multilayer plastic waste;
Marshall Stability;
Wet process;
Dry process

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ABSTRACT

Using plastic waste as an asphalt modifier supports sustainable road pavement construction while reducing environmental pollution caused by the accumulation of plastic waste. One factor that influences the success of asphalt mixture modification is the mixing method, namely the wet process and the dry process. This study aims to compare the effects of these two methods on the Marshall Stability values of Asphalt Concrete–Binder Course (AC-BC) mixtures modified with multilayer plastic waste. The study was conducted experimentally in a laboratory using 60/70 penetration asphalt and varying levels of multilayer plastic waste at 3%, 4%, 5%, 6%, and 7% by weight of the binder. The mixtures were prepared using wet and dry processes and evaluated through Marshall testing in accordance with ASTM D6927-22 and the 2018 General Specifications for Road Construction, Revision 2. The results showed that the wet process yielded higher Marshall Stability values than the dry process across all plastic waste content variations. The optimum Marshall Stability value for the wet process was obtained at a 5% plastic content, amounting to 1,701 kg, whereas for the dry process, it was 1,262 kg at a 4% content. Furthermore, the error-bar analysis showed lower variability in the wet process results, indicating more consistent mixture performance than the dry process. These findings demonstrate that the wet process is more effective than the dry process in improving Marshall Stability and achieving more consistent mechanical performance in multilayer plastic waste-modified AC-BC mixtures. Therefore, the wet process offers a promising approach for incorporating multilayer plastic waste into asphalt pavement materials.

To cite this article:

Efendy, A., Hidayati, N., Muttaqin, A., Samengasbumi, R. P., Wahyuningsih, T., & Chilongola, F. D. (2026). Influence of multilayer plastic waste content and mixing process on the marshall stability of asphalt concrete binder course. *Research in Education, Technology, and Multiculture*, *5*(4), 457-469. doi: https://doi.org/10.61436/rietm/v5i4.pp457-469

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■ INTRODUCTION

Road infrastructure is a key component of the transportation system, playing a vital role in improving public mobility, facilitating the distribution of goods and services, and driving a region's economic growth. High-quality road infrastructure has been shown to improve regional connectivity, support cost-efficient logistics, and strengthen national economic competitiveness (Varghese & Pradhan, 2025). Therefore, improving the quality of road pavement construction has become a key focus in sustainable infrastructure development.

Based on the aforementioned considerations, this study addresses the following research question: How does the mixing method (wet process and dry process) influence the Marshall Stability of AC-BC mixtures incorporating different contents of multilayer plastic waste (3%, 4%, 5%, 6%, and 7% by weight of asphalt binder)? This study hypothesizes that the wet process produces higher Marshall Stability values than the dry process due to potentially better dispersion of plastic waste within the asphalt binder. Therefore, this study experimentally investigates and compares the effects of both mixing methods to identify the more effective approach for improving the mechanical performance of multilayer plastic waste-modified AC-BC mixtures.

In flexible pavement systems, the Asphalt Concrete–Binder Course (AC-BC) layer functions as a structural layer that receives and distributes traffic loads from the surface layer to the layers beneath it.

According to the General Specifications for Road and Bridge Construction, AC-BC mixtures must satisfy specific technical requirements, including Marshall Stability and other mixture performance parameters (Directorate General of Highways, 2020). Adequate stability is essential to resist permanent deformation (rutting), fatigue cracking, and damage caused by repeated loading throughout the road's service life (Nikraz et al., 2021). One of the most widely used parameters for evaluating an asphalt mixture's load-bearing capacity is Marshall Stability, defined as the maximum load a test specimen can bear before experiencing plastic failure (American Society for Testing and Materials, 2022). A high stability value indicates that the mixture can better resist deformation, thereby extending the service life of the pavement (Wijayanti & Radam, 2022; Ziari et al., 2019).

As concern for sustainability has grown, the use of waste as an alternative material in road construction has expanded rapidly over the past decade. One material that has been extensively studied is plastic waste, as its thermoplastic characteristics can enhance the stiffness and deformation resistance of asphalt mixtures when used at optimal levels (Mohammadi & Ameri, 2024; Yu et al., 2025). In addition to improving mechanical performance, using plastic waste also supports the principles of the circular economy by reducing waste generation while increasing the value of previously underutilized materials (Kalbali et al., 2021; Ma et al., 2023).

Among various types of plastic waste, multilayer plastic is one of the most difficult to recycle. This material consists of several polymer layers, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), aluminum foil, and an adhesive layer, making it highly complex to separate its constituent materials. As a result, most multilayer plastic waste still ends up in landfills or pollutes the environment (Nugraha et al., 2022; Nizamuddin et al., 2021; Xu et al., 2021). This situation has spurred various studies on using multilayer plastic waste as an asphalt modifier to improve mixture performance and reduce environmental pollution.

Various studies have reported that adding plastic as a modifier can improve Marshall characteristics, stiffness modulus, and resistance to permanent deformation. Sukobar et al. (2021) demonstrated that using LDPE in AC-BC mixtures increases the Marshall Stability value compared to conventional mixtures. Similar results were also reported by Nikraz et al. (2021), who stated that modifying the mixture with PET waste can improve resistance to deformation and enhance its mechanical characteristics. Kumar & Shukla (2022), through a comprehensive literature review, concluded that using plastic waste as an asphalt modifier is one of the most promising approaches in developing green pavement. However, its effectiveness is still highly influenced by the type of plastic, the addition rate, and the mixing method used.

In addition to the type of plastic, the mixing method is also a critical factor determining the success of asphalt mixture modification. Generally, the two most commonly used methods are the wet process and the dry process (Duarte & Faxina, 2021). In the wet process, plastic is first mixed into hot asphalt, resulting in direct interaction between the polymer and the binder, which increases viscosity and alters the asphalt's rheological properties. Conversely, in the dry process, the plastic is mixed with the aggregate before adding asphalt, so a portion of the plastic acts more as an additive than as a binder modifier (S. K. Shah et al., 2025a).

Several studies have shown that the wet process generally yields better mechanical characteristics than the dry process because polymer dispersion occurs more homogeneously, thereby enhancing the mixture's internal cohesion (Pan et al., 2025a; P. M. Shah, 2025b). Ahmadinia et al. (2011) also reported that mixing plastic directly into the binder results in a more uniform polymer distribution compared to mixing it with aggregate. However, the dry process offers simpler production, does not require special modifications to the Asphalt Mixing Plant (AMP), and is easier to implement on an industrial scale (Moghaddam et al., 2013).

Although research on the use of plastics as asphalt modifiers has advanced rapidly, most studies still focus on single-type plastics such as LDPE, HDPE, PET, and PP. Research specifically evaluating multilayer plastics remains relatively limited, particularly studies that directly compare the effectiveness of the wet and dry processes in Asphalt Concrete–Binder Course (AC-BC) mixtures. Furthermore, most previous studies have primarily evaluated the volumetric characteristics or general performance of the mixtures, whereas studies focusing on comparing improvements in Marshall Stability resulting from different mixing methods remain very few (Alqubaysi et al., 2025; Phan et al., 2026; Sunarjono et al., 2026).

Based on this literature review, a research gap remains: few studies examine the effect of mixing methods on the Marshall Stability of AC-BC mixtures using multilayer plastic waste as a modifier. Therefore, this study offers a novel contribution through a comparative analysis of the effectiveness of wet and dry mixing processes using multilayer plastic waste in AC-BC mixtures, with a primary focus

on evaluating Marshall Stability. The research results are expected to contribute scientifically to selecting the most effective mixing method while supporting the use of multilayer plastic waste as an alternative material in sustainable road pavement construction.

METHOD

Research Design and Procedures.

This study employed a laboratory experimental research method to evaluate the effect of wet-process and dry-process mixing methods on the Marshall Stability values of Asphalt Concrete–Binder Course (AC-BC) mixtures modified with multilayer plastic waste. The experimental approach was chosen because it allows systematic control of research variables, enabling objective observation of the cause-and-effect relationship between mixing methods and the mixture's mechanical characteristics (Calderón-Ramírez et al., 2025; Montgomery, 2019). Furthermore, the experimental method is the most widely used approach in pavement material research because it can generate quantitative data for comparative analysis (American Society for Testing and Materials D6927-22).

The study employed a Completely Randomized Design (CRD) with two main treatments: the wet process and the dry process, while the multilayer plastic waste content was varied at 3%, 4%, 5%, 6%, and 7% by weight of the total binder. Three test specimens were prepared for each variation, so that the Marshall Stability values obtained represent the average of the three tests to minimize the impact of experimental error. The research stages were carried out systematically as shown in Figure 1.

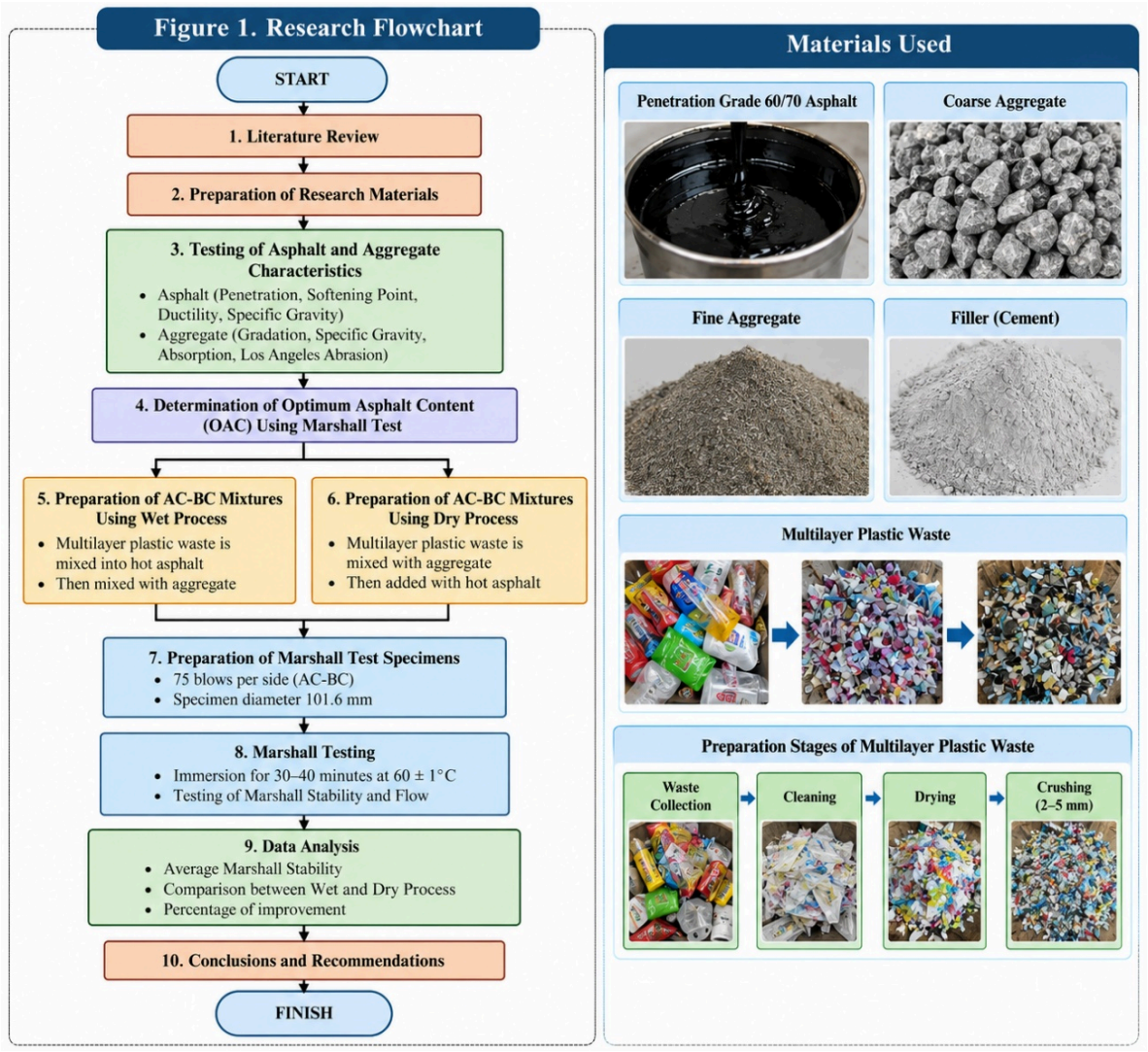


Figure 1. Research flowchart

Research Location

The research was conducted at the Road Pavement Laboratory of the Civil Engineering Program at Muhammadiyah University of Mataram. All material testing, test specimen preparation, and Marshall tests were performed using laboratory equipment that complies with American Society for Testing and Materials (ASTM) and SNI testing standards, as well as the 2018 General Specifications for Public Works, Revision 2.

Research Materials

The materials used consisted of coarse aggregate, fine aggregate, filler, 60/70 penetration asphalt, and multilayer plastic waste. 60/70 penetration asphalt was used because it is the most commonly used type of asphalt in road construction in Indonesia and meets the requirements of the 2018 General Specifications for Public Works, Revision 2. This asphalt was selected because it possesses characteristics suitable for AC-BC mixtures, particularly for moderate to heavy traffic.

Coarse and fine aggregates were obtained from an Asphalt Mixing Plant (AMP) that met the gradation specifications for AC-BC mixtures. Before use, the aggregates were tested for specific gravity, absorption, Los Angeles abrasion, and gradation analysis in accordance with SNI standards to ensure their quality met technical requirements. Portland cement was used as the mineral filler to increase the mixture's density, improve the bond between aggregates and asphalt, and enhance the mixture's stability.

The modifying material consists of multilayer plastic waste derived from single-use packaging. The waste is cleaned of impurities, dried, and then shredded to 2–5 mm to facilitate dispersion during mixing. Multilayer plastic waste was chosen because it contains polymers that can increase the mixture's stiffness while reducing environmental pollution from waste that is difficult to recycle (Nugraha et al., 2022). Specific chemical and thermal characterization methods such as Differential Scanning Calorimetry (DSC) have not yet been performed on the materials used. Therefore, the types of constituent polymers, the percentage of each fraction, and the quantitative aluminum content cannot yet be determined. This situation represents one of the limitations of material characterization in this study.

Research Variables

Research variables are categorized into independent variables, dependent variables, and controlled variables as follows: (1) Independent variables, namely the mixing methods, which include the wet process and the dry process, as well as the content of multilayer plastic waste used as an asphalt modifier, with variations of 3%, 4%, 5%, 6%, and 7% by weight of the binder. (2) Dependent variable: Marshall Stability value (kg) obtained from the Marshall test results for each mixture variation. (3) Controlled variables included the use of 60/70 penetration asphalt, aggregate gradation, filler type, Optimum Asphalt Content (OAC), mixing temperature, compaction temperature, 75 Marshall blows on each side of the test specimen, test specimen dimensions, and soaking time prior to the Marshall test. These variables were controlled to ensure that changes in Marshall stability values were influenced only by the mixing method and the plastic waste content, thereby maintaining the validity of the research results.

Determination of the Optimum Asphalt Content

Before modification using multilayer plastic waste, the conventional AC-BC mixture was first designed to obtain the Optimum Asphalt Content (OAC) using the Marshall method in accordance with American Society for Testing and Materials (ASTM) D6927-22 and the 2018 General Specifications for Road Construction, Revision 2. The OAC was determined based on the following parameters: Marshall Stability, Flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Bitumen (VFB). Based on the results of Efendy et al.'s (2026) study, an OAC of 5.15% was obtained and subsequently used as the basis for all modified mixtures.

Mixture Preparation Using the Wet Process Method

In the wet process method, asphalt is heated to 160–170°C; then multilayer plastic waste is gradually added while stirring manually for 45 minutes until a homogeneous mixture is obtained. After all the plastic is evenly dispersed in the binder, the modified asphalt mixture is blended with hot aggregate according to the AC-BC gradation composition.This method allows for direct interaction between the polymers and the binder, thereby increasing the asphalt's viscosity, improving its rheological properties, and enhancing the mixture's internal cohesion. This mechanism has been reported to improve resistance to permanent deformation compared to conventional mixtures (Hunter et al., 2015; S. K. Shah et al., 2025a).

Mixture Preparation Using the Dry Process

In the dry process, multilayer plastic waste is first mixed with hot aggregate until it is

evenly distributed across the aggregate surface. Next, hot asphalt is added to the optimum asphalt content, and mixing continues until all aggregate is coated with the binder. In this method, the aggregate is first heated to 160–170°C. At that temperature, shredded multilayer plastic packaging waste cut into 2–5 mm pieces is gradually added to the hot aggregate. Next, the mixture is stirred for 45 minutes manually until the shredded multilayer packaging waste is visually distributed across the surface of the aggregate. This method is simpler than the wet process because it does not require prior binder modification, making it easier to implement in an Asphalt Mixing Plant (AMP). However, the interaction between the plastic and the asphalt is relatively limited, so the effectiveness of the modification is highly influenced by the homogeneity of the plastic distribution within the mixture (Moghaddam et al., 2013; Pan et al., 2025b).

Preparation of Marshall Test Specimens

The homogeneous mixture is placed into a Marshall mold with a diameter of 101.6 mm and then compacted using a Marshall hammer with 75 blows on each side, in accordance with the AC-BC mixture specifications for heavy traffic. After compaction, the test specimens were cooled at room temperature for approximately 24 hours before the Marshall test was conducted.

Marshall Test

The Marshall test was conducted in accordance with American Society for Testing and Materials (ASTM) D6927-22 and the 2018 General Specifications for Highways, Revision 2. Before testing, the test specimens were immersed in a water bath at 60 ± 1°C for 30–40 minutes. Subsequently, the test specimens were tested using a Marshall Testing Machine at a loading rate of 50.8 mm/minute until the maximum load was reached.

The primary parameter analyzed in this study is Marshall Stability, the maximum force the test specimen can withstand before plastic failure. The Marshall Stability value is used as the primary indicator in evaluating the effect of mixing methods on the strength of multilayer plastic waste-modified AC-BC mixtures.

Data Analysis

The test data were analyzed using a descriptive-comparative approach by comparing the Marshall Stability values between the wet process and dry process methods for each variation in multilayer plastic waste content. The percentage increase in Marshall Stability was calculated using the following equation:

$$\%\Delta SM = \frac{SM_{modified} - SM_{control}}{SM_{control}} \times 100\%$$

with SM_modified and SM_control are Marshall Stability of the modified mixture (kg), and conventional mixture (kg), respectively. The analysis results are then presented in tables, graphs, and descriptive text to identify the optimal plastic content and determine which mixing method most effectively increases Marshall Stability. This equation aligns with the approach used in the results section of your research.

■ RESULT AND DISCUSSION

Determination of the Optimum Asphalt Content (OAC)

The initial stage of the study involved determining the Optimum Asphalt Content (OAC) of conventional AC-BC mixtures using the Marshall method in accordance with American Society for Testing and Materials (ASTM) D6927-22 and the 2018 General Specifications for Road Construction, Revision 2. The OAC was determined based on the following parameters: Marshall Stability, Flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Bitumen (VFB). The Marshall test results for the AC-BC mixture, with planned asphalt content levels of 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%, are presented in Table 1. Based on the test results by Efendy et al. (2026), an OAC of 5.15% was obtained and subsequently used as the fixed asphalt content for all variations of the multilayer plastic waste-modified mixtures.

Using a single OAC value across all variations ensures that changes in mixture characteristics are influenced only by the mixing method and the content of multilayer plastic waste, allowing for an objective comparison of the results. This approach is widely used in research on modified asphalt mixtures because it allows a more accurate evaluation of the modifying material's influence without being affected by changes in binder content (Duarte & Faxina, 2021; Ramadhani et al., 2026).

To verify the suitability of the selected optimum asphalt binder content of 5.15%, a volumetric analysis and evaluation of the Marshall mix design curves were conducted. The volumetric properties, including VIM, VMA, and VFA, were examined to ensure compliance with the specified mix design requirements. Furthermore, the Marshall parameters were evaluated across different asphalt binder contents to confirm that the selected optimum content satisfies the applicable design criteria. The results

Table 1. Marshall test results for a conventional laston AC-BC mixture

Asphalt Content (%)	4	4.5	5	5.5	6	Specifications
Stability (kg)	1,161	1,348	1,207	1,252	1,125	Min. 800
Flow (mm)	3.65	3.27	3.33	2.97	3.33	2.0 - 4.0
VIM (%)	9.05	6.31	5.93	3.73	2.68	3.0 - 5.0
VIM PRD (%)	-	3.89	2.51	1.47	-	Min. 2.0
VMA (%)	18.31	16.92	17.63	16.76	16.91	Min. 14
VFB (%)	50.59	62.69	66.35	77.73	84.12	Min. 65

of this verification are presented in Table 1 and Figure 2.

Aggregate Gradation Composition of the AC-BC Mixture

After determining the KAO to be 5.15%, the AC-BC mixtures were formulated while maintaining the aggregate composition and total binder content for each mixture variation. The total weight of each test specimen was set at 1,200 g, consisting of 1,138.2 g of aggregate and 61.8 g of binder. Multilayer plastic waste was used as a partial substitute for asphalt at levels of 3%, 4%, 5%, 6%, and 7% of the total binder weight. As plastic content increased, asphalt mass was reduced proportionally so that the total binder remained constant across all variations.

This strategy ensures that the observed differences in Marshall Stability values stem from variations in the plastic waste content and mixing methods, rather than changes in the base composition of the mixture. Thus, the effect of the modifying material on the mixture's mechanical performance can be evaluated more objectively. Three test specimens were prepared for each treatment in every variation. The AC-BC mixture compositions for each multilayer plastic waste content are presented in Table 2.

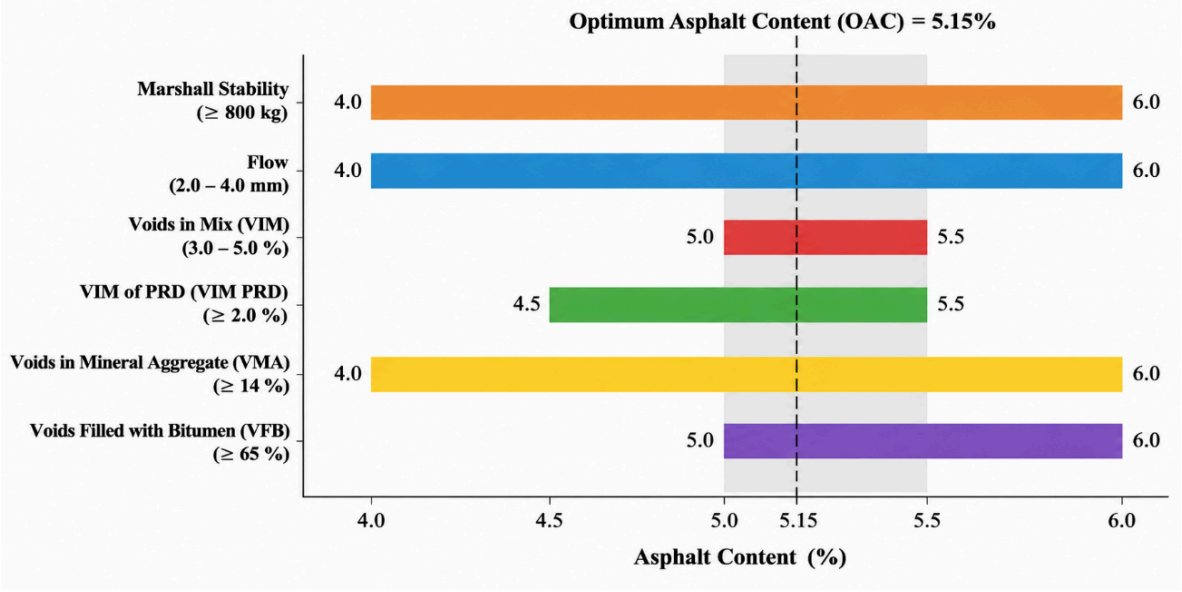


Figure 2. Determination of OAC laston AC-BC mixture

Table 2. AC-BC mixture compositions with variations in multilayer plastic waste content

Mixture Component	3%	4%	5%	6%	7%	Unit
OAC	5.15	5.15	5.15	5.15	5.15	%
Aggregate 3/4	341.5	341.5	341.5	341.5	341.5	g

Mixture Component	3%	4%	5%	6%	7%	Unit
Aggregate 3/8	284.6	284.6	284.6	284.6	284.6	g
Stone Ash	500.8	500.8	500.8	500.8	500.8	g
Filler	11.4	11.4	11.4	11.4	11.4	g
Total aggregate	**1,138.2**	**1,138.2**	**1,138.2**	**1,138.2**	**1,138.2**	**g**
Asphalt	59.95	59.33	58.71	58.09	57.47	g
Multilayer plastic waste	1.85	2.47	3.09	3.71	4.33	g
Total binder	**61.80**	**61.80**	**61.80**	**61.80**	**61.80**	**g**
Total mixture	**1,200**	**1,200**	**1,200**	**1,200**	**1,200**	**g**

Marshall Stability of AC-BC Mixtures Using the Wet Process

The results of Marshall tests on AC-BC mixtures using the wet process method show that adding multilayer plastic waste increases Marshall stability up to a certain content. The stability value increased from 1,471 kg at 3% plastic content to 1,640 kg at 4%, and reached a maximum of 1,701 kg at 5%. Beyond this concentration, stability decreased to 1,582 kg at a 6% concentration, then increased slightly to 1,593 kg at a 7% concentration. All variations yielded stability values above 1,000 kg, thereby meeting the requirements for AC-BC mixtures according to the General Specifications of the Ministry of Public Works and Public Housing.

The increase in Marshall Stability from 1,582 kg at 6% plastic content to 1,593 kg at 7% content indicates a slight fluctuation in the mixture's response. This is likely related to changes in the interactions between the polymer fraction, the binder, and the aggregates at higher modification levels. While adding plastic can increase binder stiffness, it can also affect viscosity and the effectiveness of the aggregate coating. Such shifts in the balance of these interactions may account for the slight gain in stability observed at the 7% content level. However, an increase of 11 kg is relatively minor and cannot be interpreted as a significant improvement in performance. Overall, a 5% plastic content yields the highest Marshall Stability, at 1,701 kg.

This pattern of an initial increase followed by a decrease indicates an optimal concentration of multilayer plastic waste, namely 5% by weight of the binder. At this content, the polymers in the plastic waste can disperse homogeneously within the binder, thereby increasing the mixture's stiffness and internal cohesion. Good dispersion results in stronger bonds between the binder and the aggregates, so the maximum load the mixture can bear before undergoing plastic deformation becomes greater.

This finding aligns with research by P. M. Shah (2025b), which states that modifying the binder with polymers increases asphalt viscosity, thereby enhancing the mixture's resistance to deformation. The results of Duarte & Faxina (2021) also show that the wet process yields a more homogeneous polymer distribution compared to the dry process, resulting in better Marshall characteristics. Similarly, Kurniasari et al. (2025) reported that mixing homogeneity is a key factor in the successful use of plastic waste as an asphalt modifier.

A decrease in stability when the plastic content exceeds 5% indicates that an excessively high polymer content makes the mixture stiffer, preventing the binder from coating the aggregates optimally. This condition reduces the uniformity of inter-aggregate bonding and increases the likelihood of weak zones forming within the mixture. A similar phenomenon was also reported by Ahmadinia et al. (2011), who stated that each polymer material has an optimal content level before the mixture's mechanical properties begin to decline again.

Marshall Stability of AC-BC Mixtures Using the Dry Process

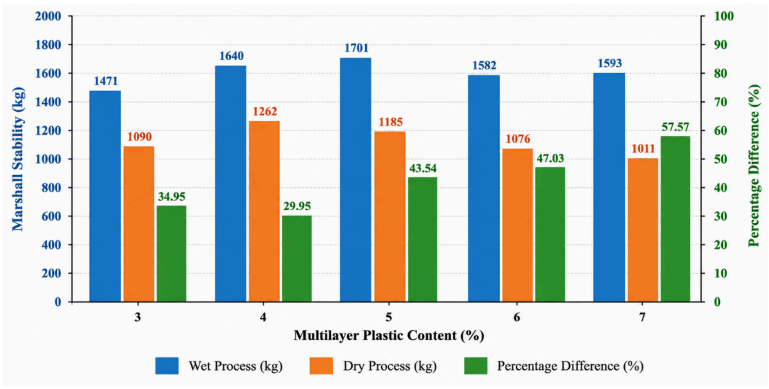
Marshall test results obtained using the dry process show a different trend compared to those from the wet process. The Marshall stability value increased from 1,090 kg at a plastic content of 3% to 1,262 kg at 4%, then decreased successively to 1,185 kg, 1,076 kg, and 1,011 kg at plastic contents of 5%, 6%, and 7%, respectively. Thus, the optimum plastic content for the dry process was 4%. The lower stability values compared to the wet process indicate that the mixing mechanism significantly influences the mixture's mechanical performance. In the dry process, the plastic first mixes with the aggregates, thereby limiting direct interaction between the polymer and the binder. Some of the plastic functions merely as an additive adhering to the aggregate surface and does not fully

undergo a modification process that alters the asphalt's rheological properties.

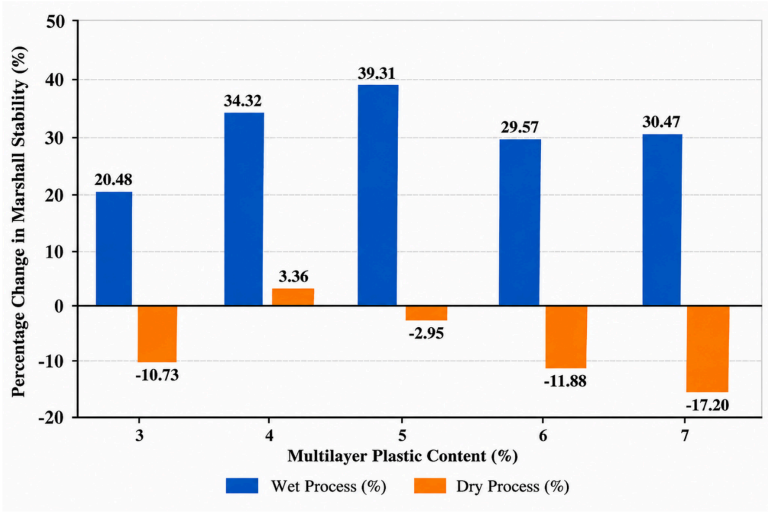
These conditions result in a smaller increase in binder viscosity than in the wet process, leading to lower resistance of the mixture to deformation. This explanation is consistent with the findings of Milad et al. (2022), who stated that the success of the dry process is highly influenced by the degree of homogeneity in the distribution of plastic within the mixture. Furthermore, Lim et al. (2024) explain that the effectiveness of using plastic waste in the dry process depends heavily on particle size, mixing temperature, and the compatibility between the plastic and the binder. The decrease in stability once the plastic content exceeds 4% indicates that increasing the amount of plastic does not always improve mixture performance. Excessively high plastic content can hinder the binder's coating of the aggregates, thereby reducing the mixture's internal cohesion and causing a decrease in the Marshall Stability value.

Comparison of Marshall Stability Between Wet and Dry Processes

Marshall stability values for the wet and dry processes were compared to determine the effectiveness of each mixing method in improving the stability of the AC-BC mixture, as shown in Figure 3.



(a)



(b)

Figure 3. Comparison of marshall stability values for the wet process and dry process

A comparison of Marshall stability values between the two methods shows that the wet process consistently yields higher stability values than the dry process across all variations in multilayer plastic waste content. The highest stability value in the wet process reached 1,701 kg at a 5% plastic content, while the highest value in the dry process reached only 1,262 kg at a 4% plastic content. The difference in stability ranges from 29.95% to 57.57%, with the largest difference occurring at a 7% plastic content.

Scientifically, these results indicate that mixing plastic directly with the binder results in a more effective modification process compared to mixing it with aggregate. In the wet process, the plastic melts and disperses within the

binder, forming a more homogeneous binding system. This more homogeneous binder structure enhances adhesion between the asphalt and aggregates, increases the mixture's internal cohesion, and improves its ability to resist deformation caused by repeated loading.

Conversely, in the dry process, some of the plastic does not fully function as a binder modifier because it merely adheres to the surface of the aggregates. As a result, the polymer distribution becomes less uniform, so the improvement in the mixture's mechanical properties is not as optimal as in the wet process. These findings are consistent with the research by Kurniasari et al. (2025); Pan et al. (2025c); and S. K. Shah et al. (2025a), which state that the homogeneity of the interaction between polymers and the binder is the primary factor determining the performance improvement of asphalt mixtures.

Analysis of Mean Values and Variability of Marshall Stability

Figure 4 presents a graph of the mean Marshall Stability values along with the standard deviation for multilayer plastic waste-modified AC-BC mixtures using the wet and dry process methods. The error bars on the graph indicate the level of variation in test results from three test specimens for each plastic content variation.

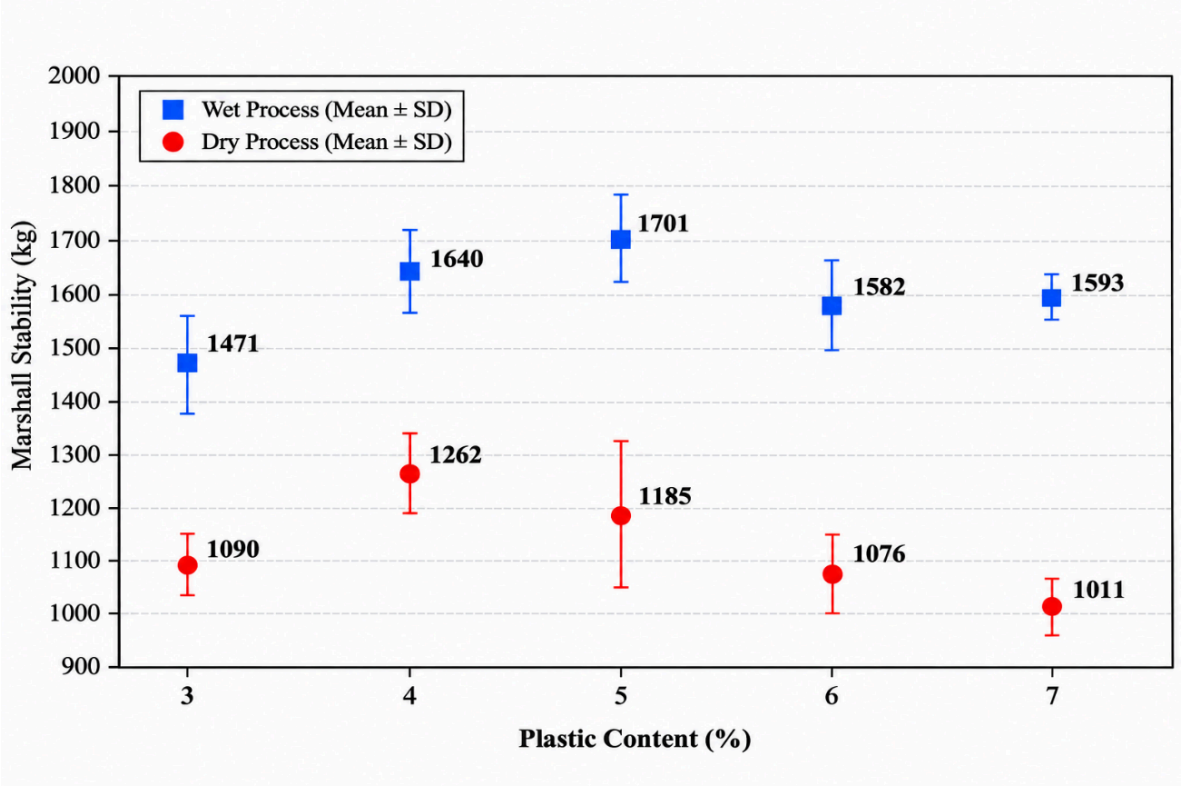


Figure 4. Graph of marshall's mean stability and standard deviation

Based on Figure 4, the wet process consistently produced higher mean Marshall Stability values than the dry process across all plastic waste content variations. The highest mean value in the wet process was obtained at a plastic content of 5%, while in the dry process, the maximum value occurred at a content of 4%. These results indicate that mixing plastic waste directly into the binder produces a more homogeneous mixture, thereby enhancing the bond strength between the asphalt and the aggregate.

In addition to showing the mean values, the graph also illustrates data variation through error bars. Most groups had relatively small standard deviations, particularly at plastic content levels of 3–5%, indicating that results across replicates were fairly consistent and showed good reproducibility. Conversely, at plastic content levels of 6% and 7%, particularly in the dry process method, the error bars are larger, indicating increased variation in the test results. This suggests that adding plastic waste at higher concentrations results in a less homogeneous distribution of plastic within the mixture, leading to more variable mechanical responses.

Scientifically, these results can be explained by the fact that in the wet process,

the plastic waste melts and mixes directly with the binder, thereby increasing the viscosity of the asphalt, improving adhesion to the aggregate, and producing a more homogeneous mixture structure. In contrast, in the dry process, some of the plastic merely coats the surface of the aggregate, so the interaction between the polymer and the binder does not occur optimally. Consequently, the resulting increase in Marshall stability is lower, and test result variations tend to be greater. These findings are consistent with the research by Kim and Kim (2025), who reported that this wet process produces a more uniform polymer dispersion than the dry process, and are supported by P. M. Shah, who stated that mixing homogeneity is a key factor in improving the mechanical performance of plastic-modified asphalt mixtures. Figure 5 illustrates a more homogeneous mixture and a less homogeneous mixture.

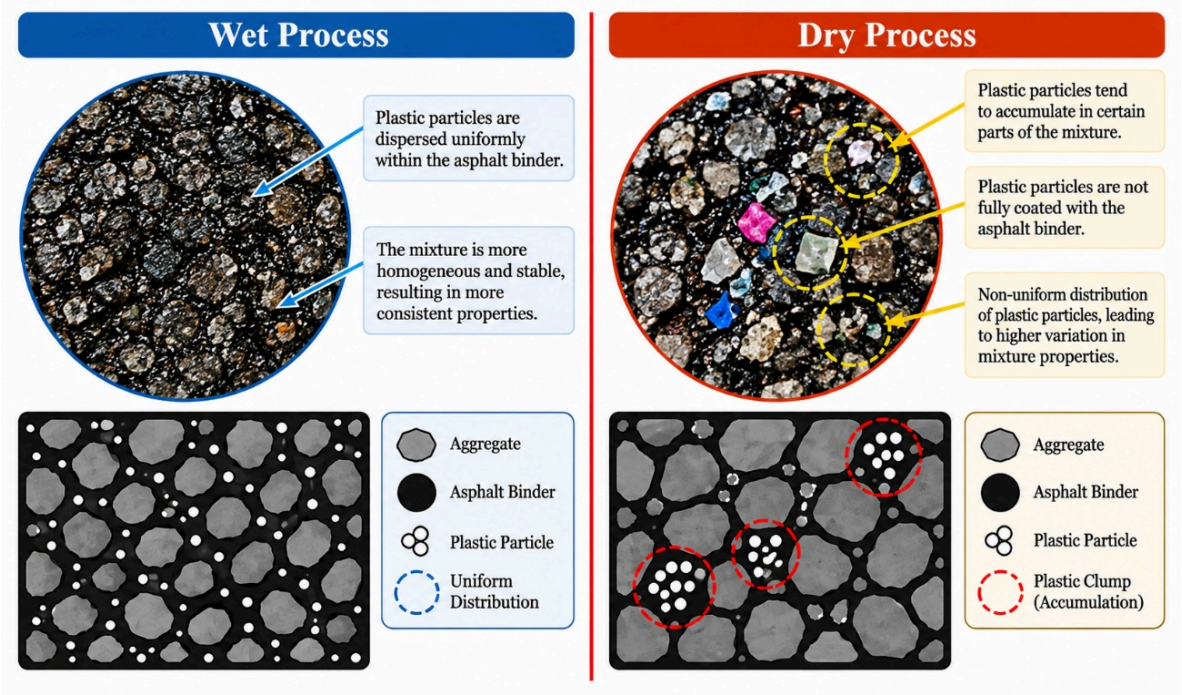


Figure 5. Illustrations of more homogeneous and less homogeneous mixtures

Overall, the Mean ± Standard Deviation graph shows that the wet process not only produces higher Marshall Stability values but also yields more consistent results than the dry process, particularly at plastic waste contents up to 5%. Therefore, the wet process can be recommended as a more effective mixing method for improving the mechanical performance of multilayer plastic waste-modified AC-BC mixtures.

■ CONCLUSION

This study shows that the mixing method has a significant effect on the Marshall Stability value of Asphalt Concrete–Binder Course (AC-BC) mixtures modified with multilayer plastic waste. The wet process consistently yields higher Marshall Stability values than the dry process, with an optimum value of 1,701 kg at 5% plastic waste content. In contrast, the dry process yields an optimum value of 1,262 kg at 4% plastic waste content. The test results also indicate that increasing plastic waste content does not always result in a consistent improvement in Marshall Stability. For the wet process, the highest stability value is obtained at a 5% content, while for the dry process, the peak value occurs at 4%. Furthermore, the variation in test results at certain plastic concentrations, notably at 7% for the dry process, shows a relatively larger standard deviation. These findings suggest that the wet process provides a superior mechanical response based on the Marshall Stability parameter tested. However, the mechanisms of plastic dispersion, changes in binder viscosity, and the nature of the bond between the asphalt and aggregates remain uncertain, as this study did not include rheological testing or microstructural characterization.

Overall, the results indicate that the wet process is a more effective mixing method than the dry process for using multilayer plastic waste as a modifier in AC-BC. This method not only improves the mixture's mechanical performance

but also produces a more homogeneous and consistent mixture structure, thereby potentially supporting the development of more sustainable road pavement materials through the utilization of multilayer plastic waste.

■ DECLARATION OF AIASSISTED WRITING

The authors acknowledge the use of artificial intelligence (AI) tools to assist in preparing this manuscript. AIbased tools were used to support language refinement, grammar checking, and text structuring to improve clarity and readability. However, all ideas, research design, data collection, analysis, and interpretation presented in this study were conducted entirely by the authors. The authors take full responsibility for the content and integrity of the manuscript.

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