



Analysis of Asphalt Concrete Wearing Course (AC-WC) with Additives Styrofoam (Expanded Polystyrene) and PVC (Polyvinyl Chloride)

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Article Info :

Received:
29-06-2026
Revised:
22-08-2026
Accepted:
06-09-2026

Abstract

Flexible pavement, particularly Asphalt Concrete Wearing Course (AC-WC), requires adequate mechanical and volumetric performance to withstand traffic loading and environmental exposure. This study evaluates the performance of AC-WC incorporating Styrofoam (Expanded Polystyrene) and PVC (Polyvinyl Chloride) as polymer additives and identifies the best-performing mixture composition. An empirical experimental design was applied through controlled laboratory testing using Styrofoam contents of 0%, 2%, 4%, and 8% and PVC contents of 0%, 1%, 2%, and 3%. Mixture performance was evaluated using Marshall Stability, Flow, Marshall Quotient (MQ), Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). The results identified Sample 2, containing 4% Styrofoam and 2% PVC, as the best-performing composition. The mixture achieved a Stability of 3040.27 kg, Flow of 3.00 mm, MQ of 608.05 kg/mm, VIM of 3.60%, VMA of 16.43%, and VFA of 89.15%. These values satisfied the adopted AC-WC requirements and demonstrated more favorable mechanical and volumetric characteristics than the conventional mixture. The findings indicate that the tested combination of Styrofoam and PVC can enhance AC-WC performance under controlled laboratory conditions. This modification particularly improved load-bearing capacity, deformation response, and internal mixture characteristics. The results provide an empirical basis for further development of polymer-modified AC-WC mixtures for sustainable pavement applications.

Keywords: AC-WC, Marshall Characteristics, Polyvinyl Chloride, Styrofoam, Waste Polymers.



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INTRODUCTION

The development of road infrastructure is essential to economic growth, public mobility, and the distribution of goods and services, making pavement performance an increasingly important concern as traffic volume, axle loads, and environmental exposure continue to intensify. Flexible pavement incorporating Asphalt Concrete Wearing Course (AC-WC) remains widely applied because the wearing course directly receives repeated traffic loading and environmental effects, requiring an appropriate balance between stability, stiffness, durability, fatigue resistance, and resistance to permanent deformation. The mechanical performance of AC-WC is strongly influenced by aggregate gradation, binder characteristics, filler proportion, and the interaction among constituent materials, with aggregate structure determining the internal load-bearing framework of the asphalt mixture (Marpaung et al., 2017). In conventional mixture design, the use of suitable filler is also important because fine mineral particles can improve the interaction between asphalt binder and aggregate, although excessive filler may increase mixture stiffness to a level that promotes brittleness and cracking (Alamsyah et al., 2024). Current pavement research has increasingly moved toward polymer modification and waste-derived additives as strategies for improving asphalt performance while responding to material sustainability challenges, particularly through the incorporation of recycled plastics into asphalt mixtures (Shah et al., 2024). This development places AC-WC research at the intersection of pavement engineering, polymer modification, and circular material utilization, where the engineering value of waste materials must be evaluated against their effects on mixture behavior.

Styrofoam, or Expanded Polystyrene (EPS), is a lightweight thermoplastic material characterized by a highly porous structure and a very high air content, properties that contribute to its low density while also creating substantial challenges for waste management because discarded EPS is

persistent and difficult to degrade naturally. Its thermoplastic behavior provides an engineering rationale for incorporation into asphalt because the material can soften under elevated temperature and interact with the asphalt binder during mixing, potentially altering viscosity, stiffness, and volumetric characteristics. Experimental studies have reported that polystyrene addition can modify the characteristics of AC-WC and influence its Marshall performance, indicating that waste Styrofoam is not merely an environmental burden but may function as a performance-modifying material when incorporated at an appropriate proportion (Fahmi et al., 2023). Research on Styrofoam-modified asphalt has also shown that mixing temperature is a critical factor because thermal conditions influence the dispersion and interaction of Styrofoam within the asphalt matrix (Fitriansyah et al., 2024). The effectiveness of Styrofoam therefore cannot be interpreted solely from the presence of the polymer, since dosage and processing conditions jointly determine whether modification produces beneficial or adverse mixture characteristics. Recent investigations continue to demonstrate the relevance of Styrofoam in AC-WC modification, while also indicating that its performance should be evaluated through systematic comparison of different addition levels rather than through a single optimum composition (Tisnawan et al., 2025). The growing body of evidence suggests that EPS modification has considerable potential, but its engineering application still requires careful determination of composition and mixture response.

PVC (Polyvinyl Chloride) represents another potentially valuable waste polymer because its extensive use in pipes, packaging, construction products, and other applications generates a persistent post-consumer material stream that requires effective reuse strategies. Unlike conventional mineral additives, PVC is a thermoplastic polymer whose relatively rigid characteristics and chemical resistance can influence the mechanical response of asphalt mixtures when incorporated into the binder or mixture system. Experimental evidence has demonstrated that recycled PVC can reinforce modified asphalt mixtures and improve selected performance characteristics, supporting its potential as a sustainable paving material (Al-Shawabkeh et al., 2024). Earlier experimental work on PVC-modified AC-WC likewise established that PVC can be used as a mixed additive material and can alter the characteristics of asphalt concrete wearing-course mixtures (Veranita & Tripoli, 2021). These findings are consistent with the broader development of recycled polymer modification, in which waste polymers are increasingly investigated as materials capable of changing stiffness, strength, and resistance to pavement distress rather than being treated solely as waste-disposal substitutes (Tayh et al., 2024). Yet polymer incorporation introduces a critical compositional issue because an increase in stiffness does not automatically represent improved pavement quality when the resulting mixture loses an appropriate balance among stability, flexibility, density, and volumetric properties. The engineering value of PVC therefore depends on identifying an addition level that produces a favorable response within the specific AC-WC mixture system rather than assuming that higher polymer content necessarily generates superior performance.

The simultaneous use of Styrofoam and PVC creates a more complex research problem because the two polymers possess different physical characteristics and may interact differently with asphalt, aggregate, and filler during the mixing and compaction processes. Research examining waste Styrofoam and waste PVC in modified asphalt has indicated that polymer addition can affect asphalt viscosity and the volumetric properties of asphalt concrete, suggesting that the combined consideration of binder behavior and mixture composition is necessary when assessing polymer-modified AC-WC (Yuniarti et al., 2022). Studies focusing on Styrofoam have generally concentrated on the effect of a single polymer and have reported performance variations according to addition percentage, material condition, and testing procedure, while research on PVC has similarly examined its influence independently rather than establishing a comprehensive comparison with EPS within the same mixture framework. Recent work on Styrofoam-modified asphalt has expanded toward chemical, morphological, and rheological characterization, reinforcing the view that polymer–asphalt interaction involves changes at both material and mixture levels (Ningrum & Buana, 2024). A further limitation emerges from the fragmentation of existing evidence, because studies often employ different polymer contents, aggregate structures, binder conditions, mixing approaches, and performance indicators, making direct comparison of optimum compositions difficult. Research combining waste-based modifiers with other additives has also demonstrated that the response of AC-WC is highly dependent on material proportion and mixture configuration rather than on the identity of a waste material alone (Fatimah & Ningtyias, 2025). The unresolved issue is therefore not simply whether Styrofoam or PVC can be incorporated

into AC-WC, but how different addition levels affect the fundamental Marshall and volumetric characteristics required to identify a technically appropriate mixture.

This unresolved relationship has both scientific and practical significance because an unsuitable polymer proportion may produce excessive stiffness, inadequate workability, undesirable volumetric characteristics, or insufficient stability, while an appropriate proportion may improve structural performance and simultaneously reduce the amount of persistent plastic waste entering the environment. The need to establish a technically defensible composition is particularly important for AC-WC because the wearing course operates under direct traffic and environmental exposure, making small changes in mixture characteristics potentially relevant to pavement serviceability and durability. Existing comparative studies of conventional and polymer-modified asphalt have shown that polymer modification can produce meaningful differences in the characteristics of wearing-course mixtures, reinforcing the need to evaluate modification against a conventional reference rather than interpreting polymer performance in isolation (Wisman & Febrina, 2023). Recent review evidence on Styrofoam-modified asphalt further indicates that physical properties and mixture characteristics remain central considerations in determining the practical suitability of EPS as an asphalt modifier (Sani et al., 2026). From a methodological perspective, Marshall stability, flow, density, and related volumetric measurements provide an established basis for evaluating whether modified mixtures satisfy the required performance characteristics under standardized testing conditions. The use of standardized Marshall testing is particularly relevant because ASTM D6927 specifies procedures for determining Marshall stability and flow of asphalt mixtures, enabling experimental results to be interpreted through a recognized testing framework (ASTM International, 2022). Within the Indonesian pavement context, mixture development must also remain consistent with applicable technical specifications governing asphalt pavement construction, including the requirements established by the Directorate General of Highways (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2018).

Against this background, the present research is positioned as an experimental investigation of AC-WC modification using two thermoplastic waste materials, Styrofoam (Expanded Polystyrene) and PVC (Polyvinyl Chloride), with emphasis on determining how different addition levels influence the characteristics of the resulting asphalt mixture. The research uses primary experimental data obtained from laboratory testing of materials sourced from the Asphalt Mixing Plant (AMP) of PT. Deltamarga Adytama, including coarse aggregate, fine aggregate, Pen 60/70 asphalt, and cement as filler, while Styrofoam and PVC are introduced as additional materials. The experimental design compares Styrofoam contents of 0%, 2%, 4%, and 8% and PVC contents of 0%, 1%, 2%, and 3%, using the AC-WC job mix formula as the basis for mixture preparation. Each variation is evaluated through Marshall testing and measurements of weight in water and saturated weight to establish the resulting stability, flow, density, and volumetric characteristics of the mixtures. This approach is intended to address the empirical gap concerning the response of AC-WC to systematically varied Styrofoam and PVC contents under a consistent material and mixture framework rather than extrapolating conclusions from studies using different compositions or testing conditions. The study aims to identify the mixture characteristics associated with each Styrofoam and PVC variation and determine the most appropriate composition for further investigation and potential application. Its theoretical contribution lies in strengthening the understanding of how two different thermoplastic waste materials can modify AC-WC mixture behavior, while its methodological contribution lies in providing a controlled comparative framework for evaluating waste-polymer contents through standardized Marshall and volumetric measurements.

RESEARCH METHODS

This study employs an empirical experimental research design, as the development and evaluation of the AC-WC mixture are conducted through controlled laboratory testing using Styrofoam (Expanded Polystyrene) and PVC (Polyvinyl Chloride) as additive materials. The experimental materials consist of coarse aggregate, fine aggregate, Penetration 60/70 asphalt, cement as filler, Styrofoam, and PVC, with the principal aggregate and asphalt materials obtained from the Asphalt Mixing Plant (AMP) of PT. Deltamarga Adytama. The experimental design applies Styrofoam contents of 0%, 2%, 4%, and 8%, while PVC contents are set at 0%, 1%, 2%, and 3%, allowing the performance response of the AC-WC mixture to be examined across systematically varied additive proportions. Material preparation includes aggregate gradation analysis using a complete set of sieves, material weighing, aggregate preparation, asphalt heating, additive preparation, mixing, and specimen

compaction, with consistent procedures applied to all mixture variations because aggregate gradation directly influences the mechanical characteristics of AC-WC mixtures (Marpaung et al., 2017). The mixture proportions are established using the AC-WC Job Mix Formula as the experimental basis, while mixing temperature is controlled to maintain appropriate interaction and dispersion of the Styrofoam within the asphalt matrix because temperature can significantly affect the characteristics of Styrofoam-modified AC-WC mixtures (Fitriansyah et al., 2024). The experimental equipment includes sieves, weighing scales, oven, Los Angeles machine, pycnometer, mixing pans, thermometer, water bath, and Marshall testing apparatus, with Marshall testing procedures referring to ASTM D6927-22 (ASTM International, 2022).

Validation is performed through Marshall and volumetric testing of all AC-WC mixture variations to determine the consistency and engineering response of each additive composition. The evaluation parameters comprise Marshall Stability, Flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), and specimen weight characteristics obtained from measurements of dry weight, saturated weight, and submerged weight. Marshall Stability represents the maximum load-bearing capacity of the mixture, whereas Flow indicates the deformation occurring at the point of maximum loading, providing complementary measures of mixture strength and deformation behavior (ASTM International, 2022). Each modified mixture is compared with the 0% additive control mixture and assessed against the applicable AC-WC technical requirements to determine whether increasing polymer content improves or adversely affects the mixture characteristics, particularly because the incorporation of waste polymers can alter asphalt viscosity and volumetric properties (Yuniarti et al., 2022). The experimental findings are also interpreted comparatively with previous evidence concerning recycled PVC reinforcement in asphalt mixtures to establish whether the observed performance trends are consistent with the broader potential of recycled polymers for sustainable pavement applications (Al-Shawabkeh et al., 2024). The methodological uniqueness of this study lies in the systematic evaluation of two different thermoplastic waste materials across distinct additive percentages within a consistent AC-WC mixture framework, providing an empirical basis for identifying the most appropriate composition for subsequent pavement-material development.

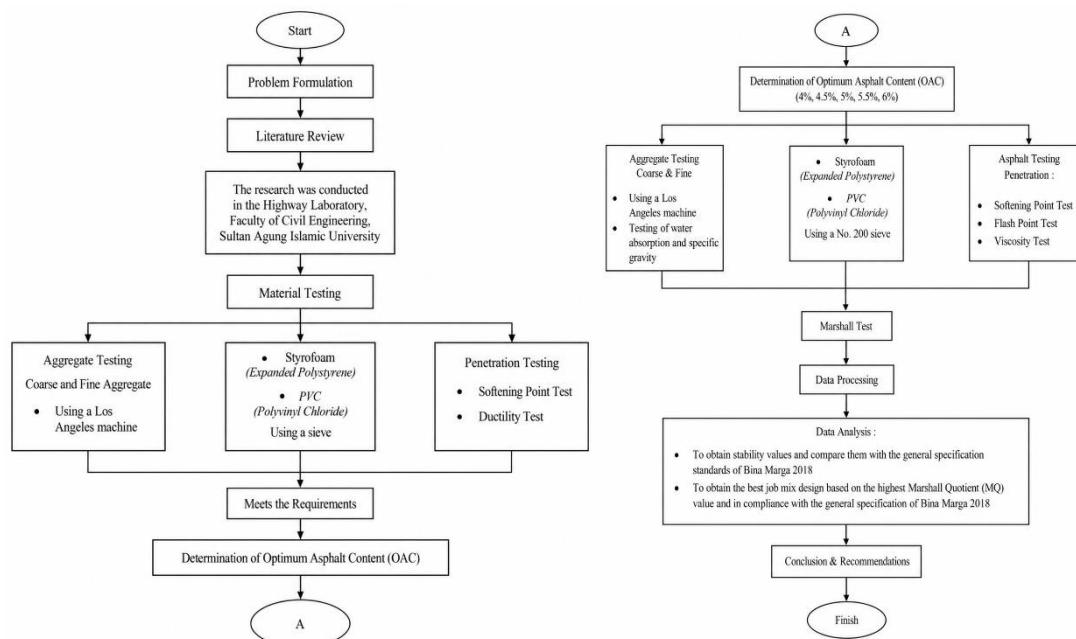


Figure 1. Experimental Procedure and Evaluation Framework for Styrofoam- and PVC-Modified AC-WC

RESULTS AND DISCUSSION

Aggregate and Penetration 60/70 Asphalt Material Properties

The preliminary material evaluation focused on verifying whether the coarse aggregate, fine aggregate, and Penetration 60/70 asphalt possessed physical characteristics suitable for subsequent AC-

WC mixture preparation. Aggregate quality is particularly influential in wearing-course mixtures because particle shape, cleanliness, absorption, density, and gradation collectively determine aggregate interlock, binder demand, and the internal structure developed after compaction. The aggregate skeleton must provide sufficient resistance to traffic-induced deformation while maintaining an appropriate void structure for asphalt distribution, making material qualification an essential stage before interpretation of Marshall performance (Marpaung et al., 2017). Laboratory examination covered flat and elongated particles, material passing the No. 200 sieve, water absorption, bulk specific gravity, and fine-aggregate angularity using the testing methods specified in the original experimental program. The measured properties were subsequently compared with their respective acceptance limits rather than interpreted independently from the technical requirements governing pavement materials. This procedure establishes whether later variations in Marshall and volumetric response can reasonably be associated with mixture composition and polymer modification rather than with clearly unsuitable constituent materials.

The coarse-aggregate results indicate a generally acceptable material structure for AC-WC production, with all reported parameters satisfying the specified limits presented in Table 1. The proportion of flat and elongated particles was 7.64% against a maximum requirement of 10%, indicating that the aggregate did not contain an excessive proportion of geometrically unfavorable particles that could weaken interlocking under compaction and loading. Material passing the No. 200 sieve was only 0.34% compared with the maximum 1% requirement, suggesting a relatively clean coarse fraction with limited excessive fines that could interfere with asphalt–aggregate contact. Water absorption values of 0.675% for the 1/2 coarse aggregate and 1.267% for the 3/4 coarse aggregate were both below the maximum threshold of 3%, indicating relatively low water uptake within the tested particles. Excessive absorption can increase effective binder demand and create greater sensitivity to moisture-related deterioration, while lower absorption generally supports more predictable binder coating and volumetric behavior. The recorded bulk specific gravity values of 2.632 and 2.915 also exceeded the stated minimum requirement of 2.5, supporting the adequacy of the coarse material according to the original test criteria. These findings are consistent with the engineering principle that aggregate physical properties should be controlled before mixture optimization because deficiencies at the aggregate level can directly influence stability, volumetric characteristics, and durability of asphalt concrete (Alamsyah et al., 2024).

The fine aggregate also satisfied the stated requirements, although its test results reveal characteristics that remain important for subsequent mixture interpretation. Material passing the No. 200 sieve reached 11.56%, remaining below the stated maximum of 15%, while angularity was 46.97%, slightly above the minimum requirement of 45%. Adequate angularity is desirable because angular fine particles increase internal friction and contribute to the shear resistance of the compacted aggregate skeleton, whereas excessive smoothness may reduce resistance to permanent deformation. Water absorption was 2.145% for sand and 2.873% for stone dust, both remaining within the maximum 3% limit reported in the experimental specification. Table 1 presents the complete quantitative aggregate data used as the material-qualification basis for the experimental mixtures. The combination of compliant coarse and fine aggregate properties indicates that the aggregate system was sufficiently suitable for use in the subsequent AC-WC testing program, allowing polymer effects to be assessed without an obvious material-quality failure at the preliminary stage.

Table 1. Coarse and Fine Aggregate Test Results

No.	Type of Examination	Method	Requirement	Result	Description
A	Coarse Aggregate				
1	Flat and elongated particles	ASTM D4791-10	Max. 10%	7.64%	Meets
2	Material passing No. 200 sieve	ASTM C117:2012	Max. 1%	0.34%	Meets
3	Water absorption by aggregate: Coarse aggregate 1/2; Coarse aggregate 3/4	SNI 03-1969-1990	Max. 3%	0.675%; 1.267%	Meets

4	Bulk specific gravity: SNI 03-1969-1990	Min. 2.5%	2.632%;	Meets
	Coarse aggregate 3/4;		2.915%	
	Coarse aggregate 1/2			
B	Fine Aggregate			
1	Material passing No. 200 sieve SNI 03-4142-1992	Max. 15%	11.56%	Meets
2	Angularity SNI 03-6877-2002	Min. 45%	46.97%	Meets
3	Water absorption by aggregate: Fine aggregate (sand); Fine aggregate (stone dust) SNI 03-1969-1990	Max. 3%	2.145%; 2.873%	Meets
4	Bulk specific gravity: Fine aggregate (sand); Fine aggregate (stone dust) SNI 03-1969-1990	Min. 2.5%	2.604%; 4.985%	Meets

The Penetration 60/70 asphalt was subsequently evaluated to determine whether the binder possessed the consistency, temperature sensitivity, safety characteristics, ductility, and density required for AC-WC mixture preparation. Five properties were examined in the original testing program: penetration, softening point, flash point, ductility, and specific gravity. Penetration at 25°C produced a value of 65 (0.1 mm), which lies between the specified minimum of 60 and maximum of 70 and therefore corresponds to the expected consistency range for Penetration 60/70 asphalt. The softening point of 51.55°C also remained within the specified range of 48–58°C, indicating that the binder retained an acceptable resistance to softening as temperature increased. Binder consistency and thermal response are particularly relevant in polymer-modified asphalt because the addition of thermoplastic materials can alter viscosity, stiffness, coating characteristics, and the temperature range required to achieve homogeneous mixing (Fitriansyah et al., 2024). The flash point reached 314°C, substantially higher than the stated minimum of 200°C, providing a considerable margin between the normal mixing temperature and the temperature associated with ignition risk. The initial binder properties therefore provided an appropriate reference condition against which changes produced by Styrofoam and PVC modification could later be interpreted.

As reported in Table 2, ductility reached 151.5 against a stated minimum requirement of 100, indicating that the Penetration 60/70 asphalt possessed substantial deformation capacity before rupture under the prescribed test condition. This property is relevant to wearing-course applications because the binder must accommodate strain within the mixture while maintaining adhesion and cohesion under repeated traffic and environmental loading. The reported specific gravity result was 1034 against the stated minimum requirement of 1.0, and the original test record classified the result as meeting the applicable requirement. The values in Table 2 are retained exactly as recorded in the initial dataset, because the empirical analysis is intended to interpret the supplied laboratory evidence without modifying the original measurements. Conventional and polymer-modified asphalt mixtures may exhibit different binder rheological and mechanical responses, making characterization of the unmodified Penetration 60/70 binder necessary before evaluating additive effects (Wisman & Febrina, 2023). The satisfactory status assigned to each binder parameter indicates that the asphalt material met the acceptance criteria applied in the experimental program and could therefore proceed to AC-WC mixture preparation.

Table 2. Penetration 60/70 Asphalt Test Results

No.	Type of Examination	Unit	Min.	Max.	Test Result	Specification
1	Penetration at 25°C, 100 g, 5 seconds	0.1 mm	60	70	65	SNI-06-2456-1991
2	Softening point 5°C (Ring and Ball Test)	°C	48	58	51.55	SNI-06-2434-1991
3	Flash point (Cleveland Open Cup)	°C	Min. 200	–	314	SNI-06-2433-1991
4	Ductility		Min. 100	–	151.5	SNI-06-2432-1991

5	Specific gravity	%	Min. 1.0	–	1034	SNI-06-2432-1991
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The combined results in Tables 1 and 2 establish that the constituent materials passed the requirements reported in the original laboratory dataset before the Marshall specimens were produced. This material qualification is analytically important because the subsequent mechanical response of an AC-WC mixture depends on interactions among aggregate structure, asphalt consistency, volumetric configuration, and any modifier introduced into the binder or mixture. The General Specifications for road and bridge construction provide the technical framework within which AC-WC constituent materials and mixture properties are assessed for pavement applications in Indonesia (Ministry of Public Works and Public Housing, 2018). From an experimental perspective, using aggregates and Penetration 60/70 asphalt that satisfy the adopted criteria strengthens internal validity because gross material inadequacy is less likely to confound the observed response to Styrofoam and PVC addition. The relatively low coarse-aggregate absorption, acceptable fine-aggregate angularity, compliant penetration value, and adequate softening and flash points together provide a technically viable starting condition for controlled modification. These preliminary findings do not imply that the resulting AC-WC mixture will automatically satisfy Marshall and volumetric requirements, because mixture performance emerges from the combined effects of proportioning, compaction, binder content, and modifier interaction. The subsequent analysis therefore focuses on the Marshall and volumetric characteristics of the conventional AC-WC mixture before examining the performance consequences of polymer incorporation.

Marshall and Volumetric Characteristics of the Conventional AC-WC Mixture

The Marshall evaluation of the conventional AC-WC mixture at the optimum asphalt content of 5.8% provides the baseline for assessing the subsequent response of mixtures incorporating Styrofoam and PVC. The test generated mechanical indicators represented by Stability and Flow, while Marshall Quotient (MQ) was used to express the relationship between load-bearing capacity and deformation at maximum loading. Volumetric performance was evaluated through Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA), which collectively characterize the internal void structure and the extent to which asphalt occupies the available aggregate void space. Marshall Stability and Flow are complementary parameters because high resistance to loading must be considered together with sufficient deformation capacity rather than interpreted independently (ASTM International, 2022). The conventional mixture produced a Stability value of 724.91 kg and a Flow value of 5.87 mm at the 5.8% asphalt content. These results provide an empirical reference for determining whether polymer incorporation subsequently produces an improvement or deterioration in the mechanical behavior of the AC-WC mixture.

The Stability value of 724.91 kg was below the specified minimum requirement of 800 kg, indicating that the conventional mixture did not achieve the required resistance to maximum loading under the applied Marshall test conditions. Stability reflects the capacity of a compacted asphalt mixture to resist deformation under load, which is strongly influenced by aggregate interlock, binder characteristics, asphalt content, and the internal structure formed during compaction. Although the aggregate and Penetration 60/70 asphalt used in the experiment satisfied the material requirements reported in the preceding section, constituent-material compliance did not automatically produce a mixture with adequate mechanical performance. Similar experimental work has demonstrated that AC-WC strength emerges from interactions among aggregate properties, binder characteristics, filler, and mixture composition rather than from the suitability of an individual constituent alone (Alamsyah et al., 2024). The result is important for the experimental design because the 724.91 kg baseline establishes a measurable performance condition against which the effects of Styrofoam and PVC modification can be evaluated. It also indicates that improvement in load resistance constitutes a relevant engineering objective when introducing polymer additives into the conventional mixture. The baseline Stability value should consequently be interpreted as a mixture-level limitation rather than evidence that the previously qualified aggregate or asphalt materials were individually unsuitable.

The deformation response reinforces this interpretation because the measured Flow of 5.87 mm exceeded the specified range of 2–4 mm, while the Marshall Quotient of 139.45 kg/mm remained below the minimum requirement of 250 kg/mm. A Flow value exceeding the allowable range indicates comparatively large deformation at maximum loading, whereas the low MQ reflects the combined influence of insufficient Stability and excessive Flow on the stiffness-related response of the mixture.

These parameters should be evaluated simultaneously because an AC-WC mixture requires a balance between load-bearing resistance and controlled deformation to perform effectively as a wearing course. Table 3 presents the complete mechanical and volumetric characteristics of the conventional mixture at the 5.8% optimum asphalt content, retaining the values and requirements reported in the original experimental data. The observed combination of low Stability, high Flow, and low MQ suggests that the conventional mixture had not developed the mechanical balance required by the adopted criteria. Polymer modification has been investigated as one means of altering asphalt-mixture stiffness and deformation response, although its effectiveness depends strongly on polymer type, proportion, and interaction with the binder–aggregate system (Shah et al., 2024). The baseline results consequently provide an important control condition for evaluating whether Styrofoam and PVC can shift the mechanical characteristics toward the specified performance ranges.

Table 3. Characteristics of the AC-WC Mixture at Optimum Asphalt Content

Mixture Characteristic	Optimum Asphalt Content 5.8%	Requirement
Stability (kg)	724.91	Min. 800
Flow (mm)	5.87	2–4
Marshall Quotient (kg/mm)	139.45	Min. 250
VIM	9.95	3–5
VMA	14.65	Min. 15
VFA	32.43	Min. 65

The volumetric results in Table 3 reveal a comparable pattern of non-conformity, with VIM reaching 9.95 compared with the required range of 3–5 and VMA reaching 14.65 against the minimum requirement of 15. The high VIM indicates that the compacted conventional mixture contained a comparatively large volume of air voids, which suggests that the internal aggregate–binder system had not achieved the degree of compactness represented by the adopted specification. Excessive air voids are undesirable because greater internal exposure can facilitate the penetration of air and water and may reduce the durability of asphalt mixtures during service. VMA was only slightly below the minimum threshold, but its relationship with VIM remains important because the mineral aggregate void structure determines the space available for both effective asphalt and air voids within the compacted mixture. Volumetric properties can change materially when polymer modifiers alter asphalt viscosity and the ability of the binder to occupy spaces within the aggregate skeleton (Yuniarti et al., 2022). The simultaneous occurrence of VIM above its specified range and VMA below its minimum value indicates that the conventional mixture requires evaluation as an integrated volumetric system rather than through isolated acceptance of individual parameters.

VFA provides further evidence of the limited volumetric condition of the conventional mixture, with a measured value of 32.43 compared with the specified minimum of 65. This result indicates that a relatively small proportion of the void space within the mineral aggregate was filled with asphalt under the experimental condition represented by the 5.8% optimum asphalt content. The low VFA is consistent with the elevated VIM because a larger proportion of unfilled internal void space necessarily reduces the fraction occupied by effective asphalt within the aggregate structure. Such a condition can influence durability, cohesion, and the ability of the mixture to resist environmental deterioration, even when the constituent aggregate and asphalt have independently satisfied their preliminary material requirements. Research on asphalt modification shows that polymer incorporation can alter binder viscosity, coating behavior, and volumetric characteristics, making changes in VIM, VMA, and VFA essential for evaluating whether modification produces a structurally more favorable mixture (Ningrum & Buana, 2024). The conventional mixture therefore exhibits not only a mechanical deficiency in Stability, Flow, and MQ but also an unfavorable volumetric configuration according to the requirements reported in Table 3. These interrelated results justify evaluating polymer modification through both mechanical and volumetric indicators rather than selecting an additive composition solely on the basis of increased Stability.

Viewed collectively, none of the six reported Marshall and volumetric parameters of the conventional AC-WC mixture at 5.8% asphalt content satisfied the corresponding requirements presented in Table 3. Stability was 75.09 kg below the minimum value, Flow exceeded the upper limit

by 1.87 mm, and MQ was 110.55 kg/mm below its minimum requirement, demonstrating a baseline characterized by limited load resistance and comparatively high deformation. The volumetric indicators reinforce this pattern because VIM exceeded its upper limit by 4.95, VMA was 0.35 below its minimum, and VFA was 32.57 below the specified minimum. The applicable pavement specifications provide performance limits precisely because AC-WC must maintain an appropriate balance among strength, flexibility, density, and internal void structure under service conditions (Ministry of Public Works and Public Housing, 2018). These deviations should not be interpreted as evidence that the experimental program failed, since the conventional mixture serves as an essential reference condition for quantifying the engineering response produced by subsequent material modification. Rather, the results establish a demanding baseline against which improvements in Stability, Flow, MQ, VIM, VMA, and VFA can be evaluated consistently using the same testing framework. The next stage of the analysis consequently examines whether the incorporation of Styrofoam and PVC produces a more favorable AC-WC response relative to this conventional mixture and the specified performance criteria.

Performance of Styrofoam- and PVC-Modified AC-WC Mixture

The incorporation of Styrofoam (Expanded Polystyrene) and PVC (Polyvinyl Chloride) produced a markedly different Marshall response from that observed in the conventional AC-WC mixture at the optimum asphalt content. The modified specimen identified in the experimental dataset as containing 4% Styrofoam and 2% PVC produced a Stability value of 3040.27 kg, substantially exceeding both the minimum requirement of 800 kg and the conventional-mixture value of 724.91 kg. Such an increase indicates that polymer incorporation altered the internal mechanical response of the asphalt mixture and substantially increased its resistance to the maximum applied Marshall load under the laboratory testing conditions. Styrofoam can modify the characteristics of asphalt through the interaction of polystyrene with the binder, although its performance is sensitive to additive proportion and the conditions under which the modified mixture is produced (Fahmi et al., 2023). PVC modification has similarly been associated with changes in the mechanical characteristics of AC-WC because thermoplastic material can affect binder stiffness and the resistance of the mixture to deformation (Veranita & Tripoli, 2021). The magnitude of the measured Stability improvement provides strong experimental evidence of enhanced load-bearing performance for the tested modified composition, although interpretation must remain confined to the specimen composition and laboratory conditions examined in this study.

The deformation characteristics also improved, as the modified mixture recorded a Flow value of 3 mm compared with 5.87 mm for the conventional AC-WC mixture. This value falls within the specified range of 2–4 mm, indicating that the mixture retained an acceptable degree of deformation at maximum loading while achieving substantially greater Stability. The corresponding Marshall Quotient reached 608.05 kg/mm, considerably higher than the minimum requirement of 250 kg/mm and the conventional-mixture value of 139.45 kg/mm, demonstrating a pronounced improvement in the relationship between load resistance and deformation. Previous experimental research has shown that Styrofoam modification can influence both Stability and Flow because changes in binder consistency affect the interaction between asphalt and the aggregate skeleton during loading (Delani & Patriotika, 2025). The combined Stability, Flow, and MQ results are particularly important because an increase in Stability would be less advantageous if it were accompanied by deformation behavior outside the acceptable range. In this experiment, the simultaneous attainment of high Stability, compliant Flow, and high MQ indicates that the tested modified mixture developed a substantially more favorable mechanical balance than the conventional reference mixture.

The volumetric characteristics exhibited a similarly pronounced shift, with VIM decreasing from 9.95 in the conventional mixture to 3.60 in the modified mixture. A VIM value of 3.60 lies within the specified range of 3–5, indicating that the compacted modified specimen contained a considerably more appropriate proportion of internal air voids than the conventional mixture. VMA also increased from 14.65 to 16.43, exceeding the minimum requirement of 15 and indicating that the aggregate structure provided sufficient void space for the combined presence of effective asphalt and air. The effects of waste Styrofoam and PVC on asphalt viscosity can influence volumetric properties by changing binder distribution and its interaction with the void structure formed during compaction (Yuniarti et al., 2022). The simultaneous reduction in VIM and increase in VMA suggests that polymer modification was associated with a more favorable internal configuration rather than merely producing

an isolated improvement in mechanical strength. These volumetric changes complement the Marshall results because they indicate that the enhanced Stability occurred together with a compacted structure that satisfied the specified VIM and VMA criteria.

Table 4. Characteristics of AC-WC Mixture with 4% Styrofoam (Expanded Polystyrene) and 2% PVC (Polyvinyl Chloride) in Sample 2

Mixture Characteristic	Fly Ash 4% and Recycled Tire 4%	Requirement
Stability (kg)	3040.27	Min. 800
Flow (mm)	3	2–4
Marshall Quotient (kg/mm)	608.05	Min. 250
VIM	3.60	3–5
VMA	16.43	Min. 15
VFA	89.15	Min. 65

The VFA result strengthens the volumetric interpretation because the modified mixture recorded a value of 89.15, substantially above the minimum requirement of 65 and markedly higher than the conventional-mixture value of 32.43. This increase indicates that a considerably greater proportion of the void space within the mineral aggregate was occupied by asphalt in the modified specimen, corresponding with the reduction in VIM observed after modification. Research concerning recycled polymer incorporation into asphalt mixtures indicates that polymer–binder interaction can alter internal mixture structure and contribute to changes in both mechanical and volumetric performance (Tayh et al., 2024). The combination of VIM at 3.60, VMA at 16.43, and VFA at 89.15 shows that all three reported volumetric parameters satisfied their respective requirements for the modified specimen. These results contrast sharply with the conventional mixture, in which VIM, VMA, and VFA each fell outside the stated limits. The evidence indicates that the modification was associated not only with increased load resistance but also with a substantially different distribution of air and asphalt within the compacted aggregate structure.

From a material-behavior perspective, the improvements observed after modification are consistent with the capacity of thermoplastic waste materials to alter asphalt stiffness, viscosity, and binder–aggregate interaction, although the mechanisms associated with Styrofoam and PVC should not be assumed to be identical. Waste polystyrene has been reported to modify the physical and rheological behavior of asphalt, which can affect mixture stiffness and its response to loading and temperature (Ningrum & Buana, 2024). Recycled PVC has also demonstrated potential as an asphalt-mixture modifier capable of improving selected pavement performance characteristics when an appropriate material proportion and processing method are employed (Al-Shawabkeh et al., 2024). The observed performance should nevertheless be interpreted in relation to the controlled laboratory conditions because polymer content, mixing temperature, dispersion, and compatibility with the base binder can materially influence the resulting mixture characteristics. The importance of processing conditions is particularly relevant to Styrofoam-modified AC-WC because variation in mixing temperature has been shown to affect the engineering response of the resulting mixture (Fitriansyah et al., 2024). The present results therefore demonstrate the performance achieved by the tested composition rather than establishing that increasing Styrofoam or PVC content will invariably generate proportional improvements in AC-WC performance.

Taken together, the modified specimen satisfied the specified requirements for Stability, Flow, Marshall Quotient, VIM, VMA, and VFA, whereas the conventional mixture reported in Section 3.2 failed to satisfy the corresponding limits for all six parameters. The contrast is especially evident in Stability, which increased from 724.91 kg to 3040.27 kg, accompanied by a reduction in Flow from 5.87 mm to 3 mm and an increase in MQ from 139.45 kg/mm to 608.05 kg/mm. Studies of Styrofoam-modified AC-WC similarly indicate that recycled polystyrene can produce meaningful changes in Marshall characteristics when incorporated at appropriate proportions (Tisnawan et al., 2025). The observed improvement also supports the broader engineering proposition that recycled polymer materials can contribute to pavement performance while creating a potential utilization pathway for difficult-to-manage plastic waste (Shah et al., 2024). Nevertheless, the experimental evidence available here should be interpreted as laboratory-scale performance evidence and does not independently

establish long-term field durability, fatigue resistance, moisture susceptibility, or rutting performance under actual traffic and environmental exposure. Within the measured Marshall and volumetric parameters, the tested modified mixture exhibited a substantially more favorable engineering response than the conventional AC-WC reference and provides the quantitative basis for the comparative performance evaluation in the following section.

Comparative Marshall Performance and Engineering Implications

The comparative Marshall results demonstrate a substantial difference between the conventional AC-WC mixture and the modified mixture evaluated with Styrofoam and PVC, particularly in their capacity to resist loading while maintaining controlled deformation. Stability increased from 724.91 kg in the conventional mixture to 3040.27 kg in the modified specimen, while Flow decreased from 5.87 mm to 3 mm, shifting the latter from outside to within the specified range of 2–4 mm. This pattern indicates that the modified specimen combined greater load-bearing capacity with lower deformation at peak loading rather than achieving higher Stability at the expense of excessive Flow. Marshall testing interprets Stability and Flow as complementary indicators because pavement mixtures require sufficient resistance to applied loads while retaining deformation characteristics appropriate for service conditions (ASTM International, 2022). Comparable investigations have reported that polymer modification can change the mechanical behavior of asphalt mixtures through alterations in binder stiffness and interactions within the aggregate–binder system (Wisman & Febrina, 2023). The contrast between the two specimens consequently provides experimental evidence that the tested modification produced a mechanically stronger response under the laboratory conditions employed.

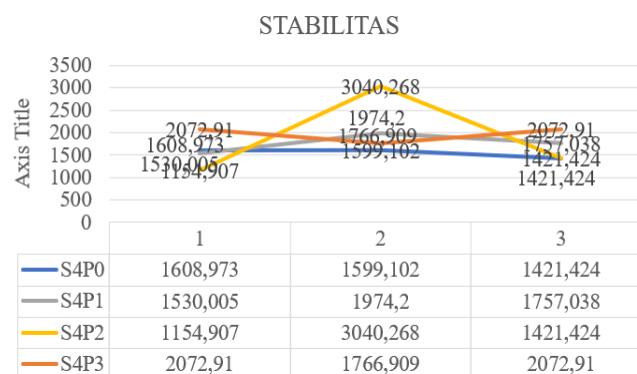


Figure 2. Stability Value

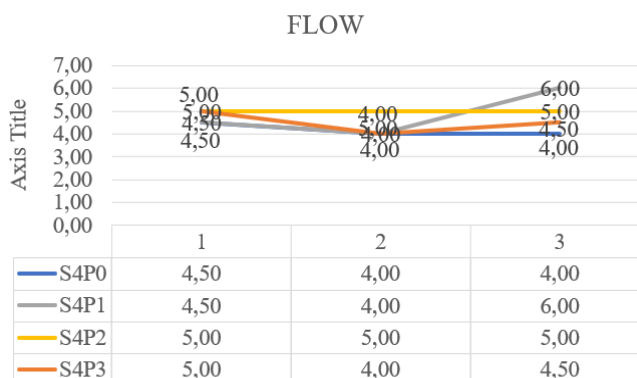


Figure 3. Flow Value

The Marshall Quotient provides further evidence of the difference in mechanical behavior because MQ increased from 139.45 kg/mm in the conventional mixture to 608.05 kg/mm in the modified specimen, compared with the specified minimum of 250 kg/mm. This increase reflects the simultaneous rise in Stability and reduction in Flow, indicating a substantially greater resistance to

deformation relative to the amount of displacement recorded at maximum loading. Polymer incorporation can increase mixture stiffness through changes in binder characteristics, although the magnitude of this effect depends on polymer type, concentration, compatibility, and processing conditions (Al-Shawabkeh et al., 2024). Research specifically examining Styrofoam-modified AC-WC has likewise reported that polystyrene incorporation can significantly influence Marshall characteristics and the resulting mechanical response of wearing-course mixtures (Amiruddin et al., 2021). The modified result should not be interpreted to mean that higher MQ values are inherently preferable without limit, because excessive stiffness may introduce other performance concerns that cannot be evaluated solely through Marshall testing. Within the parameters measured in this experiment, however, the transition from an MQ below the specified minimum to 608.05 kg/mm supports the mechanical advantage observed for the tested modified composition.

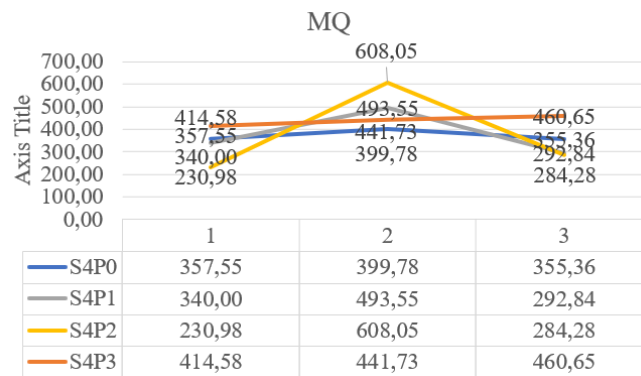


Figure 4. Marshall Quotient (MQ) Value

The volumetric comparison reveals an equally important transformation in the internal structure of the compacted mixtures, particularly through the reduction in VIM from 9.95 to 3.60. The conventional value exceeded the specified range of 3–5, whereas the modified value was positioned within that range, indicating a substantially lower proportion of air voids following modification. This reduction is relevant to pavement performance because excessive interconnected air voids can increase exposure of the internal mixture to air and moisture and may accelerate deterioration during service. Experimental studies of Styrofoam-containing AC-WC have demonstrated that the proportion and behavior of the polymer can affect volumetric properties together with Marshall performance, requiring both groups of parameters to be considered when evaluating mixture suitability (Delani & Patriotika, 2025). Recent evidence on Styrofoam-modified asphalt also emphasizes that the physical behavior of the modifier can influence the characteristics ultimately developed within AC-WC mixtures (Sani et al., 2026). The VIM comparison therefore indicates that the modified specimen achieved a denser internal condition relative to the conventional mixture without reducing the reported air-void content below the specified lower limit.

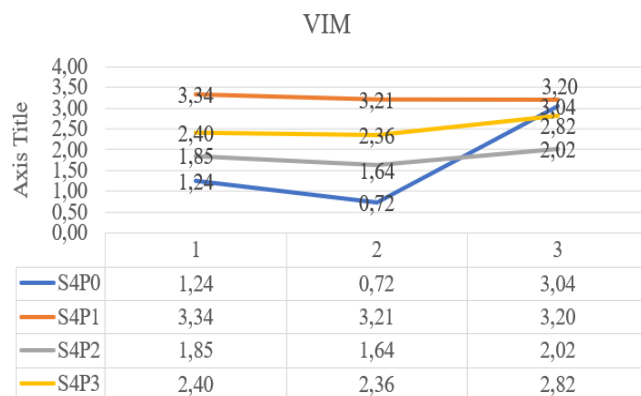


Figure 5. Void in Mix (VIM) Value

Changes in VMA and VFA complement the VIM result, with VMA increasing from 14.65 to 16.43 and VFA increasing from 32.43 to 89.15 after modification. The conventional VMA was slightly below the minimum requirement of 15, whereas the modified value exceeded this threshold, indicating sufficient space within the mineral aggregate structure for the combined volume of asphalt and remaining air voids. VFA exhibited an even more pronounced change, moving from well below the minimum requirement of 65 to 89.15, which indicates that a much larger proportion of the available mineral-aggregate void space was occupied by asphalt in the modified specimen. Variations in asphalt viscosity induced by waste Styrofoam and PVC can alter binder distribution and volumetric characteristics, providing a plausible material mechanism for changes in VIM, VMA, and VFA (Yuniarti et al., 2022). Related research using Styrofoam in modified AC-WC has also demonstrated that polymer-containing mixtures can develop distinct volumetric and Marshall characteristics when compared with conventional formulations (Ningtyias et al., 2025). The combined VIM, VMA, and VFA results consequently indicate that the improvement observed in mechanical performance was accompanied by a more favorable volumetric configuration according to the requirements adopted in the experiment.

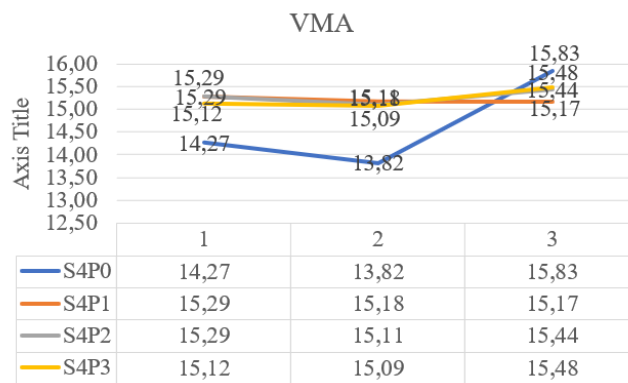


Figure 6. Void in Mineral Aggregate (VMA) Value

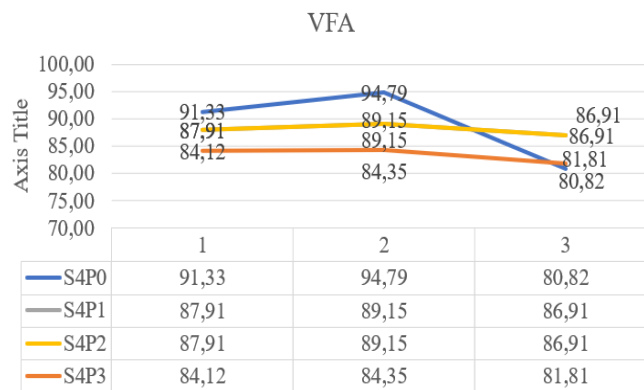


Figure 7. Void Filled with Asphalt (VFA) Value

From an engineering perspective, the simultaneous changes in Stability, Flow, MQ, VIM, VMA, and VFA are more informative than improvement in any single parameter because AC-WC performance depends on the interaction between structural resistance and internal mixture configuration. The modified specimen satisfied the stated criteria for all six evaluated parameters, whereas the conventional mixture at 5.8% asphalt content remained outside the corresponding requirements, indicating that the modification altered several interconnected aspects of mixture behavior. Research on recycled polymer materials supports the potential for such modifiers to enhance selected asphalt-mixture properties while simultaneously creating an engineering application for polymer waste that would otherwise present environmental-management challenges (Tayh et al., 2024). Studies involving Styrofoam specifically have also reported improvements in selected AC-WC

characteristics, although optimum performance remains dependent on additive content and mixture design rather than on the mere presence of polystyrene (Fatimah & Ningtyias, 2025). The experimental response is therefore best interpreted as evidence supporting the tested composition under controlled laboratory conditions rather than as proof that every combination or higher percentage of Styrofoam and PVC will produce equivalent performance. This distinction is essential for engineering application because mixture optimization requires performance-based selection of additive proportions rather than an assumption of a linear relationship between polymer content and pavement quality.

The comparative findings have practical implications for the development of polymer-modified AC-WC, but they also define clear boundaries for the conclusions that can be drawn from the experimental evidence. The substantial increase in Stability together with compliant Flow and volumetric characteristics suggests that the tested modified specimen has potential for further development as a wearing-course material, particularly when mechanical performance is considered alongside the opportunity to utilize Styrofoam and PVC waste. Prior experimental evidence involving PVC-modified AC-WC and recycled plastic asphalt similarly supports continued investigation of thermoplastic materials as pavement modifiers, while emphasizing that material compatibility and mixture design remain decisive for successful application (Veranita & Tripoli, 2021). The performance pattern also differs materially from the conventional baseline and reinforces the value of experimentally optimizing waste-derived additives rather than evaluating them solely from an environmental perspective. The present Marshall results do not, however, measure long-term rutting, fatigue cracking, moisture susceptibility, aging, thermal behavior, or field-scale performance, so those characteristics cannot be inferred from the reported Stability and volumetric improvements. Within these experimental boundaries, the combination of increased load resistance, controlled deformation, and specification-compliant void characteristics indicates that Styrofoam- and PVC-modified AC-WC warrants further mechanical and durability evaluation before its suitability for broader pavement implementation is established.

CONCLUSION

The experimental results demonstrate that the most favorable AC-WC mixture evaluated in this study was obtained with the addition of 4% Styrofoam (Expanded Polystyrene) and 2% PVC (Polyvinyl Chloride). In Sample 2, the modified mixture achieved a VIM value of 3.60%, VMA of 16.43%, VFA of 89.15%, Marshall Stability of 3040.27 kg, Flow of 3.00 mm, and Marshall Quotient of 608.05 kg/mm. These values satisfied the adopted requirements of the 2018 General Specifications of Bina Marga and showed a substantially more favorable response than the conventional AC-WC mixture evaluated at an optimum asphalt content of 5.8%. The improvement was reflected not only in the considerable increase in load-bearing capacity but also in the achievement of acceptable deformation and volumetric characteristics. The simultaneous compliance of Stability, Flow, MQ, VIM, VMA, and VFA indicates that the tested polymer composition provided an effective balance between mechanical resistance and the internal void structure of the compacted mixture. Within the scope of the laboratory experiment, the 4% Styrofoam and 2% PVC composition can consequently be identified as the best-performing mixture among the evaluated conditions and has potential for further development as a modified AC-WC pavement material.

Several methodological considerations should guide subsequent research to improve the precision, reproducibility, and engineering applicability of these findings. Laboratory conditions should be maintained in an orderly and clean state, while aggregate sieve analysis should be conducted carefully and uniformly because gradation directly influences the internal structure and mechanical response of AC-WC mixtures. Specimen compaction also requires rigorous control of the compactor operation to minimize differences in density and void characteristics attributable to preparation procedures rather than material composition. During Marshall testing, the use of digital data-recording equipment is recommended to improve the accuracy of Stability and Flow measurements and reduce potential errors associated with manual readings. Periodic inspection and calibration of laboratory equipment are equally important to prevent instrumental problems and maintain measurement reliability throughout the experimental program. Future studies should complement these procedural improvements with additional performance evaluations, including durability, moisture susceptibility, rutting, fatigue, aging, and field-scale validation, to determine whether the favorable laboratory

performance of the 4% Styrofoam and 2% PVC mixture can be maintained under long-term pavement service conditions.

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