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Styrofoam Waste as Partial Pen 60/70 Binder Replacement in AC-BC Marshall Characteristics

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Abstract – *Road pavements need materials that can improve asphalt mixture performance. This study analyzes styrofoam waste as a partial replacement for Pen 60/70 asphalt in Asphalt Concrete–Binder Course (AC-BC) mixtures. Styrofoam contents of 6%, 9%, and 12% by weight of asphalt (variations V1, V2, and V3) were compared with a normal mixture as the control. The styrofoam was added to hot asphalt before mixing with the aggregate (wet process). Marshall testing on three specimens per mixture covered Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), Voids in Mixture (VIM), flow, stability, Marshall Quotient (MQ), and density, following the 2025 General Specifications of the Directorate General of Highways (Direktorat Jenderal Bina Marga, 2025). The optimum asphalt content (OAC) was determined and compared with the control and specification limits. All variations met the AC-BC requirements. The OAC was 5.37% for the normal mixture and 5.12% for V1–V3, but the confirmation specimens were prepared at 5.37% (normal) and 4.87% (V1–V3), so their asphalt contents differ. Compared with the normal mixture, V1 (6% styrofoam, 94% asphalt) had higher stability (978.13 versus 896.46 kg) and MQ (303.98 versus 271.69 kg/mm), slightly lower flow (3.23 versus 3.30 mm) and VMA (14.86% versus 15.50%), and slightly higher VIM (3.94% versus 3.72%). No difference was statistically significant (ANOVA, $p > 0.05$), so V1 is only the most promising variation. The findings are limited to laboratory-scale Marshall results.*

Keywords: *Styrofoam waste; Pen 60/70 asphalt; AC-BC; Marshall test; asphalt modification*

I. INTRODUCTION

Roads are land transportation infrastructure that supports community mobility and smooth traffic flow, and road construction in Indonesia continues to grow along with economic growth (Pemerintah Republik Indonesia, 2006). Among the various road works, the Asphalt Concrete–Binder Course (AC-BC) layer is one of the most important. The Marshall characteristics of AC-BC mixtures, such as stability, flow, VIM, VMA, and VFA, depend on the aggregate gradation and the binder content (Direktorat Jendral Bina Marga, 2025), and previous research has shown that changes in the aggregate composition and gradation line affect these characteristics and the optimum asphalt content (Aziz et al., 2022; Frederiko et al., 2024). In this study the aggregate gradation was therefore kept constant, so that the effect of the binder modification could be examined separately.

Asphalt and aggregate are the main materials of flexible pavement. Heavy dependence on neat asphalt raises concerns about its future availability, so developing modified asphalt by blending it with other materials is an important step toward sustainable road construction (Kurniasari et al., 2022). Polymer modification is a well-established way to improve the physical and rheological properties of bitumen (Alnadish et al., 2023), and replacing part of the bitumen with plastic waste has been shown to be feasible from mechanical, economic, and environmental viewpoints (Lastra-González et al., 2022). Plastic packaging is rarely recycled and often ends up as waste, so its use in bitumen is also an environmental opportunity (Gökalp, 2022).

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Waste styrofoam has been reported to reduce the penetration and to increase the softening point and viscosity of bitumen (Gökalp, 2022), and styrofoam-modified binders show improved rutting resistance (Ramadan et al., 2020); when part of the bitumen is substituted by polystyrene in asphalt concrete, permanent deformation decreased (Vila-Cortavitarte et al., 2018). However, Gökalp (2022) found that waste styrofoam was compatible with the base bitumen only up to about 2–3% by weight and that fatigue resistance decreased as the styrofoam content increased. In contrast, polystyrene waste dissolved in a solution and blended into bitumen has been reported to improve storage stability and the elastic and rheological characteristics of the binder (Mahida et al., 2023). These findings show that compatibility depends on the polymer form and the mixing method, so the dosage and the mixing conditions must be investigated for each binder and mixture type. This study is one effort to improve the quality of AC-BC mixtures to improve pavement performance and extend its service life.

Styrofoam is a white, cork-like material that is lightweight, flexible, and resistant to acids, bases, and salts. However, it is very difficult to degrade and takes 500–1,000 years to decompose (Sampe et al., 2022). Food-packaging styrofoam is generally expanded polystyrene (EPS) (Gökalp, 2022). Polystyrene is a thermoplastic polymer that softens when heated and hardens again when cooled (Gökalp, 2022). Because it softens at the mixing temperature, it can be blended into hot asphalt, where it acts as a polymer modifier of the binder rather than as a like-for-like substitute. In this study it is therefore dosed as a percentage of the binder weight, and the term "partial replacement" is used to indicate this binder-weight basis, not that styrofoam is equivalent to asphalt.

Previous studies support this idea. Kurniasari et al. (2022) replaced Pen 60/70 asphalt with 0–15% styrofoam in Laston mixtures using wet and dry processes and obtained optimum contents of 12% (wet) and 15% (dry), with Marshall stability that still met the specification. Tisnawan et al. (2025) tested 0–12% styrofoam in AC-WC mixtures; contents of 6% and 8% gave the best Marshall characteristics, whereas 10% and 12% did not fully meet the specification. Marbun et al. (2022) reported that 1.5% styrofoam increased the stability and Marshall Quotient of AC-WC mixtures compared with unmodified Pen 60/70 asphalt. Studies on AC-BC mixtures are fewer: Sampe et al. (2022) and Faraknimela et al. (2022) used styrofoam as an additive in AC-BC mixtures made with river-stone aggregate. Internationally, EPS and polystyrene have been used both to modify bitumen and to replace part of it (Vila-Cortavitarte et al., 2018; Ramadan et al., 2020; Nciri et al., 2020; Mahida et al., 2021; Gökalp, 2022; Mahida et al., 2023), but the results depend on the dosage, the mixing conditions, and the compatibility of the polymer with the bitumen. Most of the Indonesian studies addressed AC-WC, and the optimum contents they obtained differ. The novelty of this study is that styrofoam is dosed at 6–12% of the binder weight by the wet process as a partial replacement for Pen 60/70 asphalt in AC-BC mixtures, with the OAC determined for each variation and the results evaluated against the 2025 Bina Marga General Specifications (Direktorat Jenderal Bina Marga, 2025).

Therefore, this study evaluates 6%, 9%, and 12% styrofoam waste by weight of asphalt as a partial replacement for Pen 60/70 asphalt in AC-BC mixtures, with a normal mixture as the control. The research questions are (1) how the styrofoam content affects the Marshall characteristics of the mixture and (2) which styrofoam content gives the best Marshall characteristics. The study is limited to hot-mix AC-BC with Pen 60/70 asphalt, styrofoam waste from used food packaging, and laboratory-scale testing.

II. METHODS

2.1 *Research Design and Materials*

This is a laboratory experimental study conducted at the Transportation Laboratory, Faculty of Engineering, Universitas Bengkulu. The mixtures were designed and tested in accordance with the 2025 General Specifications of the Directorate General of Highways (Direktorat Jenderal Bina Marga, 2025). Four mixtures were compared: the normal mixture (0% styrofoam : 100% asphalt) and three variations, V1 (6%: 94%), V2 (9%: 91%), and V3 (12%: 88%). The target design parameters were the OAC of each mixture and

compliance with the AC-BC Marshall criteria in Table 3: VIM 3.0–5.0%, VMA at least 14%, VFA at least 65%, stability at least 800 kg, flow 2–4 mm, Marshall Quotient (MQ) at least 250 kg/mm, and density at least 2.27 t/m³.

The binder was Pen 60/70 asphalt obtained from the laboratory. The coarse aggregate (crushed stone 1/2 and 1/1, particle size 4.75–25 mm) and the fine aggregate (passing the No. 4 sieve) came from the MRG Stone Crusher quarry and were blended to obtain the selected combined gradation (Table 1). The filler was Portland cement. The styrofoam came from food-packaging waste collected around Kandang Limun, Bengkulu, because it is abundant, relatively clean and homogeneous, and thin enough to cut easily. The styrofoam content is expressed by weight of asphalt in the dry condition, because the very low specific gravity of styrofoam would make proportions based on volume inconsistent.

The equipment used was available at the Civil Engineering Laboratory, Universitas Bengkulu, and included a Marshall testing machine, a Los Angeles abrasion machine, an automatic asphalt compactor, a set of sieves, a balance, specimen molds with a diameter of 10.2 cm and a height of 7.62 cm, an oven, a thermometer, and a water bath. The Portland cement filler was purchased from a local building-materials store. The research was carried out in stages, starting with a literature review, preparation of equipment and materials, and material testing, followed by mixed design to determine the optimum asphalt content (OAC), specimen preparation, Marshall testing, and data analysis. These stages are shown in Figure. 1.

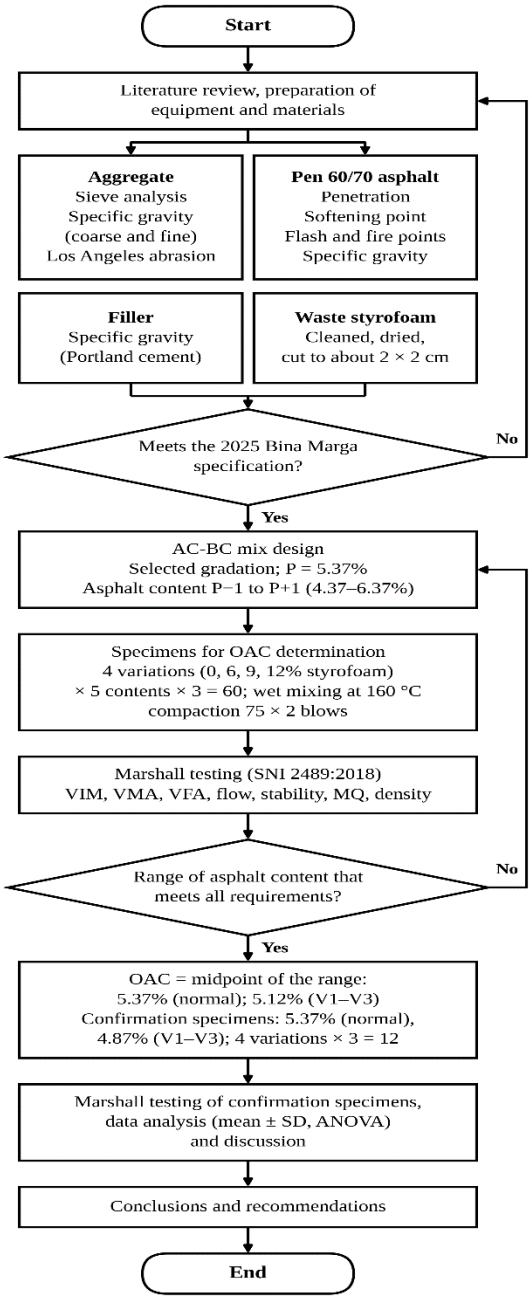


Figure 1. Research flowchart

2.2 *Material Preparation and Testing*

The styrofoam was collected, cleaned, dried to remove water, and cut into pieces of about 2 × 2 cm. Pen 60/70 asphalt was heated to 160 °C, after which the styrofoam was added and stirred until thoroughly mixed (wet process). This procedure follows the wet process of Kurniasari et al. (2022), in which the styrofoam pieces are added to the hot asphalt and mixed until completely and evenly blended before the modified asphalt is mixed with the heated aggregate. Mixing was done manually with a spatula in a pan and continued until the mixture appeared homogeneous (no fixed mixing time was recorded);

homogeneity was checked visually by inspecting the mixture to make sure that no styrofoam lumps or pieces remained. A separate container was used for each variation to prevent cross-contamination between variations, and the modified asphalt was prepared in slightly larger quantities than needed to allow for losses during heating, mixing, and transfer.

The asphalt was tested for penetration (SNI 2456:2011), softening point (SNI 2434:2011), specific gravity (SNI 2441:2011), and flash and fire points (SNI 2433:2011). The aggregate was tested for sieve analysis (SNI ASTM C136:2012), specific gravity and water absorption of coarse aggregate (SNI 1969:2016) and fine aggregate (SNI 1970:2016), and Los Angeles abrasion (SNI 2417:2008). The specific gravity of the filler was determined in accordance with SNI 2531:2015. All results were compared with the specification requirements (Direktorat Jenderal Bina Marga, 2025) before the mix design was prepared. Only the specific gravity of the modified binders (0%, 6%, 9%, and 12% styrofoam) was measured in this study.

2.3 *Mix Design*

The combined aggregate gradation was selected between the lower and upper limits of the AC-BC specification (Table 1 and Figure. 2). The aggregate and filler weight of one specimen was 1,245 g, consisting of 547.8 g of coarse aggregate, 622.5 g of fine aggregate, and 74.7 g of filler.

Table 1. Combined aggregate gradation of the AC-BC mixture (% passing)

Sieve	Lower	Selected	Upper
19 mm (3/4″)	90	95	100
12.5 mm (1/2″)	75	83	90
9.5 mm (3/8″)	66	74	82
4.75 mm (No. 4)	46	56	64
2.36 mm (No. 8)	30	40	49
1.18 mm (No. 16)	18	28	38
0.6 mm (No. 30)	12	20	28
0.3 mm (No. 50)	7	14	20
0.15 mm (No. 100)	5	10	13
0.075 mm (No. 200)	4	6	8

Source: (Direktorat Jenderal Bina Marga, 2025)

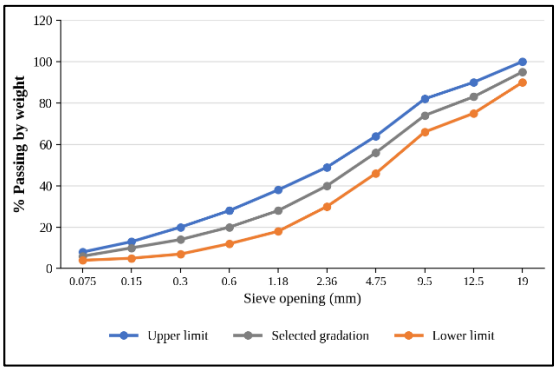


Figure 2. Selected aggregate gradation (grey line) and the upper and lower limits of the AC-BC specification (Direktorat Jenderal Bina Marga, 2025)

The mid-point asphalt content (P) was calculated using the formula of Departemen Permukiman dan Prasarana Wilayah (2002) in equation (1):

$$P = 0.035CA + 0.045FA + 0.18FF + K \quad (1)$$

where CA, FA, and FF are the percentages of coarse aggregate, fine aggregate, and filler, respectively, and K is a constant of 0.5–1.0 for Laston (0.5 was used). With CA = 44%, FA = 50%, and FF = 6%, P = 0.035(44) + 0.045(50) + 0.18(6) + 0.5 = 5.37% is obtained. The asphalt contents were then prepared as P−1 (4.37%), P−0.5 (4.87%), P (5.37%), P+0.5 (5.87%), and P+1 (6.37%). These contents are expressed as a percentage of the aggregate and filler weight (1,245 g per specimen), which corresponds to 4.19%, 4.64%, 5.10%, 5.54%, and 5.99% of the total mixture weight, respectively. The binder weight of one specimen is therefore 1,245 × P/100 g, and the styrofoam share (6%, 9%, or 12%) is part of this total binder weight, the remaining 94%, 91%, or 88% being Pen 60/70 asphalt. Table 2 gives the resulting binder and styrofoam amounts calculated from the total weight of asphalt for each planned variation.

Table 2. Binder weight per specimen and amount of styrofoam at the five asphalt contents (asphalt content as % of aggregate weight; V1, V2, and V3 = 6%, 9%, and 12% styrofoam by weight of binder; binder weight = 1,245 × P/100 g)

Asphalt (%)	Binder (g)	V1 (g)	V2 (g)	V3 (g)
4.37	54.41	3.26	4.90	6.53
4.87	60.63	3.64	5.46	7.28
5.37	66.86	4.01	6.02	8.02
5.87	73.08	4.38	6.58	8.77
6.37	79.31	4.76	7.14	9.52

2.4 *Specimen Preparation and Marshall Testing*

The aggregate and filler were oven-dried and heated, mixed with the hot asphalt at about 165 °C, and then compacted in molds at a minimum temperature of 130 °C with 75 blows on each side. After 24 hours at room temperature (20–25 °C), volumetric measurements were taken (diameter, height, dry weight, weight in water, and saturated surface-dry weight). The specimens were then immersed in a water bath at about 60 °C for approximately 30 minutes and loaded in the Marshall apparatus until failure to determine stability and flow (SNI 2489:2018).

Three specimens were made for each asphalt content and variation (4 variations × 5 contents × 3 = 60 specimens) to determine the OAC. The OAC was determined following the usual Bina Marga procedure: for each mixture, the range of asphalt contents that satisfied all Marshall requirements in Table 3 was identified, and the OAC was taken as the midpoint of this range (Section 3.2). After the OAC was obtained, three additional confirmation specimens were made for each variation (12 specimens), giving a total of 72 specimens. The confirmation specimens of the normal mixture were prepared at its OAC (5.37%), whereas those of V1, V2, and V3 were prepared at 4.87%, which lies within the range that satisfies all requirements but below their OAC of 5.12%. This content was chosen as the lowest asphalt content within that range because AC-BC is an intermediate layer whose function is to distribute traffic load, while the wearing course above it provides water-tightness, so a lower binder content is acceptable; a lower binder content also gives a stiffer mixture, which suits a layer that must resist deformation while transmitting load, and reduces binder cost. The consequences are discussed in Section 3.5. VIM, VMA, VFA, and MQ were calculated as VIM = (1 − Gmb/Gmm) × 100, VMA = 100 − (Gmb × Ps/Gsb), VFA = (VMA − VIM)/VMA × 100, and MQ = stability/flow, where Gmb is the bulk specific gravity of the compacted mixture, Gmm the maximum specific gravity of the mixture, Gsb the bulk specific gravity of the aggregate adopted in the calculation (2.614, the bulk specific gravity of the coarse aggregate in Table 4), and Ps the aggregate content as a percentage of the total mixture weight. Gmm was calculated theoretically from the mixture composition, the Gsb of the aggregate, and the specific gravity of each binder; it was not measured with a Rice test (the values are given in Table 8). Results are reported as the mean ± standard deviation (SD) of three specimens and are compared with the AC-BC requirements in Table 3. Differences among the four mixtures were tested for each parameter by one-way analysis of variance (ANOVA) at a significance level of 0.05.

Table 3. Marshall requirements for AC-BC mixtures

Mixture property	Requirement
VIM (%)	3.0–5.0
VMA (%)	min. 14
VFA (%)	min. 65
Stability (kg)	min. 800
Flow (mm)	2–4
Marshall Quotient (kg/mm)	min. 250
Density (t/m³)	min. 2.27
Blows per face	75

Source: (Direktorat Jenderal Bina Marga, 2025)

III. RESULTS AND DISCUSSION

3.1 *Material Properties*

The aggregate test results are summarized in Table 4. The differences between the specific gravities of the coarse and fine aggregates are 0.06 (bulk), 0.07 (SSD), and 0.10 (apparent), all below the maximum limit of 0.20, which indicates uniform aggregates. The water absorption of the coarse and fine aggregates is 2.02% and 2.46%, respectively. The Los Angeles abrasion values are 20.68% and 19.64% (average 20.16%), below the 30% limit, so the aggregate is hard enough to withstand abrasion and impact during mixing, compaction, and traffic loading. The sieve analysis curve lies between the upper and lower limits of the AC-BC gradation (Figure. 2).

Table 4. Specific gravity (SG) and water absorption of the coarse and fine aggregates and the difference

between the specific gravities (maximum allowed 0.20)

Test	Coarse	Fine	Difference (max. 0.20)
Bulk SG	2.61	2.67	0.06
SSD SG	2.67	2.74	0.07
Apparent SG	2.76	2.86	0.10
Water absorption (%)	2.02	2.46	–

The properties of the asphalt and filler are given in Table 5. The Pen 60/70 asphalt has a penetration of 65.9 (0.1 mm), which falls within the 60–70 class, and a softening point of 50.5 °C, which is above the minimum of 48 °C for Pen 60/70 asphalt in the Bina Marga specification. The flash point of 325 °C and the fire point of 375 °C are consistent with safe heating; the flash point is above the minimum of 232 °C for Pen 60/70 asphalt, so the asphalt can be heated to the mixing temperature of about 165 °C without ignition. The specific gravity of the Portland cement filler is 2.778.

Table 5. Properties of the asphalt and filler (requirements are for Pen 60/70 asphalt)

Test	Result	Requirement	Standard
Penetration (0.1 mm)	65.9	60–70	SNI 2456:2011
Softening point (°C)	50.5	≥48	SNI 2434:2011
Flash point (°C)	325	≥232	SNI 2433:2011
Fire point (°C)	375	–	SNI 2433:2011
Asphalt specific gravity	1.007	≥1.0	SNI 2441:2011
Filler specific gravity	2.778	–	SNI 2531:2015

The specific gravity of the material decreases as the styrofoam content increases, namely 1.007 (0%), 0.993 (6%), 0.984 (9%), and 0.977 (12%) (Figure. 3). This occurs because styrofoam has a much lower density than asphalt, so replacing part of the asphalt lowers the specific gravity of the modified asphalt. This shows that styrofoam changes the physical properties of the asphalt, which are then evaluated through the following mixture tests. The penetration, softening point, and viscosity of the modified binders were not measured, so the effect of styrofoam on binder consistency could not be assessed directly.

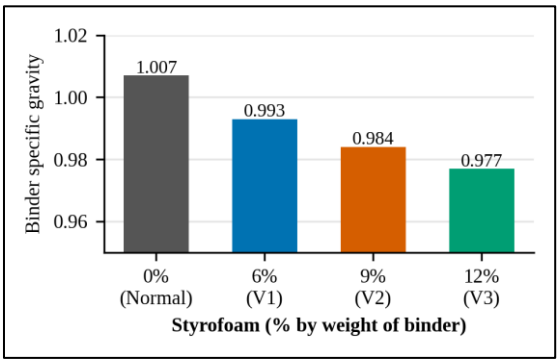
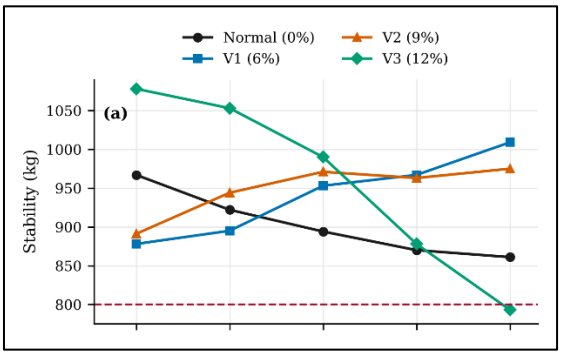


Figure 3. Specific gravity of the binder at 0%, 6%, 9%, and 12% styrofoam by weight of binder (Normal, V1, V2, and V3)

3.2 *Determination of Optimum Asphalt Content*

Figure 4–6 show the Marshall properties of the four mixtures at five asphalt contents, and Table 6 lists all Marshall properties, with values outside the requirements marked by an asterisk. The error bars in Figure 4–6 show ±1 SD of three specimens. For the normal mixture, stability decreased from 966.97 kg at an asphalt content of 4.37% to 860.50 kg at 6.37%. For V1 and V2, stability increased with asphalt content up to 1,008.87 kg and 974.96 kg at 6.37%. For V3, the highest stability occurred at the lowest asphalt content (1,077.18 kg) and decreased to 792.68 kg at 6.37%, below the minimum limit of 800 kg. The flow of V3 also rose to 4.03 mm at 6.37% and exceeded the 4 mm limit.



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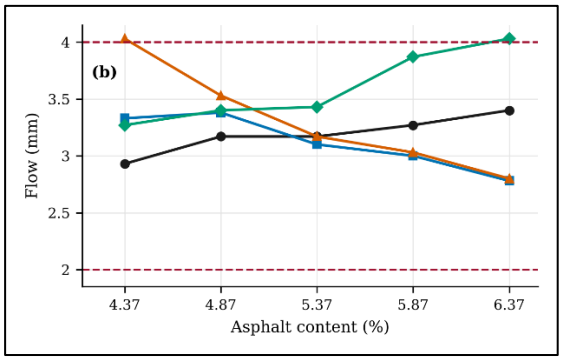


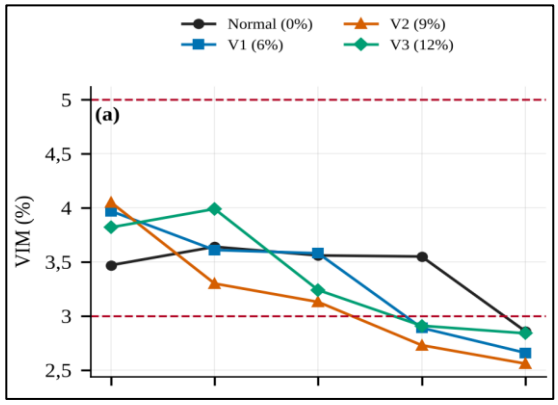
(b)

Figure 4. Effect of asphalt content on (a) stability and (b) flow of the normal mixture and V1–V3 (6%, 9%, and 12% styrofoam by weight of binder); dashed lines are the specification limits, and error bars are ±1 SD (n = 3), with the points shifted slightly sideways for clarity

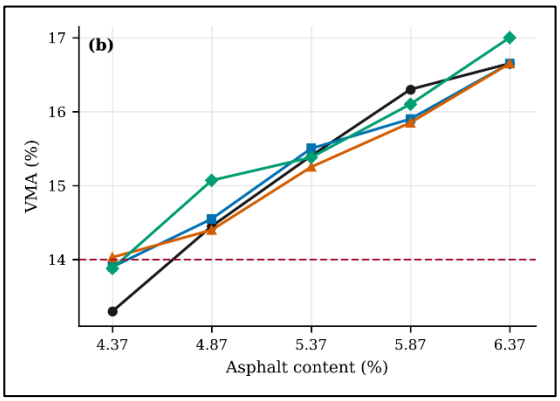
Table 6. Marshall properties at the five asphalt contents (mean of three specimens; P = asphalt content as % of aggregate weight; Normal = 0% styrofoam; V1–V3 = 6%, 9%, and 12% styrofoam by weight of binder; * = outside the requirements in Table 3)

P (%)	VIM (%)	VMA (%)	VFA (%)	Flow (mm)	Stab. (kg)	MQ (kg/mm)	Dens. (t/m³)
Normal (0% styrofoam)							
4.37	3.47	13.30*	73.97	2.93	966.97	338.81	2.365
4.87	3.64	14.46	74.80	3.17	921.23	291.64	2.345
5.37	3.56	15.36	76.85	3.17	893.33	282.22	2.331
5.87	3.55	16.30	78.35	3.27	868.98	266.24	2.316
6.37	2.86*	16.64	82.83	3.40	860.50	260.96	2.318
V1 (6% styrofoam)							
4.37	3.97	13.88*	71.47	3.33	877.61	264.72	2.350
4.87	3.61	14.56	75.27	3.37	894.91	268.85	2.342
5.37	3.58	15.52	76.99	3.10	951.84	309.21	2.327
5.87	2.89*	15.89	81.80	3.00	966.48	324.46	2.328
6.37	2.66*	16.64	84.02	2.77	1,008.87	366.61	2.318
V2 (9% styrofoam)							
4.37	4.05	14.03	71.58	4.03*	890.42	221.50*	2.345
4.87	3.30	14.38	77.11	3.53	943.16	267.16	2.347
5.37	3.13	15.23	79.45	3.17	971.11	306.85	2.335
5.87	2.73*	15.85	82.79	3.03	962.24	319.83	2.329
6.37	2.56*	16.66	84.68	2.80	974.96	349.08	2.317
V3 (12% styrofoam)							
4.37	3.82	13.89*	72.64	3.27	1,077.18	331.45	2.349
4.87	3.99	15.06	73.49	3.40	1,052.83	309.76	2.328
5.37	3.24	15.39	79.01	3.43	989.40	288.29	2.330
5.87	2.91*	16.09	81.92	3.87	877.46	226.91*	2.322
6.37	2.84*	16.99	83.34	4.03*	792.68*	196.68*	2.308

The volumetric properties show the expected trends (Figures. 5 and 6). VMA and VFA increase and VIM generally decreases with asphalt content because more of the voids are filled with asphalt. MQ decreases with asphalt content for the normal mixture and V3, from 338.81 to 260.96 kg/mm and from 331.45 to 196.68 kg/mm, respectively, but increases for V1 and V2, from 264.72 to 366.61 kg/mm and from 221.50 to 349.08 kg/mm, respectively. The very high VFA of 82–85% at the highest asphalt content also indicates that a large proportion of the voids is filled with asphalt at this content. The stability of the normal mixture and V3 was highest at the lowest tested asphalt content (Table 6), and the stability of V2 did not increase monotonically (971.11, 962.24, and 974.96 kg at 5.37%, 5.87%, and 6.37%), which suggests that specimen scatter is considerable so the stability alone does not determine the OAC.



(a)



(b)

Figure 5. Effect of asphalt content on (a) VIM and (b) VMA of the normal mixture and V1–V3 (6%, 9%, and 12% styrofoam by weight of binder); dashed lines are the specification limits, and error bars are ±1 SD (n = 3)

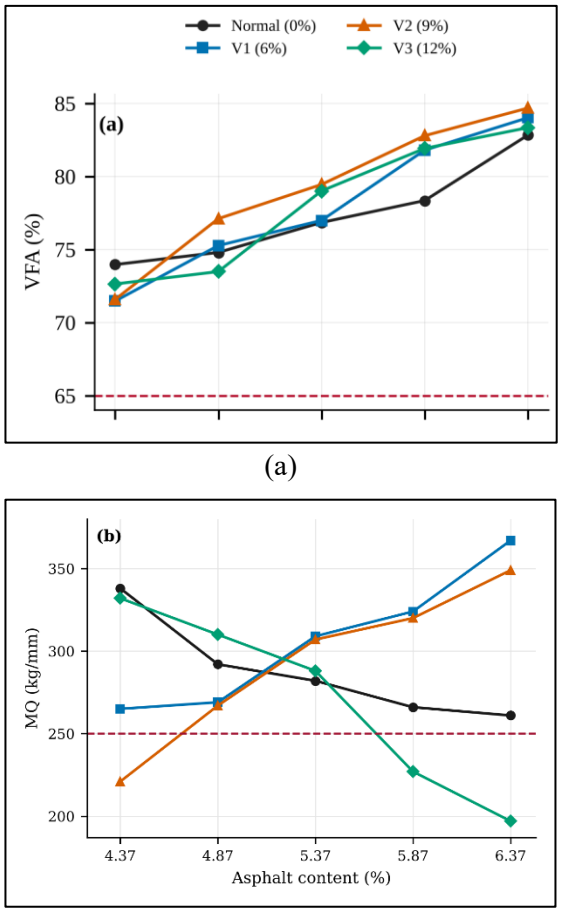


Figure 6. Effect of asphalt content on (a) VFA and (b) Marshall Quotient of the normal mixture and V1–V3 (6%, 9%, and 12% styrofoam by weight of binder); dashed lines are the specification limits, and error bars are ±1 SD (n = 3)

The OAC was determined as the midpoint of the range of asphalt contents that met all requirements (Section 2.4). For the normal mixture, all requirements were met at 4.87–5.87% (Table 6; VMA was below 14% at 4.37%, and VIM was below 3% at 6.37%), which gives an OAC of 5.37%. For V1, V2, and V3, all requirements were met at 4.87–5.37%: at 4.37% the requirements were not met (VMA for V1 and V3; flow and MQ for V2), and at 5.87% VIM fell below 3%, which gives an OAC of 5.12% (Table 7). A possible explanation is that the melted styrofoam stiffens the binder and improves its adhesion to the aggregate, which would allow the requirements to be met with less asphalt. This is a hypothesis: the viscosity of the modified binders was not measured, and a higher viscosity would normally make compaction more difficult rather than easier, so binder tests and microscopy are needed to confirm the mechanism. The lower OAC (5.12% versus 5.37%) corresponds to about 4.7% less asphalt by aggregate weight, which suggests a possible saving in asphalt, although this was not evaluated economically in this study. The confirmation specimens of V1–V3 were prepared at 4.87%, about 9% less asphalt than the 5.37% of the normal specimens (Section 3.5).

Table 7. Optimum asphalt content (OAC, % of aggregate weight), taken as the midpoint of the range that met all requirements; Normal = 0% styrofoam, V1–V3 = 6%, 9%, and 12% styrofoam by weight of binder. The confirmation specimens were prepared at 5.37% (Normal) and 4.87% (V1–V3)

Mixture	OAC (%)
Normal	5.37
V1	5.12
V2	5.12
V3	5.12

3.3 *Marshall Characteristics at the OAC*

Table 8 gives the Marshall characteristics of the confirmation specimens of the four mixtures (asphalt content 5.37% for the normal mixture and 4.87% for V1–V3), and Figures. 7 and 8 compare them with the specification. All parameters of all mixtures met the requirements of the 2025 Bina Marga specification. None of the differences among the mixtures was statistically significant (Section 3.4). The theoretical maximum specific gravity (Gmm) used in the calculations is also listed in Table 8.

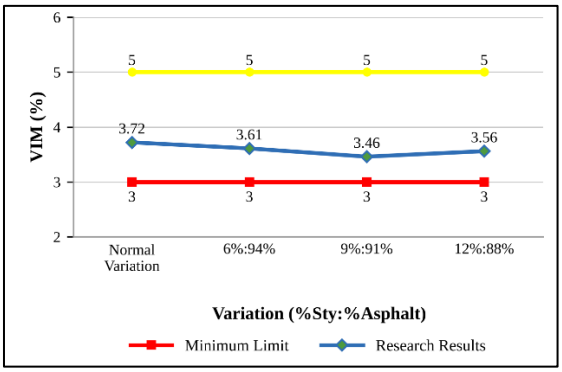
Table 8. Marshall characteristics of the confirmation specimens (mean ± SD, n = 3; asphalt content 5.37% for Normal and 4.87% for V1–V3; Normal = 0% styrofoam; V1–V3 = 6%, 9%, and 12% styrofoam by weight of binder; Gmm = maximum specific gravity of the mixture,

calculated from the composition; limits from Direktorat Jenderal Bina Marga, 2025)

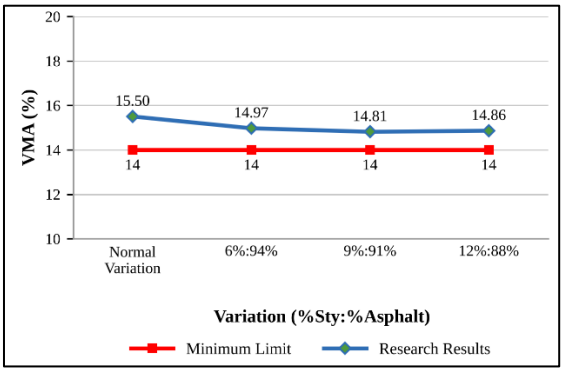
Parameters	Normal	V1	V2	V3	Limit
Gmm (t/m³)	2.417	2.430	2.427	2.425	–
VIM (%)	3.72 ± 0.44	3.94 ± 0.44	3.79 ± 0.42	3.89 ± 0.19	3–5
VMA (%)	15.50 ± 0.39	14.86 ± 0.39	14.81 ± 0.37	14.97 ± 0.17	≥14
VFA (%)	76.04 ± 2.25	73.52 ± 2.29	74.44 ± 2.20	74.00 ± 0.97	≥65
Flow (mm)	3.30 ± 0.17	3.23 ± 0.25	3.27 ± 0.15	3.00 ± 0.20	2–4
Stability (kg)	896.46 ± 48.1	978.13 ± 53.2	964.97 ± 54.8	974.82 ± 92.0	≥800
MQ (kg/mm)	271.69 ± 6.0	303.98 ± 33.2	295.85 ± 21.8	324.80 ± 17.3	≥250
Density (t/m³)	2.327 ± 0.011	2.334 ± 0.011	2.335 ± 0.010	2.331 ± 0.005	≥2.27

3.3.1 Voids in the mixture (VIM)

VIM is 3.72% for the normal mixture, 3.94% for V1, 3.79% for V2, and 3.89% for V3, which is a relative increase of 5.91%, 1.88%, and 4.57% compared with the normal mixture (Figure. 7a). All values are within the 3.0–5.0% range. The differences are smaller than the standard deviations (0.19–0.44 percentage points), so the VIM of the styrofoam mixtures cannot be distinguished from that of the normal mixture (ANOVA, p = 0.89). The slightly higher VIM may be related to the lower asphalt content of V1–V3 (4.87% compared with 5.37% for the normal mixture), because VIM generally decreases with asphalt content (Figure. 5a). A direct effect of styrofoam on the voids is doubtful, because at 6–12% of the binder it is only about 0.3–0.6% of the mixture weight, and a possible effect of changed binder behavior during compaction was not verified here. This result differs from Sampe et al. (2022), who reported fewer air voids with styrofoam added to AC-BC. All VIM values are above the 3.0% lower limit, but the asphalt content, styrofoam content, and compaction still need to be controlled in the field.



(a)



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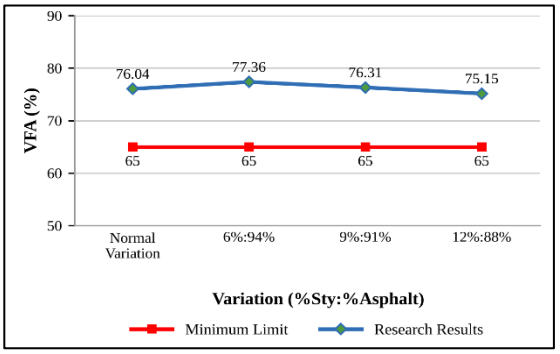


(c)

Figure 7. Volumetric properties of the confirmation specimens: (a) VIM, (b) VMA, (c) VFA; the red and yellow lines are the minimum and maximum specification limits, "Research Results" are the mean values (Normal at 5.37%; 6%:94%, 9%:91%, and 12%:88% styrofoam:asphalt at 4.87%), and error bars are ±1 SD (n = 3)

3.3.2 Voids in mineral aggregate (VMA)

VMA is 15.50% (normal), 14.86% (V1), 14.81% (V2), and 14.97% (V3). All styrofoam mixtures are 0.53–0.69 percentage points (3.42–4.45% relative) lower than the normal mixture but remain above the 14% minimum, so sufficient space is still available for the asphalt. This is consistent with Marbun et al. (2022), who found lower VMA in AC-WC with 1.5%

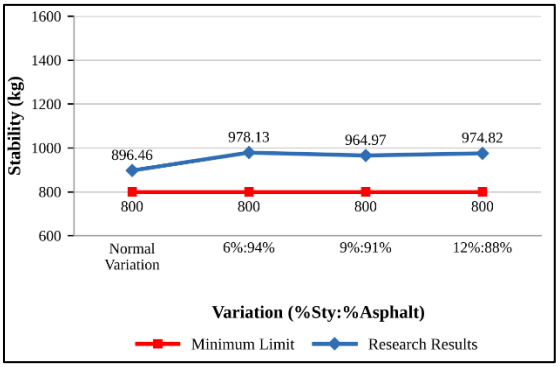
styrofoam. In this study, the lower VMA is also consistent with the lower asphalt content of the styrofoam mixtures (4.87% compared with 5.37%), because VMA increases with asphalt content (Kurniasari et al., 2022). The lowest VMA (14.81%, V2) is only 0.81 percentage points above the minimum limit, and the difference from the normal mixture is not statistically significant (ANOVA, p = 0.13).

3.3.3 Voids filled with asphalt (VFA)

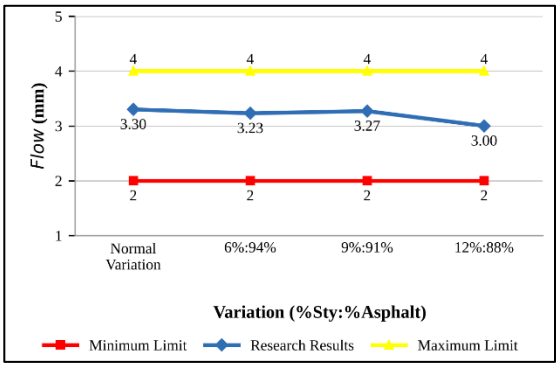
VFA is 76.04% (normal), 73.52% (V1), 74.44% (V2), and 74.00% (V3). All styrofoam mixtures are 1.60–2.52 percentage points lower than the normal mixture (relative decreases of 3.31%, 2.10%, and 2.68% for V1, V2, and V3), but all values exceed the 65% minimum. The lower VFA, together with the slightly higher VIM and lower VMA, means that a slightly smaller share of the voids is filled with asphalt, which is consistent with the lower asphalt content of V1–V3 (4.87% compared with 5.37%). The standard deviations (0.97–2.29 percentage points) are of the same order as the differences (ANOVA, p = 0.49), so they should not be over-interpreted, and a higher or lower VFA is not in itself a performance advantage.

3.3.4 Stability, flow, and Marshall Quotient

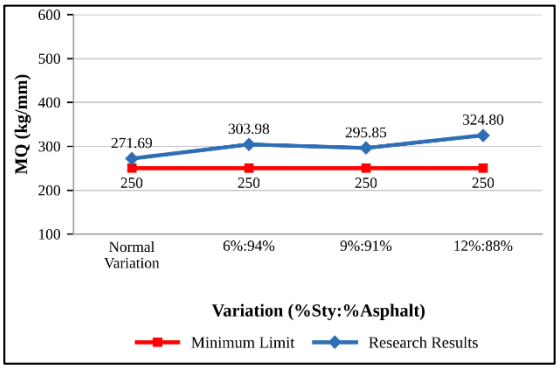
Stability is 896.46 kg for the normal mixture and 978.13 kg (V1), 964.97 kg (V2), and 974.82 kg (V3), relative increases of 9.11%, 7.64%, and 8.74% (Figure. 8a). All values are above 800 kg. Higher stability means that the mixture can withstand a greater load before failure. This is consistent with Marbun et al. (2022), who found a 12.95% increase in AC-WC stability with 1.5% styrofoam, and Kurniasari et al. (2022), who attributed it to better adhesion of the modified asphalt to the aggregate. The increase is not proportional to the styrofoam content: V1 (6%) is the highest and the other two variations are similar, so adding more than 6% styrofoam gives no additional stability in this study. The standard deviations (48–92 kg) are of the same order as the differences, and the increase is not statistically significant (one-way ANOVA, p = 0.41; V1 versus normal, t-test, p = 0.12), so it should be regarded as a trend only. Because the Marshall test does not measure rutting resistance directly, the higher stability and MQ only indicate that the mixtures may resist rutting better under heavy traffic; this needs to be confirmed with wheel-tracking tests.



(a)



(b)



(c)

Figure 8. Mechanical properties of the confirmation specimens: (a) stability, (b) flow, (c) MQ of the normal mixture (5.37%) and V1–V3 (6%, 9%, and 12% styrofoam by weight of binder, 4.87%); the red and yellow lines are the minimum and maximum specification limits, and error bars are ±1 SD (n = 3)

Flow decreases from 3.30 mm (normal) to 3.23 mm (V1), 3.27 mm (V2), and 3.00 mm (V3), relative decreases of 2.12%, 0.91%, and 9.09% (Figure. 8b; ANOVA, p = 0.31). All values are within the 2–4 mm range. A lower flow indicates a stiffer mixture with less

capacity for deformation, consistent with Sampe et al. (2022) and Faraknimela et al. (2022), who reported lower flow with styrofoam. The lowest flow (3.00 mm, V3) is still 1.00 mm above the lower limit.

MQ, the ratio of stability to flow, rises from 271.69 kg/mm to 303.98 kg/mm for V1 (a relative increase of 11.88%), 295.85 kg/mm for V2 (8.89%), and 324.80 kg/mm for V3 (19.55%) (Figure. 8c). The overall ANOVA for MQ was not significant ($p = 0.09$); only V3 differed from the normal mixture in an unadjusted pairwise t-test ($p = 0.007$), which should be interpreted with caution because of the small number of specimens and the multiple comparisons. This increase results from higher stability combined with lower flow, and it is largest for V3 because its decrease in flow is the greatest. Marbun et al. (2022) also reported a higher MQ for modified asphalt (261.07 compared with 207.02 kg/mm). A high MQ indicates stiffness, which can help the mixture resist deformation but makes it more prone to cracking; therefore, the balance between stability and flow needs attention at high styrofoam contents. In practice, higher stiffness may be beneficial on heavily trafficked roads in hot climates because it may improve rutting resistance, but it may also increase the risk of cracking, especially under repeated loading, and this needs to be checked with fatigue and cracking tests.

3.3.5 Density

Density is 2.327 t/m³ for the normal mixture and 2.334, 2.335, and 2.331 t/m³ for V1, V2, and V3 (relative increases of 0.30%, 0.34%, and 0.17%). All values are above the 2.27 t/m³ minimum. The differences (at most 0.008 t/m³) are smaller than the standard deviations (0.005–0.011 t/m³; ANOVA, $p = 0.75$) and should not be over-interpreted.

3.4 *Overall Comparison and Best Variation*

Each parameter has its own best variation: the normal mixture has the lowest VIM (3.72%) and the highest VMA (15.50%), VFA (76.04%), and flow (3.30 mm); V1 has the highest stability (978.13 kg); V2 has the highest density (2.335 t/m³); and V3 has the highest MQ (324.80 kg/mm). Because all mixtures meet all requirements, the choice depends on the balance between strength and flexibility. V1 has the highest stability (+9.11%), its flow is almost the same as that of the normal mixture (−2.12%), and its VIM, VMA, VFA, and density remain within the limits. V1 (6% styrofoam: 94% asphalt) is therefore considered the most promising variation at laboratory scale, but this choice rests on stability and MQ only and is not supported by a statistically significant difference. This result is consistent with Tisnawan et al. (2025), who stated that 6% is among the best contents in AC-WC, whereas Kurniasari et al. (2022) reported a higher optimum content (12%) in a different mixture.

The confirmation specimens are represented by three specimens per variation. One-way ANOVA showed no significant difference among the four mixtures for any parameter at the 0.05 level ($p = 0.09$–0.89), so small differences among V1, V2, and V3, for example in stability (964.97–978.13 kg), cannot be considered significant. The limitations of the study are discussed in Section 3.5.

3.5 *Limitations of the Study*

Statistical and specimen limitations. Each mixture is represented by only three specimens. Standard deviations are reported, but no significant difference was found among the mixtures (ANOVA, Table 8), so the gains in stability and MQ are indicative only. Specimens made at the same asphalt content in two separate sets also differed: at 4.87%, the stability of V1, V2, and V3 was 894.91, 943.16, and 1,052.83 kg in the OAC-determination set (Table 6) and 978.13, 964.97, and 974.82 kg in the confirmation set, differences of +9.3%, +2.3%, and −7.4%, which are of the same order as the reported gains. The comparison with the control is also affected by the different asphalt contents: the normal specimens were prepared at 5.37% and the V1–V3 specimens at 4.87% (about 9% less asphalt), and the V1–V3 specimens were not prepared at their OAC of 5.12%, so the effect of styrofoam cannot be separated from the effect of asphalt content. At the same 4.87% in the OAC-determination set (Table 6), the stability of V1 (894.91 kg) was lower than that of the normal mixture (921.23 kg), whereas V2 and V3 (943.16 and 1,052.83 kg) were higher. At 5.37%, the stability of V1, V2, and V3 (951.84, 971.11, and 989.40 kg) is 6.5%, 8.7%, and 10.8% higher than that of the normal mixture (893.33 kg).

Material and procedural limitations. Only the specific gravity of the modified binders was measured; penetration, softening point, viscosity, and storage stability were not determined, so the mechanisms discussed above (viscosity, void filling, and adhesion) remain hypotheses. Polystyrene-modified bitumen may be prone to phase separation during hot storage (Gökalp, 2022), which was not examined here. The OAC was identified only to the resolution of the tested contents (0.5% steps), and the V1–V3 confirmation specimens were prepared at 4.87% instead of the OAC of 5.12%. Gmm was calculated from the aggregate bulk specific gravity and the binder specific gravity and was not measured by the Rice test, so the absolute values of VIM, VMA, and VFA should be taken as indicative. The same Gsb of 2.614 (the bulk specific gravity of the coarse aggregate) was used for all mixtures; a Gsb weighted over the coarse aggregate, fine aggregate, and filler would be slightly higher (about 2.65 from Tables 4 and 5), which would raise the calculated Gmm, VIM, and VMA and lower VFA, so the values should be read as relative comparisons among mixtures prepared with the same calculation basis.

Performance and economic limitations. The Marshall test does not measure rutting, fatigue, or moisture damage. Durability, moisture susceptibility (for example the tensile strength ratio test of ASTM D4867/D4867M; ASTM International, 2014), and wheel-tracking tests were not performed. Economic feasibility (the cost of collecting, cleaning, and processing styrofoam waste compared with the asphalt saved) and environmental effects were not evaluated, so the possible asphalt saving of about 4.7% by aggregate weight at the OAC and about 9% at the 4.87% used for the confirmation specimens is only indicative.

IV. CONCLUSION

This study evaluated 6%, 9%, and 12% styrofoam waste by weight of binder as a partial replacement for Pen 60/70 asphalt in AC-BC mixtures, asking how the styrofoam content affects the Marshall characteristics and which content gives the best overall characteristics. All mixtures met the 2025 Bina Marga requirements for AC-BC. The OAC was 5.37% for the normal mixture and 5.12% for V1, V2, and V3 (about 4.7% less asphalt by aggregate weight), and the V1–V3 confirmation specimens were prepared at 4.87%. Compared with the normal mixture, stability (964.97–978.13 kg versus 896.46 kg) and MQ (295.85–324.80 kg/mm versus 271.69 kg/mm) were higher and flow was lower (3.00–3.27 mm versus 3.30 mm) in all styrofoam mixtures, whereas VIM was slightly higher (3.79–3.94% versus 3.72%) and VMA (14.81–14.97% versus 15.50%) and VFA (73.52–74.44% versus 76.04%) were lower. Variation 1 (6% styrofoam and 94% asphalt) had the highest stability (+9.11%) with a flow close to that of the normal mixture and was therefore considered the most promising variation at laboratory scale; the differences among V1, V2, and V3 were small. These findings indicate that styrofoam waste could reduce asphalt use and provide an outlet for plastic waste, but cost and environmental effects were not evaluated. The conclusions are limited to laboratory Marshall results from three specimens per mixture, none of the differences among the mixtures was statistically significant, the normal and modified specimens were prepared at different asphalt contents, and durability, moisture susceptibility, and field performance were not assessed. Further research is recommended around the 6% styrofoam content, for example 4–8% in smaller increments, with more specimens and statistical testing, together with binder characterization (penetration, softening point, viscosity, and storage stability), performance tests (rutting and moisture susceptibility, for example ASTM D4867/D4867M), and field-scale trials, to confirm the optimum composition for AC-BC mixtures.

AUTHOR CONTRIBUTIONS

Conceptualization: CAL, SB, AF;
Data curation: CAL, SB, AF;
Formal analysis: CAL, SB, AF;
Methodology: CAL, SB, AF, MW, FS;
Validation: SB, AF, MW, FS;
Visualization: CAL, SB, AF, MW, FS;
Writing: CAL, SB, AF, MW, FS;

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of this study (Marshall test measurements for all specimens) are available from the corresponding author upon reasonable request.

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