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Performance Analysis of Porous Asphalt Incorporating Siwalan Fruit Shell Powder as Sustainable Filler Material

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ABSTRACT: Porous asphalt is an open-graded combination with a lot of air voids that is meant to improve drainage on the surface. Nonetheless, the utilization of organic waste as an alternate filler remains inadequately investigated. This study seeks to assess the Marshall properties of porous asphalt utilizing siwalan (*Borassus flabellifer*) shell powder as a sustainable filler alternative. The study commenced with preliminary material testing (coarse and fine aggregates, PG 70 asphalt, and filler) in accordance with Bina Marga 2018 specifications, succeeded by laboratory evaluations of Marshall parameters, Asphalt Flow Down (AFD), and Cantabro Loss at asphalt contents of 4%, 4.5%, 5%, 5.5%, and 6%. The results showed that all of the materials met the required specifications. At 4% asphalt concentration, the Marshall stability was at its highest. As the asphalt percentage went up, the VIM and VMA went down, and the VFB went up. AFD results met AAPA (2004) criteria (≤0.3%) only when the asphalt content was 4% or 4.5%. The Cantabro Loss requirements were met when the asphalt content was between 4.5% and 6%. The best amount of asphalt was found to be 4% based on the VIM, AFD, and Cantabro Loss standards. These results indicate that siwalan shell powder is a technically feasible filler material in porous asphalt mixtures and promotes the sustainable utilization of organic waste. It is advisable to do additional research to evaluate the long-term efficacy of the mixture in real-world settings. The study suggests an effective method for encouraging environmentally friendly pavement building through the use of locally sourced waste materials.

KEYWORDS: Porous asphalt; siwalan shell powder; sustainable filler; optimum asphalt content; Marshall stability

1. Introduction

Road infrastructure was very important for socio-economic development, as it facilitated mobility, trade, and connectivity between regions. According to Indonesian Road Law No. 13 of 1980, road networks were required to include pavement structures and supporting facilities to ensure the safety and comfort of drivers. Flexible pavements that used asphalt as a binder needed appropriate materials and mix design to withstand traffic loads and environmental changes. Porous asphalt (PA) was an open-graded asphalt mixture designed to enhance surface drainage, reduce the risk of hydroplaning, and lower the likelihood of skidding by incorporating a high volume of interconnected air voids. Recent studies demonstrated that, although porous asphalt exhibited enhanced functional performance, it was significantly prone to durability issues, including raveling, binder drain-down, and diminished abrasion resistance, attributable to its low fine aggregate content and thin binder layer [1–3].

To address these constraints, recent research focused on improving mixture composition through binder modification, regulation of aggregate morphology, and the integration of alternative fillers [4–6]. Examples of modified binders, such as bio-based epoxy asphalt [4], asphalt rubber [6], and high-viscosity binders [5], were shown to improve the raveling resistance and fatigue performance of porous asphalt mixtures. Additionally, the incorporation of cured carbon fiber composites [7], basalt fiber [8], and synthetic fiber [9] to reinforce the mixtures was found to reduce cracking and increase durability. Besides modifying binders and fibers, the use of various filler materials gained popularity as an environmentally friendly approach to enhance asphalt mixture performance. Numerous studies showed that fillers made from waste and biomass significantly affected the stiffness, internal friction, and binder absorption capacity of asphalt mastic [10–12].

Fine solid wastes such as recycled concrete powder [13], waste glass fiber-reinforced polymer [14], coal gangue [15], and oil shale waste [16] were successfully utilized to strengthen and increase the longevity of porous asphalt and asphalt mastics. Recent assessments revealed that fillers derived from organic and agricultural waste generally had irregular particle shapes and rough surfaces, which improved binder interaction and resistance to raveling [17–19]. In Indonesia, the processing of siwalan (*Borassus flabellifer*) fruit generated significant amounts of shell waste, particularly in East Java. Statistical data indicated that over 937 tons of siwalan products were recorded in Gresik in 2016, resulting in considerable organic waste that was typically underutilized [20, 21]. Earlier research on siwalan shell materials primarily focused on electromagnetic absorption and bioactive composite applications rather than pavement engineering [20, 21]. Therefore, the potential use of siwalan shell powder as a functional filler in asphalt mixtures, particularly porous asphalt, had not been thoroughly explored.

Biomass-based fillers generally exhibited lower mineral crystallinity, porous microstructures, and rougher surfaces compared to conventional mineral fillers like Portland cement or limestone dust, potentially improving asphalt mastic cohesion and reducing binder drain-down [10, 17, 22]. Recent studies on fillers predominantly focused on coconut shell, palm kernel shell, fly ash, and industrial waste fillers [23–25], with no comprehensive evaluation of siwalan shell powder in porous asphalt. Consequently, a clear research gap existed regarding its mechanical and durability performance in open-graded asphalt mixtures.

This study aimed to assess the Marshall properties, volumetric characteristics, Asphalt Flow Down (AFD), and Cantabro Loss of porous asphalt incorporating siwalan shell powder as a sustainable filler alternative. The research adhered to the requirements set forth by Bina Marga (2018) and AAPA (2004), focusing on determining the optimal asphalt content. The uniqueness of this study lay in the use of locally sourced siwalan shell waste as an alternative aggregate for porous asphalt, promoting sustainable pavement construction and waste repurposing without altering traditional mixture design principles.

2. Materials and Methods

Figure 1 shows a flowchart that summarizes the overall research technique used in this work. It shows the order of operations from choosing and characterizing materials to designing the mixture, preparing the specimens, and assessing their performance.

2.1. Materials characterization.

The materials utilized in this investigation comprised coarse aggregate, fine aggregate, PG 70 asphalt binder, and siwalan shell powder as filler. We tested the aggregate's specific gravity, water absorption, abrasion resistance, and gradation according to Bina Marga Revision 2 (2018). These qualities are very important for porous asphalt mixes because the density and absorption of the aggregate directly affect the amount of binder needed and the stability of the mixture [10, 26]. We tested the asphalt binder's penetration, specific gravity, flash point, and softening point to make sure it met Bina Marga (2018) standards and was good for open-graded mixtures [26].

2.2. Preparation of siwalan shell powder.

People in Gresik, East Java, collected Siwalan shell trash from local processing sites. The shells were washed to get rid of dirt, dried in an oven, and then ground into powder that could pass through a No. 200 sieve. Earlier research has shown that biomass fillers made by mechanical grinding tend to have uneven particle shapes and surfaces that are full of holes. This makes the interaction between the asphalt and the filler better and increases the internal friction in asphalt mixtures [10, 17, 22]. We checked the siwalan shell powder's specific gravity and fineness to make sure it would work with porous asphalt filler.

2.3. Mixture design.

The Australian Asphalt Pavement Association (AAPA, 2004) approach was used to make porous asphalt mixtures. We chose asphalt concentrations of 4%, 4.5%, 5%, 5.5%, and 6%. Recent studies on porous asphalt frequently indicate that the ideal asphalt content lies between 4.5% and 6.0%, contingent upon aggregate density, filler type, and binder characteristics [1, 2, 10]. In this study, a marginally broader range was utilized to evaluate the impact of high-density aggregate and biomass-based filler on binder demand and mixture performance.

2.4. Testing procedures.

We did Marshall stability and flow tests to see how well the mixtures could hold up under strain and how they would change shape. We used established methods to figure out the volumetric qualities, such as Voids in Mixture (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB). We did Cantabro Loss tests to see how well the material resisted raveling and Asphalt Flow Down (AFD) tests to see how well the binder drained down at high temperatures. These test methods are commonly employed to assess the durability and functional performance of porous asphalt mixtures [7–9, 10, 26]. To guarantee repeatability and statistical reliability, each test parameter in subsequent experimental phases was assessed using at least three replicate specimens for each variation in asphalt content, and the reported values was presented as average results.

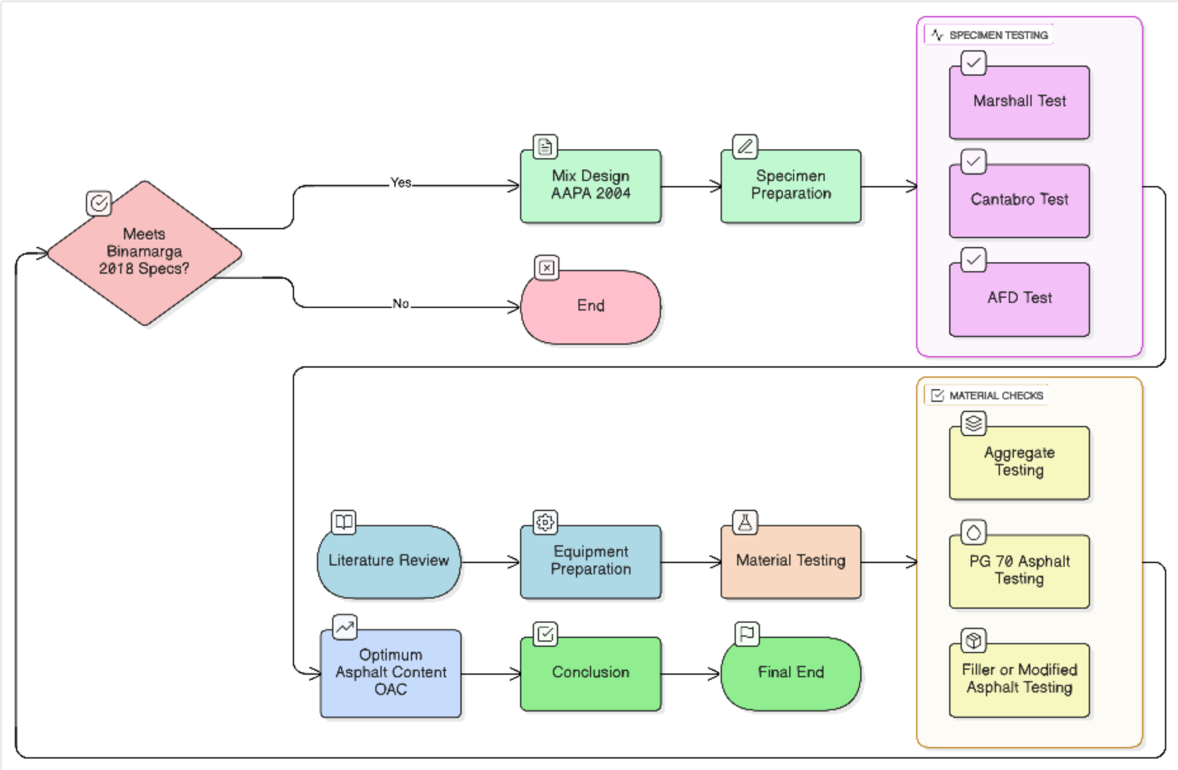

Figure 1. Flowchart of the research procedures.

3. Results and Discussion

3.1. Aggregate, filler, and binder properties.

Figure 1 shows the study flowchart that shows the order of the experimental activities, which include characterizing materials, designing mixtures, preparing specimens, and evaluating performance. Tables 1–4 provide the physical parameters of the materials employed in this investigation, which include coarse aggregate, fine aggregate, filler, and asphalt binder. The precise parameters of the coarse aggregate are shown in Table 1. The results show that the specific gravity values are much higher than those of regular crushed stone aggregates, which usually range from 2.6 to 2.7 g/cm³. The bulk specific gravity of 4.25 g/cm³ shows that the mineral content is dense. This directly affects how the combination behaves by lowering the amount of binder needed per weight and making the mixture stiffer. High-density aggregates can change the best amount of asphalt and the load-bearing capacity [1, 26]. The water absorption value of 1.48% in Table 1 also shows that the aggregate particles don't have a lot of holes inside them. This trait is good for porous asphalt mixtures because it reduces too much binder absorption and helps the binder spread out more evenly over the aggregate surface. This kind of behavior makes things more stable and less likely to change performance, as shown in recent studies of porous asphalt [3, 27]. The Los Angeles abrasion value of 35.94% shown in Table 1 also meets Bina Marga's standards, which means that the aggregate is strong enough to withstand deterioration. This is important in open-graded mixtures where the interlock of the aggregate is what keeps the structure strong [9, 28].

Table 1. Coarse aggregate test results.

Tested Parameter	Result	Specification Min	Specification Max	Unit

Bulk Specific Gravity	4.25	2.5	>2.5	g/cm^3
SSD Specific Gravity	4.31	2.5	>2.5	g/cm^3
Apparent Specific Gravity	4.57	2.5	>2.5	g/cm^3
Water Absorption	1.48	-	3	%
Los Angeles Abrasion	35.94	-	40	%
Sieve Analysis (Fineness)	0.98	-	1	%

Table 2 shows the physical properties of the fine aggregate employed in this study. The results show that the specific gravity values are correct and that the water absorption is regulated, which means that the aggregates fit together without blocking the air spaces that are connected. Prior research has underscored the significance of appropriately graded fine particles in preserving stability and permeability within porous asphalt systems [5, 29].

Table 2. Fine aggregate test results.

Tested Parameter	Result	Specification Min	Specification Max	Unit
Bulk Specific Gravity	2.68	2.5	>2.5	g/cm^3
SSD Specific Gravity	2.74	2.5	>2.5	g/cm^3
Apparent Specific Gravity	2.85	2.5	>2.5	g/cm^3
Water Absorption	2.22	-	3	%

Table 3 shows the physical parameters of the siwalan shell powder filler. The filler has a specific gravity of 3.08 g/cm^3, which is higher than that of many biomass-based fillers and about the same as that of common mineral fillers like fly ash and Portland cement. The filler can help make asphalt mastic stiffer because it has a relatively high specific gravity [30, 31]. Also, the high proportion of particles that pass through the No. 200 sieve given in Table 3 shows that the particles are small enough to fill in the micro-voids in the asphalt mastic. A lot of people have said that biomass fillers with uneven particle shapes and rough surface textures can help porous asphalt mixtures avoid raveling and increase internal friction [17, 18].

Table 3. Filler test results.

No	Test Type	Specification	Unit	Result
1	Specific Gravity	-	g/cm^3	3.08
2	No. 200 Sieve Passing	%	%	90.05

Table 4 shows the test results for the PG 70 asphalt binder utilized in this investigation. The moderate penetration value and high flash point show that the binder is stable and consistent enough for use in porous asphalt. Table 4 shows that the softening point of 50.5°C makes the binder less likely to drain down at high temperatures. This is especially relevant for open-graded combinations that use different fillers [4, 8].

Table 4. Asphalt binder test results.

No	Tested Parameter	Unit	Requirement	Result
1	Penetration	0.1 mm	-	80
2	Specific Gravity	g/cm^3	-	1.72
3	Flash Point	°C	$\geq$ 230	338
4	Softening Point	°C	Reported	50.5

3.2. Aggregate gradation and volumetric characteristics.

Figure 2 shows the combined aggregate gradation that was made to meet the AAPA (2004) standards. The gradation curve fits perfectly between the upper and lower limits for porous asphalt mixtures, as shown in the figure. This means that there is a good balance between having a lot of coarse aggregate and having enough fine material to keep the mixture stable while yet allowing air spaces to connect. Table 5 shows the trial mixture gradation and design asphalt content (Pb) that were used to prepare the specimens.

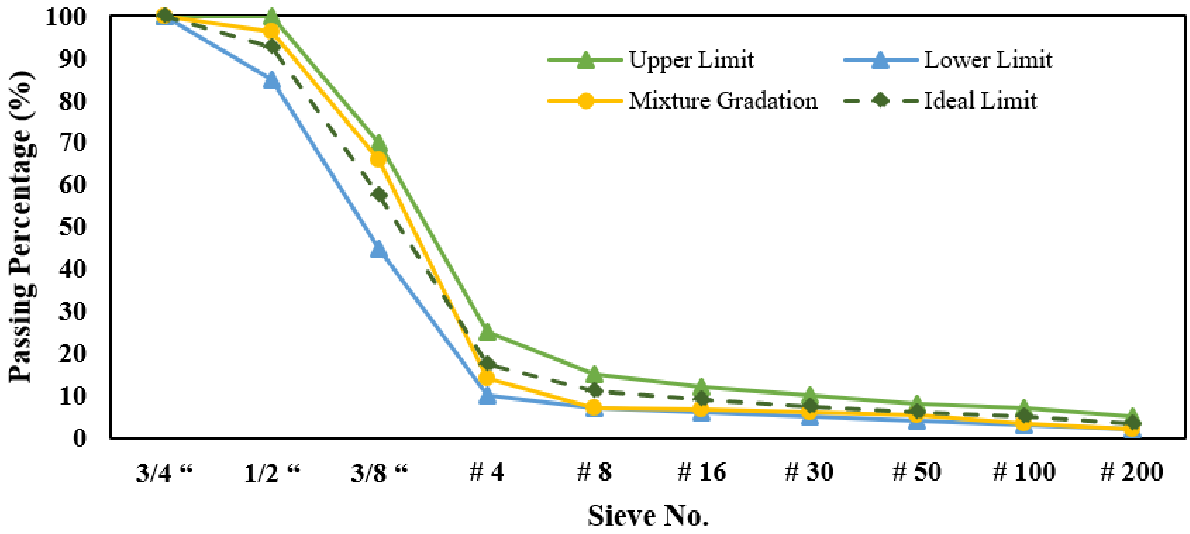

Figure 2. Combined aggregate gradation curve.

Table 5. Design Asphalt Content (Pb) and Trial Mixture Gradation

Sieve No	Size (mm)	Total Mix (%)	Retained (%)
3/4"	19	100	-
1/2"	12.5	96.37	3.63
3/8"	9.5	65.78	30.59
#4	4.75	14.28	51.5
#8	2.36	7.05	7.23
#16	1.18	6.63	0.42
#30	0.6	6.14	0.49
#50	0.3	5.51	0.64
#100	0.15	3.44	2.07
#200	0.075	2.06	1.38
CA	-	0.035	-
FA	-	0.045	-
Filler	-	0.18	-
Pb	-	4.85 (rounded to 5%)	-

Figures 3–5 show how the amount of asphalt affects volumetric properties like Voids in Mixture (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB). Table 6 summarizes the numerical results. Figure 3 shows that the VIM values went down as the amount of asphalt went up. This is because the binder filled in the interconnected air voids. This trend is consistent with what has been reported in previous studies on porous asphalt, where more binder reduces air voids and permeability while improving aggregate coating [1, 9]. The VIM values shown in Figure 3 and Table 6 are within the range that is acceptable for functional porous pavements [27, 29, 30]. This is because typical porous asphalt mixtures in the literature usually have VIM values between 15% and 25%. When the asphalt content is less than 4.5%, higher VIM values mean that the binder coverage is not enough, which could make the pavement more likely to ravel. On the other hand, when the binder content is too high, the voids are reduced and the permeability may be compromised.

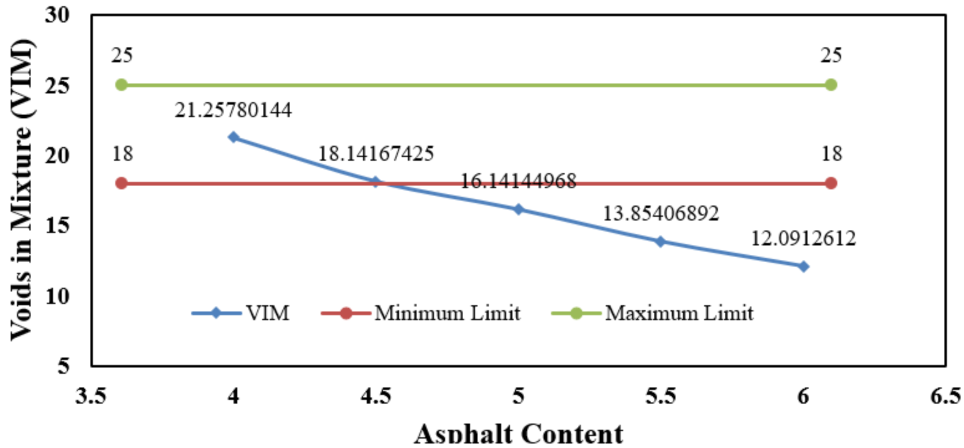

Figure 3. VIM (Void in Mixture) vs asphalt content.

Figure 4 shows how VMA changes with the amount of asphalt. The trend of VMA going down shows that as the amount of asphalt increases, the binder and filler fill in the empty spaces between the aggregate particles. Similar VMA behavior has been seen in porous asphalt mixtures with different fillers, where more binder makes the mastic stick together better while reducing the amount of void volume [10, 31].

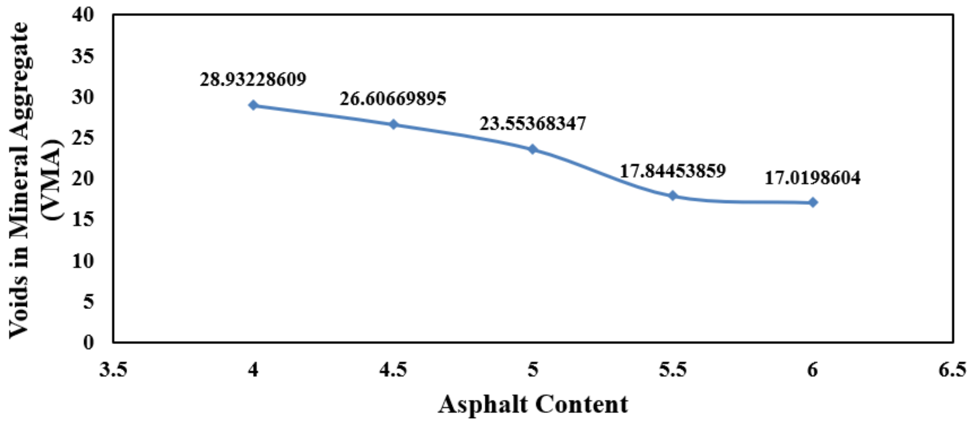

Figure 4. VMA (Void in Mineral Aggregate) vs asphalt content.

Figure 5 shows the link between asphalt content and VFB, and Table 6 gives the numbers. The results show that more binder leads to more voids filled with bitumen, which means that the binder covers the aggregates better. However, too much binder can lead to over-lubrication, which can make the aggregates less stable and less interlocked, as has been shown in many studies of open-graded asphalt mixture design [12, 26].

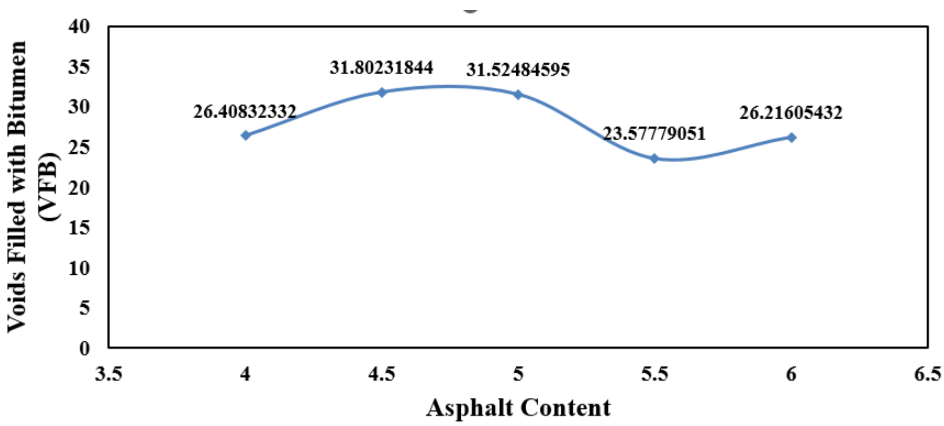

Figure 5. VFB (Voids Filled with Bitumen) vs asphalt content.

3.3. Mechanical performance.

We used Marshall stability and flow parameters to test the mechanical performance of the porous asphalt mixtures. The full results are in Table 6 and Figures 6 and 7. Figure 6 shows how Marshall stability changes with asphalt content. It shows that the highest stability was reached at 4% asphalt content, and then it dropped significantly at higher binder contents. This trend suggests that there is an optimal binder level beyond which more asphalt acts as a lubricant instead of a bonding agent, which lowers internal friction between aggregate particles [13, 32]. The rapid drop in stability seen in Figure 6 may also be due to the high specific gravity of the aggregates used in this study. When the temperature rises, dense aggregates tend to push binder out of the way more easily, which makes them less resistant to shear under load. Similar behavior has been seen in porous asphalt mixtures with heavy aggregates and recycled materials when tested under Marshall conditions [13, 26]. Figure 7 shows the Marshall flow values for different amounts of asphalt, and Table 6 gives a summary of the results. The results show that higher binder content leads to more deformation because the binder film is thicker. While more flow may make the mixture more flexible, too much deformation can make it less resistant to permanent deformation. This trend is in line with what has been found in recent porous asphalt literature [8, 27].

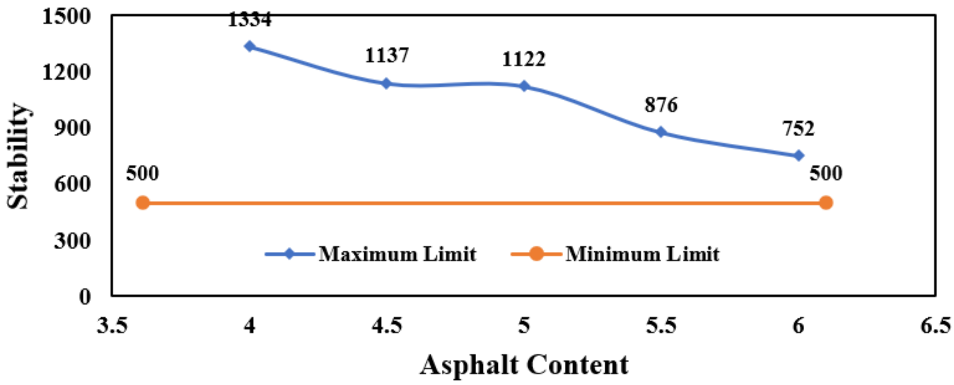

Figure 6. Stability vs asphalt content.

Table 6. Marshall test results.

Parameter	0.04	0.045	0.05	0.055	0.06	Specification
Stability (kg)	1334	1137	1122	876	752	≥500
Flow (mm)	2	2.25	2	3	3	-
VIM (%)	21.26	18.14	16.14	13.85	12.09	18–25
VMA (%)	28.9	26.6	23.6	17.8	17	-
VFB (%)	26.41	31.8	31.52	23.58	26.22	-
MQ	676	539	583	320	789	≤400

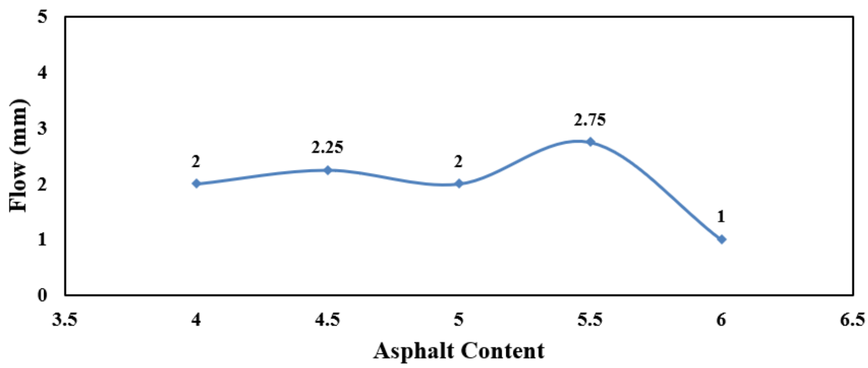

Figure 7. Flow vs asphalt content

3.4. Durability indicators: asphalt flow down and cantabro loss.

We used the Asphalt Flow Down (AFD) and Cantabro Loss tests to see how long the porous asphalt mixtures would last. The results are shown in Tables 7 and 8 and Figures 8 and 9. Figure 8 shows how the amount of asphalt in the mixture affects the binder drain-down behavior. It shows that the AFD goes up sharply as the amount of asphalt increases. Only mixtures with 4% and 4.5% asphalt content met the AAPA (2004) requirement of ≤0.3%, as shown in Table 7. This behavior can be explained by the fact that the open-graded structure can only hold so much binder once the binder film gets too thick [30, 33, 34]. Biomass-based fillers with porous and rough surfaces, like siwalan shell powder, have been shown to improve binder retention by making it easier for the binder to absorb and stick to the surface, especially when there isn't much binder [20, 21]. Figure 9 shows the link between asphalt content and Cantabro Loss, and Table 8 shows the values that go with it. The results show that as the asphalt content goes up, the mass loss goes down, which means that the mixture is less likely to ravel because the binder and aggregate are better at sticking together. However, mixtures with low asphalt content had higher Cantabro Loss values because the binder did not cover the surface well enough [19, 34]. Figures 8 and 9 show the combined results of AFD and Cantabro Loss. This shows the inherent trade-off in porous asphalt design between controlling binder drain-down and ensuring adequate durability. This represents what has been called the "critical binder point," where permeability is maximized without sacrificing structural integrity [35]. Based on the combined criteria of VIM, AFD, and Cantabro Loss presented in Tables 6–8, the best amount of asphalt for the porous asphalt mixture with siwalan shell powder was found to be 4%.

Table 7. Asphalt flow down (afd) test results.

Asphalt Content	0.04	0.045	0.05	0.055	0.06	Limit
AFD (%)	0.19	0.28	0.38	0.77	1.62	≤0.3

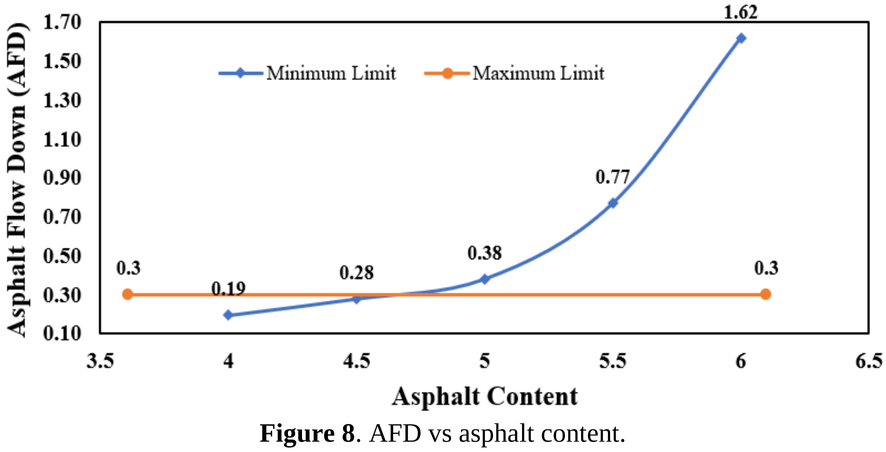

Figure 8. AFD vs asphalt content.

Table 8. Cantabro loss test results.

Asphalt Content	4%	4.50%	5%	5.50%	6%	Limit
CL (%)	35.6	28.92	24.6	20.94	16.7	≤35

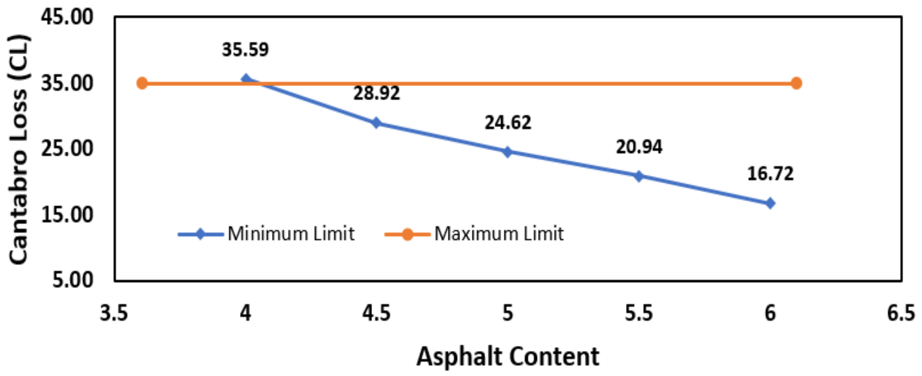

Figure 9. Cantabro Loss vs asphalt content.

4. Conclusions

This study shows that porous asphalt with siwalan shell powder as a sustainable filler can meet important volumetric, mechanical, and durability standards when designed using the AAPA (2004) framework. The best asphalt content of 4% struck a good balance between air void content, raveling resistance, and binder drain-down behavior. The absorptive and rough surface properties of siwalan shell powder helped lower Asphalt Flow Down at lower binder contents while keeping Cantabro Loss values within acceptable limits. This study is confined to laboratory-scale testing and short-term performance evaluation. It did not examine aging effects, moisture susceptibility, or long-term durability under traffic loading. Future research should concentrate on long-term aging, moisture damage resistance, microstructural analysis of filler–binder interaction, and field-scale trials to confirm the practical applicability of siwalan shell powder in porous asphalt pavements. Furthermore, environmental and economic assessments should be performed to quantify carbon footprint reduction and cost efficiency relative to conventional mineral fillers.

Competing Interest

All authors should disclose any financial, personal, or professional relationships that might influence or appear to influence their research.

Author Contributions

Dharma Gusti Ramadhan: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing—Original Draft. Aditya Rizkiardi: Validation, Software, Visualization, Writing—Review & Editing. Nurani Hartatik: Supervision, Project Administration, Funding Acquisition, Writing—Review & Editing, Correspondence. I Gede Agus Punarta: Resources, Data Collection, Technical Support, Validation.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Raw data, including laboratory test results and material properties, have been securely archived and can be provided for verification or further research purposes.

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