REVOLUTIONIZING ASPHALT ENGINEERING: UNVEILING THE INFLUENCE OF OIL PALM FIBER REINFORCEMENT ON THE MECHANICAL ATTRIBUTES OF ASPHALT MIXTURES

Tamalkhani Syammaun*, Hafnidar A. Rani*, Suhana Koting**

**Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Aceh, Banda Aceh, Indonesia, tamalkhani@unmuha.ac.id, hafnidar.ar@unmuha.ac.id*

***Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, Malaysia, suhana_koting@um.edu.my*

Email Correspondence : tamalkhani@unmuha.ac.id

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Abstract: The increasing demand for environmentally and economically sustainable technologies necessitates innovative approaches in material engineering. This study investigates the repurposing of waste materials by integrating oil palm fiber (OPFib) as reinforcement in porous asphalt mixtures. The primary objective is to examine the effects of adding varying amounts of OPFib (1%, 2%, 3%, 4%, and 5%) on the mechanical properties of asphalt, specifically aiming to improve the asphalt's softening point, viscosity, binder drain-down, and air void characteristics. The methodology involves a series of controlled laboratory tests under diverse conditions to measure these properties. The results indicate that adding OPFib enhances the performance of asphalt by raising the softening point and viscosity, decreasing binder drain-down, and achieving optimal air void levels at certain OPFib concentrations. However, higher OPFib content leads to diminished overall performance. These findings provide insights into the use of OPFib in asphalt mixtures, offering a sustainable solution that enhances road durability and performance, while effectively utilizing waste materials.
Keywords: Oil palm fiber; reinforcement; porous asphalt; sustainable

Abstrak: Meningkatnya permintaan akan teknologi yang ramah lingkungan dan berkelanjutan secara ekonomi membutuhkan pendekatan inovatif dalam rekayasa material. Penelitian ini menyelidiki pemanfaatan kembali bahan limbah dengan mengintegrasikan serat kelapa sawit (OPFib) sebagai penguat pada campuran aspal porus. Tujuan utamanya adalah untuk menguji pengaruh penambahan OPFib dalam jumlah yang bervariasi (1%, 2%, 3%, 4%, dan 5%) terhadap sifat mekanik aspal, khususnya untuk meningkatkan titik lembek aspal, viskositas, aliran aspal dan karakteristik rongga udara. Metodologi yang digunakan adalah serangkaian pengujian laboratorium sebagai kontrol dalam berbagai kondisi untuk mengukur sifat-sifat tersebut. Hasilnya menunjukkan bahwa penambahan OPFib meningkatkan kinerja aspal dengan meningkatkan nilai titik lembek dan viskositas, mengurangi binder drain-down, dan mencapai tingkat rongga udara yang optimal pada konsentrasi OPFib tertentu. Namun, kandungan OPFib yang lebih tinggi menyebabkan penurunan kinerja secara keseluruhan. Temuan ini memberikan pemahaman tentang penggunaan OPFib dalam campuran aspal, menawarkan solusi berkelanjutan yang meningkatkan daya tahan dan kinerja jalan, sekaligus secara efektif memanfaatkan bahan limbah.
Kata kunci: Serat kelapa sawit; penguatan; aspal porus; berkelanjutan

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Introduction

Asphalt engineering stands at the crossroads of innovation and sustainability, with an increasing focus on developing materials that not only meet the rigorous mechanical demands of modern infrastructure but also contribute to environmental well-being (Bocci, 2022; Mantalovas & Di Mino, 2019; Syammaun et al., 2023). Porous asphalt (PA), an innovative solution conceived in the United States and Europe, has emerged as a cornerstone of global road infrastructure, revolutionizing water drainage and noise reduction (Praticò et al., 2021). The transformative impact of PA was echoed in Malaysia's embrace in 1991, marked by the pivotal Cheras-Beranang Road trial. In 2008, the Malaysia Public Works Department (PWD) underscored PA's significance, introducing specifications denoted as Grades A and B. Despite its myriad advantages, encompassing heightened traffic safety, noise reduction, and augmented comfort for drivers and residents, PA contends with inherent challenges linked to its microstructure. The exposed binder in its open structure is vulnerable to environmental factors, leading to accelerated aging, moisture damage, and structural distress.

Amidst these challenges, the global community of asphalt researchers has diligently explored the potential of various fibers, ranging from polyester and cellulose to glass and mineral fibers, to augment asphalt performance (Chen & Yang, 2020; Gupta et al., 2019; Landi et al., 2020; Shahnewaz et al., 2023; Slebi-Acevedo et al., 2020; Wu et al., 2022). These fibers act as stabilizers, preventing leakage, particularly in stone mastic asphalt (SMA) mixtures and open-graded-friction-course (OGFC) (Sharma et al., 2024), offering an eco-friendly solution that addresses both cost and solid waste disposal concerns. However, the exploration of OPFib in asphalt pavement remains a largely untapped territory. Extracted from oil palm empty fruit bunches (Tang et al., 2020), OPFib emerges as a sustainable alternative due to its abundance post-oil extraction. Notably rich in cellulose and lignin, OPFib holds the promise of a pivotal role in mitigating binder drain-down in PA mixtures.

Derived from empty fruit bunches post-oil extraction, OPFib is an overlooked byproduct laden with untapped potential. OPFib has a substantial reservoir for applications such as road construction, with 23% of empty fruit bunch (EFB) produced per ton of fresh fruit bunch (FFB) and 7.0 million tons of oil palm trunks and fronds, respectively (Karim et al., 2023). While manufacturers have incorporated OPFib into various fiber composites, its application in asphalt road pavement remains an enigma. Its cellulose and lignin composition position OPFib as a promising additive to arrest binder drain-down in asphalt mixtures (Yaro et al., 2021). This study addresses a critical research gap, probing the feasibility of OPFib as reinforcement in PA mixtures with the overarching goal of introducing an enduring solution to challenges ingrained in traditional asphalt engineering practices.

Embarking on the exploration of OPFib and its intricate influence on PA mixtures stands as a focal point in this research. The primary objective is to unravel the multifaceted effects of OPFib by meticulously examining the impact of varying OPFib fiber concentrations on a spectrum of performance factors within PA mixtures. Through the application of robust statistical methodologies, encompassing regression analysis and analysis of variance (ANOVA), the aim is not only to articulate but also to substantiate the performance enhancements brought about by the incorporation of OPFib in PA mixtures.

Methodology

Materials

In the pursuit of elucidating the transformative impact of Oil Palm Fiber (OPFib) reinforcement on the mechanical attributes of asphalt mixtures, meticulous attention was given to the selection and preparation of materials, adhering to Malaysia's Standard Specification.

The fundamental basis of the mix design is the precise gradation of coarse aggregate, fine aggregate, and mineral filler. The coarse aggregate, obtained from a reputable quarry in Kajang, Malaysia, consisted of granite stones that had been pulverized and varied in size from 10 mm to 20 mm. This deliberate choice was made to mirror real-world conditions and align with the strict size specifications outlined in the Malaysian Public Works Department (PWD) for porous asphalt (PA-Grading B), ensuring conformity with established industry standards (Figure 1). As an integral component of the asphalt mixture, 2% of hydrated lime served as the mineral filler, meeting stringent criteria for optimal performance. A comprehensive overview of the physical properties of the aggregate particles is detailed in Table 1.

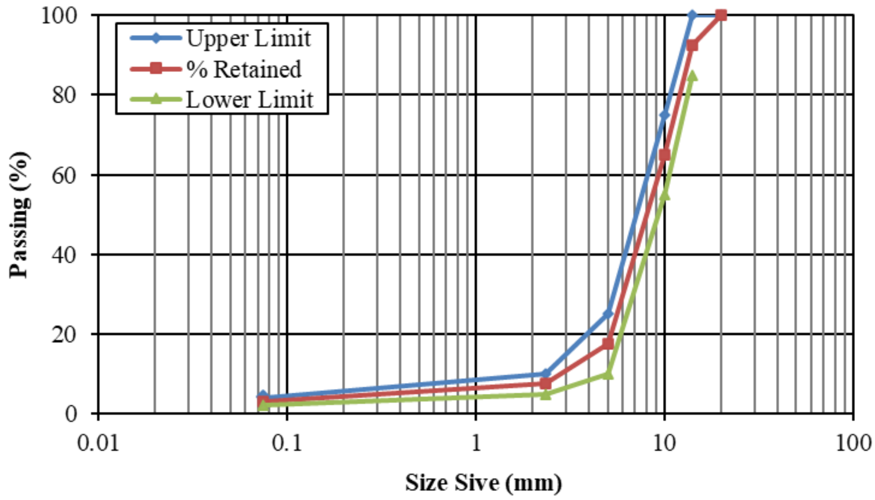

Figure 1. Aggregate gradation curves for porous asphalt (Grading-B)

Table 1. Findings on aggregate properties

Properties	Test method	Test Value (%)
Flakiness index	BS182:Part3	4
Impact value	BS812:Part3	20
Elongation index	BS182:Part3	17
Soundness	BS812:Part3	4.2
Aggregate crushing value	BS812:Part3	20
Los Angeles abrasion value	ASTM C-131	21

A conventional asphalt binder with the grade PG 80/100 was meticulously chosen to maintain consistency in the asphalt mixture compositions, aligning with prevailing industry standards. Table 2 shows all of the physical properties of the asphalt binder. It is an important reference for making sure that the same results are obtained and for getting a good idea of how the binder's properties affected the performance of the asphalt mixture as a whole.

Table 2. Findings on asphalt binder properties

Properties	Test method	Unit	Test Value
Penetration at 25 °C	ASTM D 5-97	1/10 mm	85
Ductility at 25 °C	ASTM D-113	cm	>100
Softening point	ASTM D-92	°C	47
Specific gravity	ASTM D-70	g/cm	1.03
Viscosity at 135 °C	ASTM D-4402	mPa.s	416

Central to this investigation was the inclusion of the stabilizing additive, Oil Palm Fiber (OPFib), which was sourced directly from the Malaysian Palm Oil Board (MPOB). Chosen for its raw and untreated state, OPFib was selected to preserve the integrity of the original material and closely replicate real-world scenarios. Ensuring its suitability for incorporation into the asphalt mixture involved a meticulous preparation process. Thorough washing was conducted to eliminate extraneous materials, followed by sieving through a 425 µm sieve to achieve a consistent particle size. Subsequently, a minimum 4-hour drying period in an oven was undertaken a crucial step to eradicate moisture and prevent potential influences on the test outcomes. The physical parameters of OPFib, as shown in Table 3, provide crucial information about its features. This information is important for ensuring consistent results and gaining complete knowledge of how OPFib affects the mechanical properties of the asphalt mixture.

Table 3. Findings on physical parameters of OPFib

Properties	Unit	Range
Tensile strength	MPa	20-400
Density	g/cm^3	0.7-1.55
Diameter	µm	150-500

Specimen preparation

To systematically assess the influence of OPFib reinforcement on the mechanical attributes of asphalt mixtures, varying asphalt contents (AC) and OPFib percentages were meticulously designated in this study. AC was varied at 4%, 4.5%, 5%, 5.5%, and 6% by weight of aggregate particles. Simultaneously, different percentages of OPFib (1%, 2%, 3%, 4%, and 5% by weight of asphalt) were employed in the experimental design (Figure 2). It is imperative to note that specimens without fibers were included as control specimens to establish a baseline for comparative analysis.

The experiment started by mixing the aggregates with the asphalt binder at a temperature of 160±5 °C. This made sure that all the parts were mixed evenly before the fibers were added. This temperature was chosen to simulate the asphalt mixture's working conditions and promote optimal blending. Subsequently, specimens were meticulously prepared and subjected to a battery of tests to comprehensively evaluate various mechanical properties.

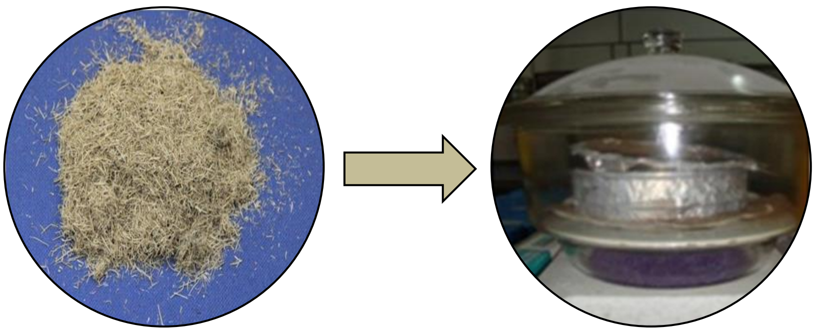

Figure 2. OPFib and OPFib stored in the desiccators

Experimental

Rheology of OPFib-modified bitumen

The objective of the softening point test was to identify the temperature at which a phase change occurs in the mixture (Al-Mansob et al., 2022; Ming et al., 2022). This property of bitumen 80/100 was determined in accordance with ASTM D36-86 (reapproved 1993) or BS 2000: Part 58:1988, utilizing the ring and ball method. According to BS2000: Part 58: 1998, the softening point is defined as the temperature at which a substance attains a specific degree of softness under the specified test conditions. For each specimen, bitumen and varying fiber contents were poured into the ring and allowed to cool at room temperature for approximately 30 minutes. Subsequently, the specimens were levelled and placed on the ring holder. These prepared specimens were then immersed in a water bath, maintaining a depth between 102 mm and 108 mm from the bath's bottom. A steel ball of specified mass was positioned onto a bitumen disk within a metal ring of specific dimensions. The assembled apparatus was submerged in a bath of liquid, and the liquid's temperature was elevated at a specified rate.

The Brookfield Thermosel apparatus was employed to determine the viscosity of the binder at elevated temperatures with the addition of OPFib. The test followed the procedure outlined in ASTM D4402-87 (reapproved 2000). The controller was calibrated according to on-screen instructions, and the specimen in the oven was heated. Approximately 10±0.5g of the specimen was placed into the holder and cooled to ambient temperature (90 °C) using the extracting tool before transferring it to the Brookfield Thermosel. The specimen holder was then placed into the thermal container, aligned, and coupled with the viscometer using a spindle (No.27). The specimen was rotated at a lower speed, with the required speed set at 20 rpm. In cases where the specimen was too hard, the temperature was incrementally increased by 10 °C (e.g., to 100 °C) until the desired speed was achieved. Viscosity and shear stress readings were taken after the torque stabilized, providing essential insights into the binder's behavior under varying conditions (Lee et al., 2023).

Binder drain-down

The binder drain-down test, a pivotal assessment in asphalt engineering, was conducted to evaluate the asphalt mixture's proficiency in retaining binder without excessive drainage-a critical consideration for ensuring optimal performance throughout manufacturing, transportation, and laying processes (Sharma et al., 2024). This assessment aligns closely with established guidelines outlined by the Malaysian Public Works Department (PWD).

This test is indispensable in addressing concerns related to binder drainage, a phenomenon that can adversely impact the long-term durability and performance of asphalt pavements. The issue of excessive binder drainage during the various stages of asphalt pavement construction is well-documented in the literature, emphasizing the importance of meticulous testing methodologies to mitigate potential challenges. The calculation of the percentage of retained binder after the oven treatment is a crucial metric derived from the test. This metric is substantiated by existing literature highlighting the significance of binder retention in preserving the integrity of asphalt mixtures. Notably, studies have underscored the correlation between effective binder retention and enhanced resistance to factors such as rutting and fatigue cracking.

Voids in the mix

To understand the complex properties of asphalt mixtures, the study did full tests for density and air void analysis that were in strict accordance with the ASTM D2726-90 standard. This is a method that is known for being accurate and dependable. This standardized approach not only ensures the reproducibility of results but also facilitates meaningful comparisons across various studies. The asphalt specimens underwent meticulous preparation, and their weight in both air and water was precisely determined. This initial step laid the groundwork for subsequent analyses, enabling the accurate gauging of density and air void content (Garcia et al., 2019; Giuliani et al., 2021).

Precision played a paramount role in the experiment, where vernier calipers were employed to measure the average height and diameter of the specimens to the nearest 0.1 mm. This meticulous level of detail is crucial for capturing the nuanced geometric features that significantly influence the mechanical attributes of the asphalt mixture. To maintain the integrity of the specimens and prevent water infiltration that could compromise the results, each specimen was tightly enveloped in plastic. This protective measure ensures that the voids within the specimens remain unaffected, thereby preserving the accuracy of the analysis.

Results and discussion

Rheological properties analysis of OPFib-modified bitumen

As Figure 3 shows, the softening point values observed in this study reveal a discernible trend that corresponds to variations in OPFib content within the bituminous mixture. Notably, specimens with higher OPFib content demonstrated a consistent increase in softening point values. This positive correlation suggests that as the OPFib content increased, there was a corresponding upward trend in softening point values. Conversely, a decrease in OPFib content was associated with a reduction in softening point values.

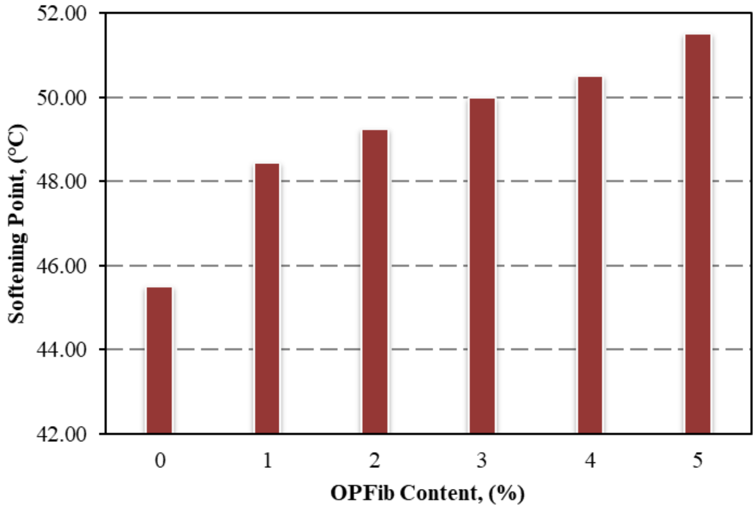

Figure 3. Softening point test with different OPFib contents

These findings underscore the influential role of temperature and OPFib content in shaping the softening behavior of the asphalt mixture. Elevated temperatures, coupled with increased OPFib content, appear to augment the resistance to flow in the specimens, particularly in comparison to control specimens with no fiber. Subsequent, in-depth statistical analyses and correlation studies will be undertaken to validate and reinforce these initial observations. This comprehensive approach aims to contribute to a nuanced understanding of the intricate impact of OPFib on the mechanical attributes of asphalt mixtures, paving the way for advancements in asphalt engineering.

Table 4 shows the softening point test for single-factor ANOVA as the statistical technique. The p-value (1.030E-10) is below the significance threshold of 0.05, signifying a noteworthy distinction in softening point values across various OPFib content levels. With an F-statistic of 62.0118 surpassing the critical F-value of 2.7729, there is additional reinforcement for rejecting the null hypothesis. In essence, the findings underscore a statistically significant divergence in softening point values among distinct OPFib content levels.

Table 4. Results of ANOVA: Single factor for softening point test

Source of Variation	SS	df	MS	F	P-value	F crit
Between OPFib content	73.2083	5	14.6417	62.0118	1.030E-10	2.7729
Within OPFib content	4.2500	18	0.2361			
Total	77.4583	23				

Meanwhile, Figure 4 shows the Brookfield Viscosity test results revealed a significant increase in viscosity with the addition of OPFib contents, spanning from 0% to 5%. Specifically, viscosity values at 0% OPFib content were observed to be the lowest, measuring 4093.27, 986.50, 438.10, 418.13, and 128.29 mPa.s at temperatures of 90ºC, 110ºC, 130ºC, 135ºC, and 150ºC, respectively. In contrast, specimens with 5% OPFib content exhibited higher viscosity values, registering 12010.14, 3948.02, 1675.65, 1016.50, and 813.87 mPa.s for the corresponding temperature levels.

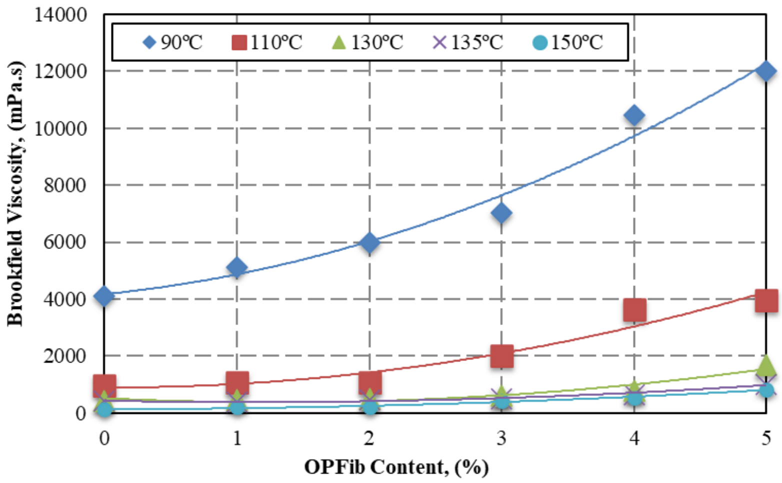

Figure 4. Viscosity test with different OPFib contents

A two-factor ANOVA without replication was conducted to further analyze the viscosity test results, revealing a significant effect arising from different OPFib contents (Table 5). The F-value of 34.287 exceeded the critical F-value of 2.866, indicating a statistically significant impact. The associated P-value, which is smaller than 0.05, further supports the conclusion of a significant effect. This statistical analysis enhances the robustness of the findings, reinforcing the influence of varying OPFib contents on viscosity values and emphasizing the importance of these results in the context of material stability. The controlled blending process to maintain optimal OPFib content becomes crucial in achieving desired viscosity effects for enhanced applications.

Table 5. Results of ANOVA: Two-factor for viscosity test

Source of Variation	SS	df	MS	F	P-value	F crit
Binder content	2.13E+08	4	53335180.82	34.2871	1.0844E-08	2.86608
OPFib content	2.87E+07	5	5738698.05	3.6892	0.0158	2.71089
Error	3.11E+07	20	1555545.87			
Total	2.73E+08	29				

Binder drain-down test results

The binder drain-down test plays a pivotal role in evaluating optimal binder levels for asphalt mixtures. This study scrutinizes the performance of both control specimens (without fiber) and those incorporating Oil Palm Fiber (OPFib) concerning binder drain-down, adhering to industry standards that prescribe a maximum allowable binder drain-down of 0.3% by weight of the total mix (REAM–SP, 2008). Figure 5 shows that the introduction of OPFib led to a conspicuous reduction in binder drain-down. Particularly, mixtures containing 2% to 5% OPF content exhibited enhanced performance at binder contents of 4%, 4.5%, and 5%. Notably, at 4% binder content, zero drainage was observed across all mixes, signifying a substantial improvement in resistance to binder separation.

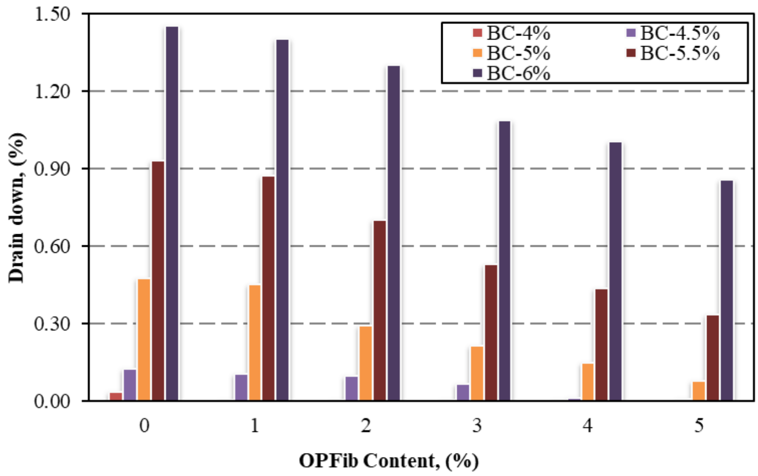

Figure 5. Binder drain-down test with different OPFib contents

The incorporation of fiber increases the demand for asphalt to coat the surface due to the heightened specific surface area and absorption of lighter asphalt components by the fiber. Favorable outcomes in the 2% to 5% OPFib content range suggest an optimal range for improving binder retention and mitigating drainage issues in PA mixtures. Surprisingly, control specimens (without fiber) and those with 1% fiber content exhibited minimal impact on binder drainage. This finding implies that the addition of 1% fiber had negligible effects on surface area and absorption, indicating that the unit weight of 1% fiber did not significantly influence these aspects.

Table 6. Results of ANOVA: Two-factor for binder drain-down test

Source of Variation	SS	df	MS	F	P-value	F crit
Binder content	5.6700	4	1.4175	121.1626	1.014E-13	2.86608
OPFib content	0.4809	5	0.0962	8.2204	2.359E-04	2.71089
Error	0.2340	20	0.0117			
Total	6.3849	29				

In tandem with the binder drain-down test, a comprehensive two-factor ANOVA without replication was conducted to evaluate the significance of adding OPFib to PA (Table 6). The analysis demonstrated a substantial impact, as evidenced by an F-value of 121.163, surpassing the critical F-value of 2.866. The associated P-value, smaller than 0.05, bolsters these findings, signifying a statistically significant effect resulting from the inclusion of OPFib in PA. These robust statistical results further emphasize the influential role of OPFib in optimizing the performance of PA mixtures.

Voids in the mix test results

The testing of voids in the mix shows interesting patterns in the amounts of air voids that change when the amount of OPFib in PA mixtures changes, as shown in Figure 6. A discernible pattern emerges as OPFib content increases from 1% to 3%, resulting in a decrease in air voids. However, at higher OPFib content levels (4% to 5%), there is an observable increase in air voids. This dichotomy underscores the importance of a balanced OPFib proportion to maintain optimal air void characteristics. Furthermore, the interplay between OPFib content and binder content reveals a crucial relationship. Regardless of the OPFib content, a reduction in binder content leads to an increase in air voids. This finding emphasizes the need for meticulous control over both OPFib and binder content during asphalt mixing to avoid excessive voids. Excessive voids can potentially lead to oxidative hardening, compromising pavement durability and longevity.

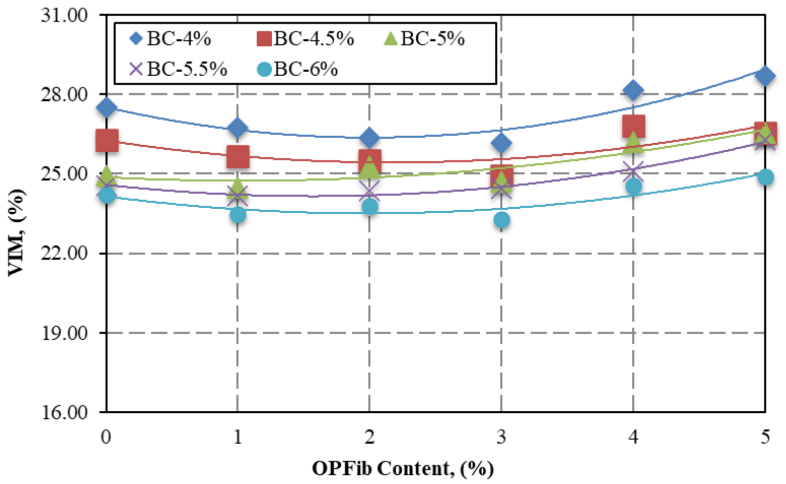

Figure 6. Voids in the mix test with different OPFib contents

For further verification, a two-factor ANOVA without replication was used to statistically analyze the air void test results. An F-value of 81.853 (F=81.853>F-critical=2.866), with a P-value less than 0.05, indicates that the addition of OPFib significantly affected air void values (Table 7). This statistical confirmation backs up the trends that have been seen, showing that OPFib does affect the amount of air voids in PA mixtures. This comprehensive understanding contributes to the refinement of asphalt mix designs for optimal performance and durability.

Table 7. Results of ANOVA: Two-factor for void in the mix test

Source of Variation	SS	df	MS	F	P-value	F crit
Binder content	35.9896	4	8.99741	81.8531	4.168E-12	2.8661
OPF content	13.9930	5	2.79861	25.4601	4.958E-08	2.7109
Error	2.1984	20	0.10992			
Total	52.1811	29				

Conclusion

In conclusion, the research highlights the substantial impact of oil palm fiber (OPFib) on crucial asphalt properties. Higher OPFib content consistently increases softening point values, demonstrating improved resistance to flow, particularly at elevated temperatures. Brookfield Viscosity tests confirm this trend, emphasizing the importance of meticulous OPFib content control for material stability. With strong statistical validation, the binder drain-down test highlights OPFib's contribution to improving binder retention. Investigation into air void values reveals a delicate balance: 1% to 3% OPFib reduces voids, while 4% to 5% leads to an increase. Meticulous OPFib and binder content control during mixing is crucial to prevent excessive voids. Overall, the findings support an ideal OPFib content range of 2% to 5%, which will lead to improved asphalt mix designs and advancements in material performance and durability for superior asphalt engineering.

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