IOP Conference Series:
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To cite this article: Fatin Fahira Nisha Mohd Fazilah *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1444** 012026

Performance Evaluation of Porous Asphalt Mixture Reinforced by Lignin Fiber

Fatin Fahira Nisha Mohd Fazilah, Khairil Azman Masri*, Ammar Al-Attab, Ramadhansyah Putra Jaya

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300, Gambang, Kuantan, Pahang, Malaysia

**Corresponding author: khairilazman@umpsa.edu.my*

Abstract. This study aims to investigate the performance evaluation of porous asphalt (PA) mixture reinforced by lignin fiber. A kind of pavement called porous asphalt is made to let water percolate through its surface, minimising runoff and enhancing water management. Because of the unique combination of aggregates and asphalt used in its construction, water can percolate through and be absorbed into the ground below. However, there is always room for improvement in terms of enhancing its mechanical properties and overall performance. In this research, lignin fiber is incorporated into Porous Asphalt to evaluate their influence on key performance indicators such as rutting resistance, fatigue life, cracking, and mechanical strength. The study includes laboratory tests and performance assessments to compare the modified PA with conventional PA. To achieve the research objectives, various proportions of lignin fiber additives are introduced into the PA mix design (0%, 1%, 2%, 3%, 4%). The modified asphalt mixtures are then prepared and subjected to comprehensive laboratory tests, including Marshall stability, Indirect tensile strength, Binder drain down test, LA abrasion loss, Softening point and Penetration test. The performance evaluation also involves rutting and fatigue tests to assess the resistance of the modified mixtures to permanent deformation and fatigue cracking under simulated traffic loading conditions. The results obtained from the experimental investigations are analyzed and compared with the performance characteristics of conventional LF. In conclusion, the addition of 2-3% of LF additives enhanced the performance of PA in terms of rutting resistance, fatigue life, moisture susceptibility, and mechanical strength.

KEYWORDS | Asphalt Mixture; Lignin Fiber; Porous Asphalt; Marshall Stability

1. INTRODUCTION

New pavement construction techniques and the increased use of recycled materials have led to unexpected and premature pavement failure in recent years. The pavement's exposure to daily and seasonal extreme temperature and repeated vehicular loads accumulates damage [1]. Pavement infrastructure that is resilient and sustainable is essential given the current environmental and economic issues. The pavement infrastructure has been a major contributor to the global social economy's rapid development over the last ten years. In the field of pavement engineering, new theories, techniques, technologies, and materials are constantly being developed [2, 3, 4, 19, 20].

In terms of longevity and serviceability, compaction is a vital component of asphalt pavement quality and performance [3]. The asphalt mixture is composed of aggregate and a binder and will appear to perform differently under different temperature conditions [4, 6, 7]. Asphalt mixture design methods have an important influence on both the microscale structure formed and the corresponding properties [5, 8, 20, 21].

The asphalt mixture is a typically temperature-sensitive material; its mechanical characteristics and operational performance will also dramatically change with temperature variations [6]. One of the purposes for the asphalt pavement structural design is to select an appropriate asphalt mixture to ensure that the asphalt pavement will still have enough stability at critically high temperatures and enough strength to resist cracking at critically low temperatures [7]. High temperature and ultraviolet light result in serious aging of asphalt binder and asphalt pavement [6]. The binder is a fragile solid at low temperatures; it behaves more like a viscoelastic matter at medium temperature and will soften to liquid form in high temperature [8, 22, 23].

Next, the various acknowledged benefits given using fibre for construction materials made this component essential for specific applications including asphalt pavements [9, 24]. Lignin is a complex organic polymer that plays a crucial role in the structure of plant cell walls. Lignin, as the second most abundant natural polymer in the world and mainly produced as a residue from the pulp and paper industry and ethanol production, is an attractive material for the development of eco-friendly, low-cost, and biodegradable products [10]. Fibers and polymers provide a three-dimensional networking effect in asphalt concrete and stabilize the binder on the surface of aggregate particles, preventing any movement at higher temperatures [11].

The potential of lignin fibre, Ih Is derived from plant cell walls, to Improve the performance and sustainability of road surfaces has drawn attention to it as a promising addition to asphalt mixtures. [10, 11] studied how lignin and ceramic fiber influenced with the asphalt mixture. Stone matrix asphalt (SMA-13) mixtures' overall road performance was examined using wheel tracking tests, low temperature bending tests, moisture susceptibility tests, and fatigue tests to determine the impact of various fibre proportions [10, 11]. Even though it is anticipated that double-adding fiber-reinforced asphalt mixtures will enhance overall road performance, current research only examines one performance factor. Results from these studies showed that when LF and CF were added together, the improvements in mechanical strength, antirutting performance, moisture susceptibility, and fatigue life were greater than when either fibre was used alone. The SMA mixtures using both fibres improved in 11% dynamic stability, 8.6% low temperature bending stress, 2.1% moisture susceptibility, and 20% fatigue life, respectively, when compared to those using LF. Additionally, the mixtures using both fibres showed an increase in low temperature bending strain of 11% and fatigue life of 8% when compared to SMA mixtures using CF. The experimental results from [4, 25] demonstrated a significant improvement in the bituminous mix's water stability, low-temperature stability, and quality upon the addition of 0.30% lignin fibre and 0.30% glass fibre.

Additionally, the mixtures using both fibres showed a slight improvement in low temperature bending stress, moisture susceptibility, and dynamic stability, respectively. The suggested ratio of LF to CF in the asphalt mixture is 1:2, offering a more balanced and thorough improvement of road performances, based on the efficiency coefficient method results [10, 25].

Furthermore, single-adding fiber technology only plays a role in improving one performance of asphalt mixture, such as high temperature or low temperature or water damage performance [12]. In addition, fibers in asphalt mixtures usually play two important roles: acting as an asphalt stabilizer to decrease the drain-down effect and as a reinforcing additive to enhance the mechanical performance of asphalt mixtures [13]. Different types of modifiers, such as fibers, can be used to improve the quality of asphalt pavements [14].

Previous study on asphalt mixture reinforced by lignin fiber found that the addition of fiber affects the properties of bituminous mixes significantly. Since it is abundant and renewable, lignin a natural polymer derived from plant cell walls has drawn interest as a possible fibre reinforcement in asphalt mixes. Lignin fibres are being investigated by experts and industry professionals to improve asphalt's mechanical qualities and give it more resilience against fatigue, rutting, and cracking. By using a bio-based material, the addition of lignin fibres to the asphalt mixture enhances performance while also supporting sustainability objectives. Trees that possess lignin, a remarkable natural polyphenol, can withstand physical and biological stresses and grow to significant heights. Additionally naturally circular and having a slow rate of biodegradation, lignin provides soils with a source of carbon [18].

The aim of this study is to identify the performance evaluation of asphalt mixture reinforced by lignin fiber. Among the objectives are to evaluate the impact of different proportions of lignin fiber on the mechanical properties of asphalt mixtures and to identify the optimum proportion of lignin fiber that maximizes the performance and durability of asphalt mixtures.

2. Methodology

This research investigates the performance evaluation of asphalt mixtures reinforced by lignin fiber (LF). Various proportions of LF were incorporated into porous asphalt (PA) to enhance key performance indicators such as rutting resistance, fatigue life, cracking, and mechanical strength. The methodology includes laboratory tests to compare the modified PA with conventional PA mixtures. The research started with the collection of all relevant data on the performance of asphalt mixture and ends with the results and data analysis.

IOP Conf. Series: Earth and Environmental Science **1444** (2025) 012026 doi:10.1088/1755-1315/1444/1/012026

2.1 Material Properties

The material's properties, including the addition of fibre, binder, and aggregates, must be used in accordance with the ASTM and BS-EN guidelines.

2.1.1 Type of Aggregate

Both coarse and fine aggregates were used in this study. It is necessary to screen crushed hard rock to remove any potentially harmful contaminants such as dust, clay, plant and other organic waste, and angular-shaped openings. Fine aggregates need to be non-plastic and devoid of harmful contaminants such as clay, loam material aggregates, and other organic matter and vegetation.

2.1.2 Type of Bitumen

To create asphalt mixture material samples, grade 60/70 of asphalt mixture was used. Often used as the matrix of asphalt concrete composites, asphalt binder is a viscoelastic crude oil compound made up of a complex mixture of hydrocarbons and heteroatoms. It is essential to the adhesion and integrity of aggregates within a pavement.

Table 1. Properties of 60/70 Grade Bitumen

Bitumen 6070	Test method	Unit	Specification
Specific gravity	ASTM D70	kg/cm^3	1.01-1.06
Penetration, mm	ASTM D5	mm/10	60-70
Softening point	ASTM D36	°C	49-56
Ductility @ 25°C	ASTM D113	cm	100 min
Loss on heating	ASTM D6	wt%	0.2 max
Drop in penetration after heating	ASTM D5-D6	%	20 max
Flashpoint	ASTM D92	°C	232 min
Solubility in Trichloroethylene	ASTM D2042	wt%	99 min

2.1.3 Type of Fiber

There are various types of fibers, such as cellulose fiber, steel fiber, bamboo fiber, and glass fiber. For this study, lignin fiber is used as shown in Figure 1. Lignin is a versatile and important component in plants, offering support, protection, and potential applications in various industries. The fiber is obtained from local supplier with the average length around 3mm.

Figure 1. Lignin Fiber.

2.2 Sample Preparation

Asphalt mixtures reinforced by lignin fiber were produced by including 0%, 1%, 2%, 3%, and 4% of the asphalt mixture by weight. The base of the asphalt mixture is heated in an aluminum container to 150–160°C or until it becomes liquid. Next, the preheated asphalt mixture was mixed with the required quantities of lignin fiber.

2.3 Testing Methods

Performance evaluation of asphalt mixture reinforced by lignin fiber is prepared using Porous Asphalt Design, and the performance tests conducted include:

2.3.1 Sieve Analysis Test

One technique to determine the particle size distribution of granular materials is sieve analysis, which can be applied to soil, gravel, or sand. To conduct a sieve analysis and prepare porous asphalt samples, aggregate samples were collected, thoroughly dried, and sieved using progressively smaller mesh sizes. Weight retained on each sieve was recorded, and a gradation curve was plotted.

2.3.2 LA Abrasion Test

The LA Abrasion test is a widely used method for assessing the abrasion resistance of aggregates. The aggregate sample was dried and placed in a rotating steel drum with steel balls. After 500 revolutions, the material retained on the sieve was weighed, and the percentage of abrasion loss was calculated.

2.3.3 Penetration Test (ASTM D35)

One common technique for evaluating the hardness and consistency of asphalt mixtures is the penetration test. A bitumen sample is cooled to room temperature, and a penetrometer with a standard needle is allowed to penetrate the bitumen under a 100g load for 5 seconds.

2.3.4 Softening Point Test (ASTM D36)

The softening point test determines the temperature at which the asphalt binder softens to a certain degree. A bitumen sample was placed in a ring and ball apparatus and heated in a temperature-controlled bath. The temperature at which the bitumen reached a predefined softness was recorded.

2.3.5 Marshall Stability Test

The Marshall Stability Test as shown in Figure 2 measures the stability and flow of asphalt mixtures. Cylindrical samples were prepared and compacted using the Marshall compaction method. These samples were subjected to a vertical load until failure, and the maximum load and deformation were recorded.

Figure 2. Marshall Stability Test

2.3.6 Binder Draindown Test

The binder draindown test evaluates the tendency of the binder to drain from the aggregate. A sample was placed in a wire basket and heated to a specific temperature, and the amount of binder that drained from the aggregate was measured.

2.3.7 Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) test evaluates the tensile properties of asphalt mixtures. A cylindrical asphalt sample was subjected to diametrically applied stress, and the maximum load was recorded. The ITS value was calculated to assess the cracking resistance of the asphalt.

3. RESULTS AND DISCUSSION

This section provides a thorough analysis of the findings from the study on the performance evaluation of asphalt mixtures reinforced with lignin fibers. Numerous performance metrics, including mechanical strength, durability, and resistance to environmental factors, have been determined through extensive experiments and data collection. Properties used in Malaysian construction must adhere to JKR-SPJ-2008 specifications.

3.1 Sieve Analysis test

Sieve analysis is used to determine the exact mass of the required aggregate that meets the Porous Asphalt (Grading B) target specification. A sample of weight 1100g was chosen for all experiments as shown in Figure 3.

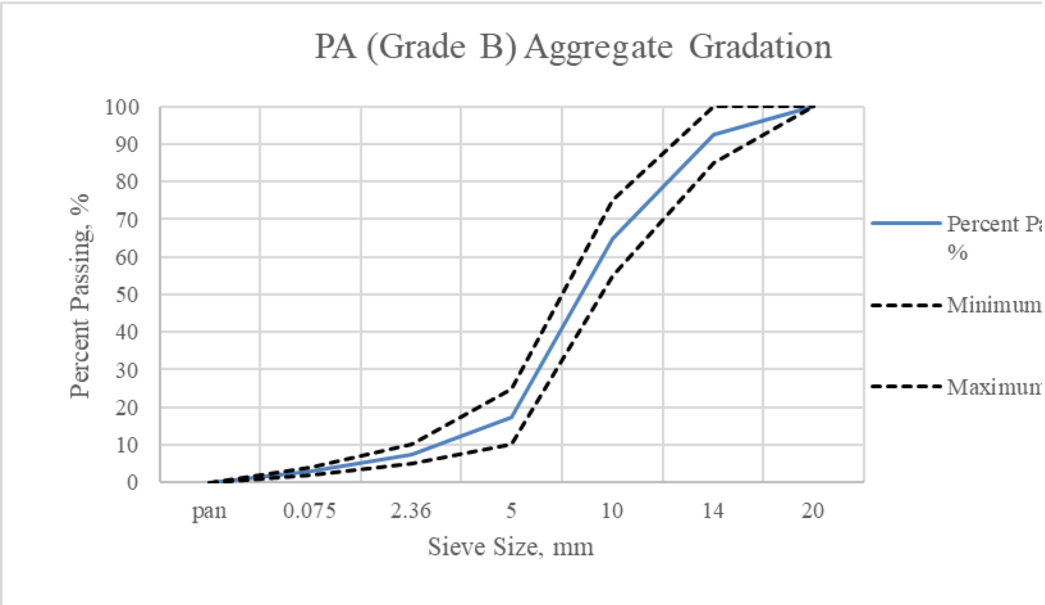

Figure 3. Aggregate Gradation for PA

3.2 LA Abrasion test

At first, there was a noticeable increase and decrease in the abrasion rate when the additive percentage was added from 0% to 4% as shown in Figure 4. It was evident that varying LF percentages resulted in varying abrasion loss values. The maximum value of abrasion loss, which was 21.56% and 31.27%, was obtained by the control sample with 0% LF and 4% of LF, while the lowest value was 1.02% (1% LF). This most likely occurred as a result of the specimens and drum abrasive force, which caused the samples to disintegrate and lose some amount. The abrasion loss value trend pattern also suggested that the ideal amount of LF to use to minimise the abrasion loss of PA is between 1% and 2%. Following the addition of 4% LF, the value of abrasion loss increased, suggesting that adding too much LF will not improve PA's resistance to abrasion. The percentage of lignin fibre demonstrates how the durability of the mixture is affected by the concentration of the additive.

By comparing to a result from previous study which is [15], the control sample (0% nanosilica) obtained the highest value of cantabro loss which was 17%, while the lowest cantabro loss value was 9% (4% nanosilica). This happened likely due to the abrasion force between specimens and drum, resulting in disintegrated samples with certain amount loss. The trend pattern of cantabro loss value also indicated that 3 to 5 % nanosilica as the optimum amount to be utilized to reduce the abrasion loss of PA. The outcome is consistent with this study where the usage of LF able to increase the abrasion resistance of PA.

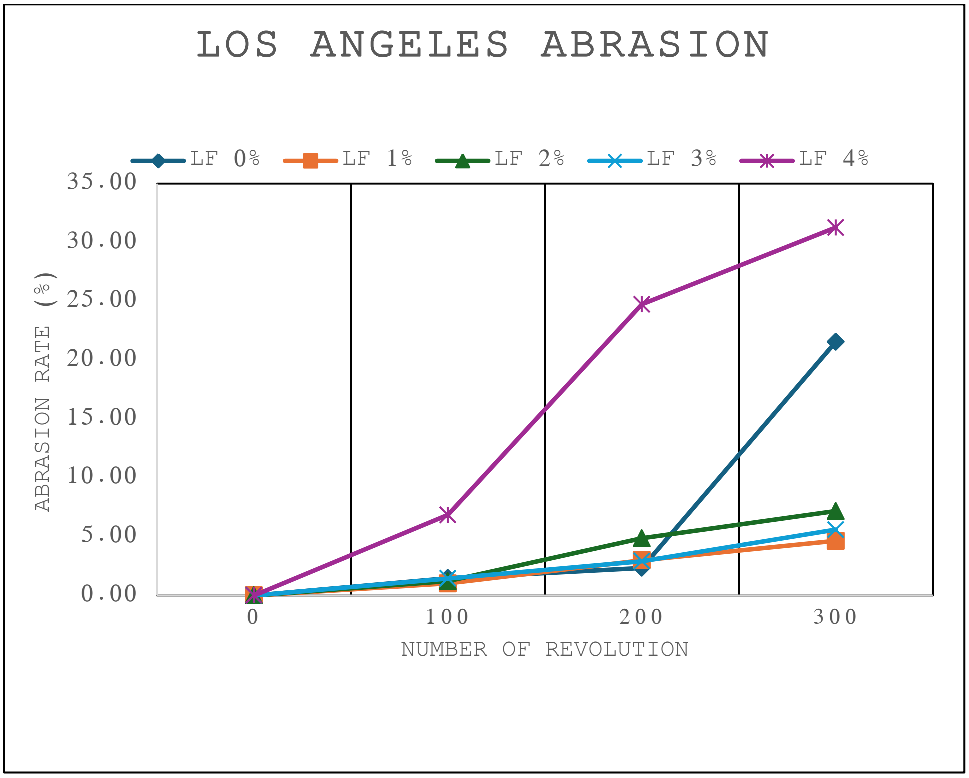

Figure 4. Cantabro Loss

3.3 Penetration test (ASTM D35)

Two samples showed differing results in the bitumen penetration test, indicating variation in bitumen hardness. The first sample, with a penetration value of 52.17 mm, is below the normal range for 60/70 grade bitumen, suggesting it is harder and more resistant to deformation, suitable for applications requiring higher rigidity. Conversely, the second sample, with a penetration value of 71.83 mm, exceeds the upper limit of the 60/70 grade, indicating weaker bitumen that may be more prone to deformation, especially in high-temperature regions. These variations highlight the importance of quality control in bitumen manufacturing to ensure consistent performance in paving applications.

3.4 Softening point test

The softening point test indicates the temperature susceptibility of bitumen; a higher softening point means the bitumen is less likely to soften at high temperatures, crucial for hot climates. The observed softening point for 60/70 grade bitumen should be between 46°C and 54°C. In this study, the bitumen's softening point was 45.4°C, slightly below the typical range but still close enough to be acceptable for most standard paving applications in moderate temperature climates. This suggests that while slightly lower, the bitumen can still perform adequately in most conditions.

3.5 Marshall stability test

Figure 5 shows that a 0% LF mixture has a stability of 3506N, suitable for medium to heavy traffic areas, indicating good resistance to deformation. Its flow value of 3.317mm falls within the optimal range of 2-4mm, providing adequate flexibility to prevent cracking. Overall, this mixture is durable and resilient for various traffic conditions. For mixtures with 1%, 2%, 3%, and 4% LF, stability values are beneficial, but the flow exceeds 4mm, indicating less stiffness and failing the optimal flow test. Notably, the 2% LF sample has the highest stability at 10060.50N, suggesting it can bear higher loads without significant deformation, ideal for heavily trafficked pavements.

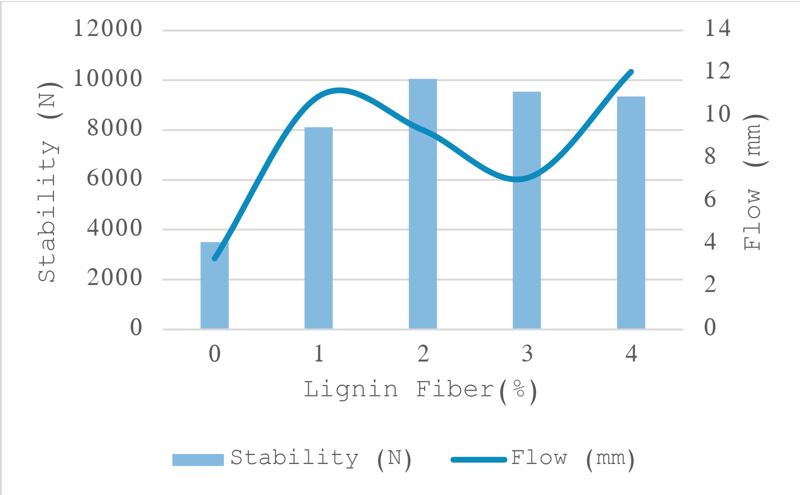

Figure 5 Stability and Flow VS LF

For Figure 6, the target density range is approximately 1.92 to 2.11 g/cm^3, representing 80% to 88% of the maximum theoretical density. The study shows a positive correlation between lignin fiber (LF) content and density, with density increasing as LF increases, indicating better compaction and strength. However, at 3% LF, density decreases before increasing again at 4%. The highest densities observed were at 2% and 4% LF (1.948 g/cm^3), while the lowest were at 0% and 1% LF (1.83 g/cm^3 and 1.902 g/cm^3), suggesting potential issues with mix quality. Flow values, higher than specified except for the control sample, reflect the mix's flexibility, which, alongside stability values, is crucial for overall performance.

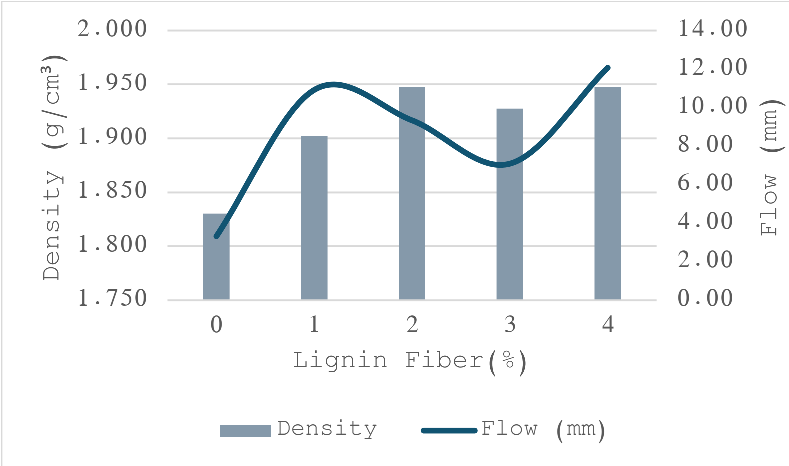

Figure 6 Density and Flow Against LF

Figure 7 indicates that the highest stability and density were achieved with 2% lignin fiber (LF), at 10060.50 N and 1.948 g/cm^3, respectively. Additionally, 3% and 4% LF also showed good stability and density results. Overall, the Marshall stability test results suggest that LF is an effective additive for enhancing the performance of asphalt paving mixtures.

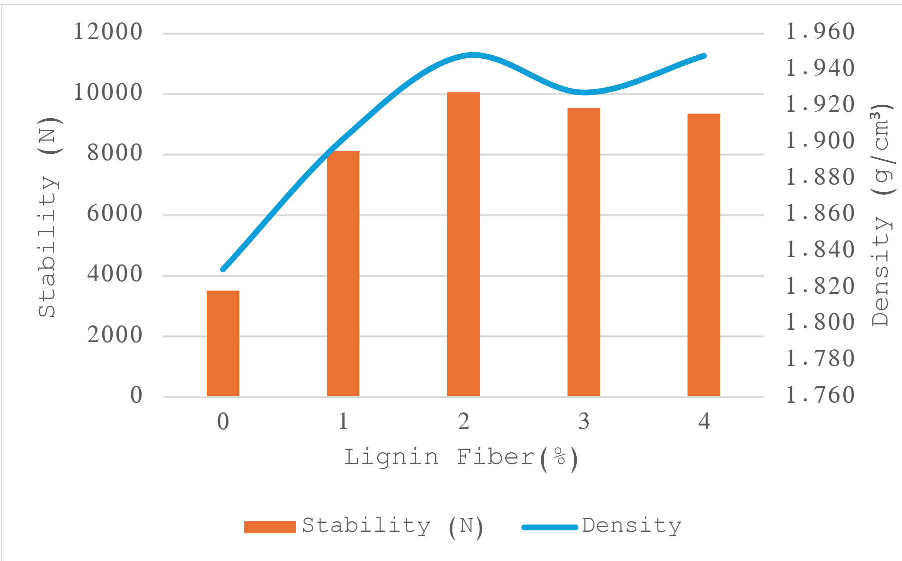

Figure 7 Stability and Density VS LF

According to Figure 8, the highest stiffness value of 1346.60 N/mm was achieved with 3% lignin fiber (LF), along with a flow of 7.09 mm, indicating good load-bearing capacity and flexibility. However, 2% LF had the lowest stiffness at 107.78 N/mm and a flow of 9.33 mm, suggesting poor support for heavy loads. Given the balance of stiffness and flow, the 0% LF mixture might still be optimal, as it provides a more suitable combination of these properties compared to other percentages.

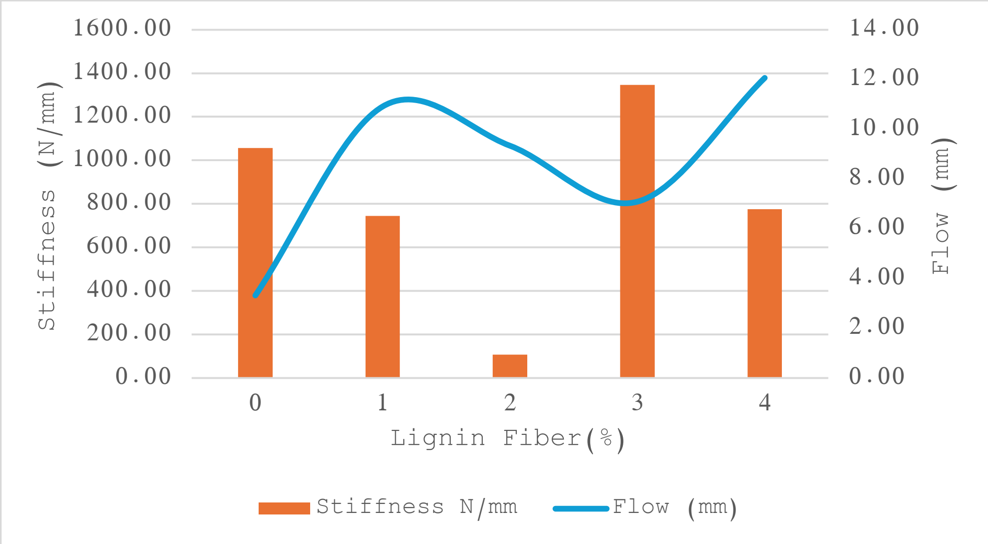

Figure 8 Stiffness and Flow VS LF

Figure 9 shows that 1% lignin fiber (LF) significantly decreases stiffness compared to the control sample, though it increases density, suggesting better compaction but reduced stiffness. At 2% LF, there is a dramatic reduction in stiffness (107.8 N/mm), indicating an overly flexible mixture that may compromise load-bearing capacity. This low stiffness and high density combination suggests that 2% LF disrupts the asphalt's internal structure. However, at 3% LF, both high stiffness and high density indicate a well-balanced mixture, with lignin fibers effectively enhancing mechanical properties without compromising compaction or workability.

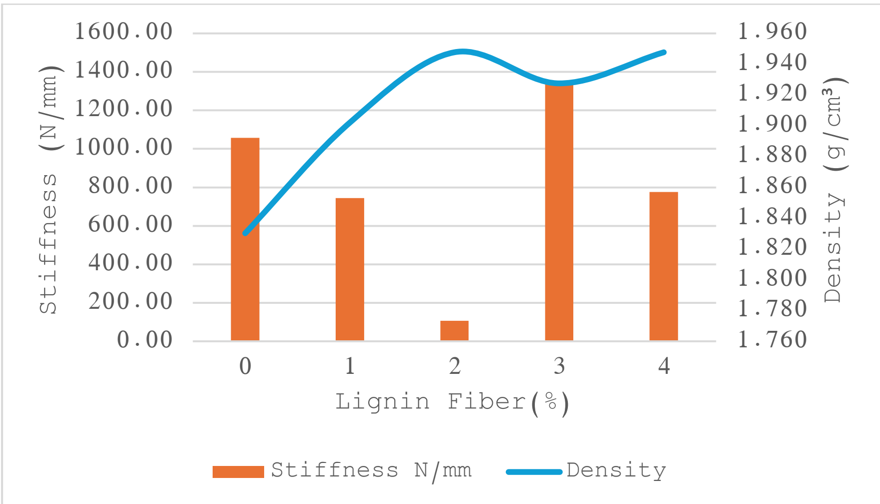

Figure 9 Stiffness and Density VS LF

The control sample (0% lignin fiber) shows moderate stiffness and stability. While adding lignin fiber generally reduces stiffness, it doesn't always compromise stability or load-bearing capacity. Sample 3 (2% lignin fiber) demonstrates a good balance of stiffness and stability, indicating this fiber content optimally enhances performance without compromising flexibility or load-bearing capacity as shown in Figure 10.

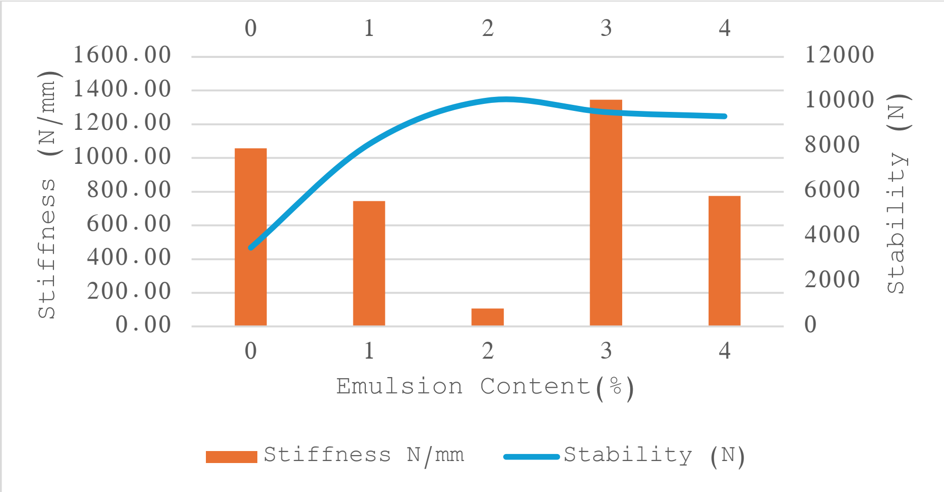

Figure 10 Stiffness and Stability VS LF

3.6 Binder drain down

Figure 11 shows that binder draindown decreases with increasing lignin fiber (LF) content. This suggests that LF improves bonding between the binder and aggregates. Adding 1-4% LF significantly reduces binder draindown, helping the mix maintain its designed air void content and permeability, which are essential for effective water drainage, reducing hydroplaning risk, and improving skid resistance in porous asphalt.

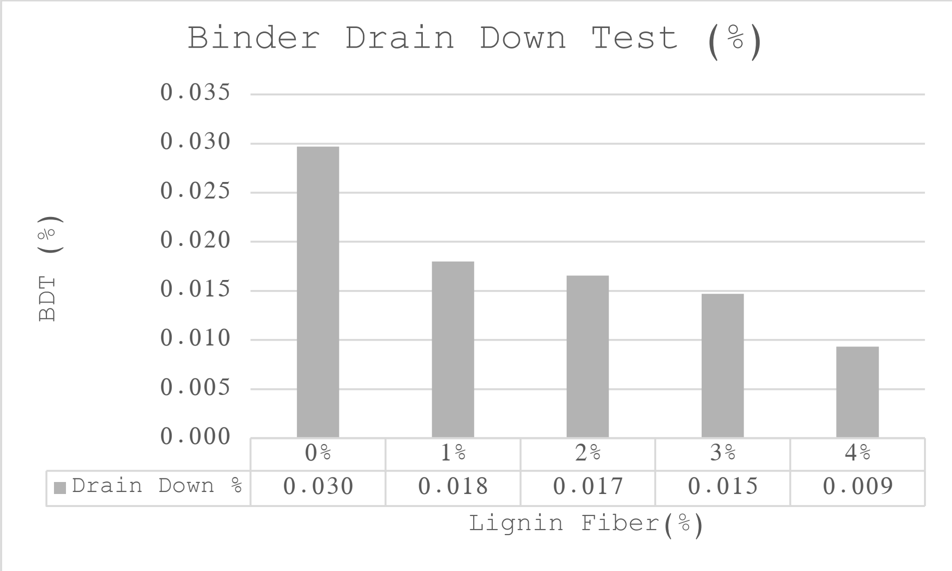

Figure 11 Binder Draindown

3.7 Indirect tensile strength

Porous asphalt generally has lower Indirect Tensile Strength (ITS) values compared to dense-graded asphalt because of its higher air void content. ITS values for porous asphalt typically range from 0.3 to 0.7 N/mm^2, depending on the mix design and materials used. In the graph for Figure 12, ITS values increase from 0% to 3% LF, then decrease at 4% LF. The highest ITS value under dry conditions is at 3% LF (114.08 N/mm^2), while the lowest is from the control sample (0% LF) at only 49.82 N/mm^2. Higher ITS values indicate better crack resistance, as porous asphalt can withstand higher strains before failing. It is also resulting in better crack resistance. From [17], the TSR value was 74%. It was also determined from the tests that 2% of LF was the ideal amount needed for PA to achieve both values.

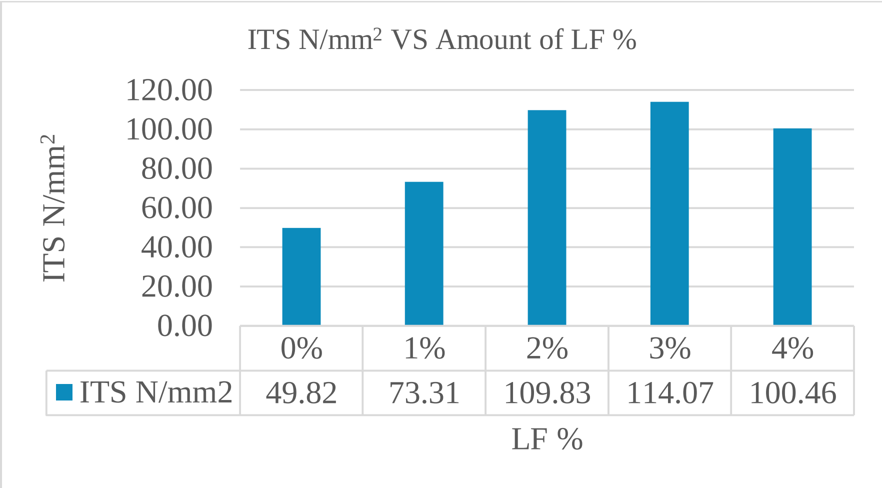

Figure 12 Indirect Tensile Strength

4. Conclusion

In conclusion, this study successfully achieved its primary objectives. Firstly, it thoroughly evaluated the impact of different proportions of lignin fiber (LF) on the mechanical properties of asphalt mixtures. Various tests, including the abrasion test, Marshall stability test, binder draindown test, and indirect tensile test, demonstrated that varying LF percentages significantly influence these properties. The addition of 1-2% LF reduced abrasion loss, indicating enhanced wear resistance, while 2% LF yielded the highest stability and density, showing improved load-bearing capacity and compaction. Additionally, tensile strength increased up to 3% LF, indicating better crack resistance. The study identified that an LF content of 2-3% offers the best balance of mechanical properties and workability, with 2% LF showing optimal tensile strength, stability, and density. While 3% LF also had good mechanical qualities, its higher flow values suggested potential workability issues. Thus, 2-3% LF is the ideal content to maintain workability while enhancing performance and durability. This study provides valuable insights into using lignin fiber to reinforce asphalt mixtures, confirming that adding LF can significantly improve the mechanical properties and longevity of porous asphalt mixtures.

5. Acknowledgements

The authors would like to acknowledge Malaysian Higher Education and Universiti Malaysia Pahang Al-Sultan Abdullah for funding this research under University Internal Grant RDU233302.

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