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LABORATORY EVALUATION OF BASALT FIBER-REINFORCED DENSE-GRADED ASPHALT

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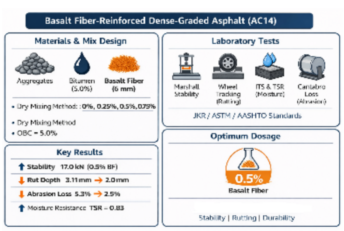
Graphical abstract



Abstract

The use of additives in asphalt has become an important approach to improve pavement performance and extend its lifespan. Among the additives, fiber reinforcements in asphalt are getting considerable attention as they have the potential to enhance stability and resistance to rutting and moisture damage. In this study, basalt fiber, a natural material known for its strength and durability, was used to modify dense-graded asphalt of AC14 prepared using 60/70 penetration grade bitumen, which is widely used for flexible pavement construction due to its balance of stiffness and workability under typical conditions. Basalt fiber was added at 0%, 0.25%, 0.5%, and 0.75% by total weight of aggregate, using the dry mixing method. The mixtures were tested for Marshall stability, moisture-induced damage, rutting performance using a wheel-tracking test, and abrasion resistance using the Cantabro loss test. The results generally demonstrated improved asphalt performance with the incorporation of basalt fiber, although the level of improvement varied with fiber content. Basalt fiber-modified mixtures exhibited improved moisture resistance compared with the conventional asphalt. The maximum stability was recorded at 17.0 kN for mixture containing 0.5% basalt fiber, which is higher than that of the conventional asphalt. Additionally, the rut depth decreased from 5.1 mm to 4.0 mm, while the abrasion loss reduced from 4.4% to 2.5%. Therefore, the findings justified that 0.5% basalt fiber is the optimum dosage among the fiber content investigated in improving the asphalt mixture performance.

Keywords: Basalt Fiber, Asphalt Mixture, Dense-Graded, Moisture Damage, Fiber-reinforced

1.0 INTRODUCTION

Increasing traffic loads, extreme climate conditions, and high maintenance costs have driven the exploration of improved asphalt materials for road construction. Conventional dense-graded asphalt (DGA), currently in use, exhibits several performance issues, including cracking, rutting, and moisture damage. To address this, improving asphalt mixtures is often necessary to achieve better mechanical performance for pavement surfaces. One improvement method is to add fibers to the asphalt mix as reinforcement [1-3]. In general, the use of fibers in concrete is well-established [4-6], but their application in asphalt remains limited in practice. Therefore, more studies are needed to investigate and validate the benefits of using fibers in asphalt mixtures. Several types of fibers have been used in asphalt, both natural and synthetic, such as cellulose [7], glass [8-10], steel [11,12], aramid [13], and polypropylene [14,15]. Numerous laboratory and field studies have demonstrated that the addition of fiber can enhance tensile strength, improve crack-bridging ability, increase toughness, and provide better water resistance [7,9-11,14]. By strengthening the asphalt matrix, fibers help slow the formation of microcracks, which, in turn, reduce water penetration and delay moisture-related damage.

Among the various fiber types, basalt fiber has gained more attention in recent years due to its unique combination of mechanical and environmental advantages [16-18]. It is produced from volcanic basalt rock, formed by the rapid cooling of lava, making it abundant and naturally occurring. Chemically, basalt consists mainly of silica, alumina, iron oxide, calcium oxide, and magnesium oxide [19]. The fibers are typically dark brown to black, with a glossy finish, produced by melting basalt rock at around 1400°C and extruding it into continuous filaments. Basalt fiber has a tensile strength of approximately 4000 MPa and a modulus of elasticity of around 80-100 GPa, with high thermal resistance up to 800°C. It is also chemically durable and absorbs less than 0.5% water, making it suitable for extreme environmental conditions [20,21].

The use of basalt fiber in asphalt mixtures has shown clear benefits. Research indicates that basalt fiber mixtures exhibited improved Marshall properties, rutting resistance, moisture resistance, and fatigue performance [22-25]. Wu et al. [26] found that adding 0.3% basalt fiber improved Marshall stability and indirect tensile strength by around 20%. Yan et al. [27] reported enhanced rutting and cracking resistance, while Wu et al. [28] observed a 40% increase in fatigue life compared to conventional asphalt. Furthermore, Cheng et al. [29] noted that increasing basalt fiber content can gradually increase the optimum bitumen content (OBC). This indicates that basalt fiber can influence the OBC, although the extent of this effect depends on the fiber content. Overall, these findings underscore the potential of basalt fiber as a potentially effective reinforcement for asphalt pavements.

Despite numerous studies supporting the use of basalt fiber as a reinforcement for asphalt mixtures, varying results have also been reported. The effectiveness of basalt fibers varied with fiber content, length, and the dispersion technique or mixing method used during asphalt mix preparation [30-32]. Recent studies have also explored hybrid modification approaches using basalt fiber combined with other additives to achieve a balance, complementing their performance in asphalt [33,34]. Limited studies have highlighted the impact of varying amounts of basalt fiber on the mechanical performance of DGA. A more comprehensive laboratory evaluation is crucial in understanding the impact of basalt fiber additive on the mechanical properties of DGA. The determination of factors, such as the optimum fiber content, needs to be clarified in accordance with the specific mix design selected, which in this case follows the Malaysian Public Works Department (JKR) Standard Specification for Road Works, Section 4: Flexible Pavement (JKR/SPJ/2008-S4) [35]. Therefore, this study investigated the laboratory performance of dense-graded asphalt mixtures reinforced with varying basalt fiber contents. Several parameters were evaluated, including Marshall properties, indirect tensile strength, moisture susceptibility, abrasion resistance, and rutting resistance. The findings of this study provide a better understanding of the effects of basalt fiber on DGA and offer practical recommendations for asphalt mix designers and practitioners to support the design of more durable asphalt mixtures for long-term pavement performance.

2.0 METHODOLOGY

This study was divided into two parts: the first involved sample preparation and the determination of the optimum bitumen content (OBC). The second part consists of laboratory performance testing, which includes the rutting resistance, Marshall stability and flow, abrasion loss, and moisture susceptibility.

2.1 Materials

The materials used in this study include bitumen 60/70 PEN, crushed granite aggregate, and basalt fiber. This study utilized a fiber size of 6 mm in length and 13 microns (µm) in diameter, as shown in Figure 1, at varying contents of 0.25%, 0.5%, and 0.75% by weight of the aggregate. The basalt fiber was supplied by Chongqing Roadbuilding New Material Technology Co., Ltd., China. According to the manufacturer's technical specifications, the basalt fiber has a tensile strength of approximately 4000 MPa, a modulus of elasticity of 80-100 GPa, a density of about 2.650 g/cm^3, and excellent thermal stability with service temperatures up to approximately 800^{o}C. These properties make basalt fiber a suitable reinforcing material for asphalt mixtures, providing improved strength, stiffness and durability under traffic loading and environmental exposure. The physical and mechanical properties of the basalt fiber used in this study are summarized in Table 1. The bitumen and aggregate properties were verified in accordance with the Malaysian Public Works Department (PWD) requirements [35]. Table 2 provides the detailed properties of the bitumen 60/70 PEN grade used for sample preparation. For the granite aggregate, detailed mechanical and physical properties are given in Table 3. Both materials show compliance with the specified requirements.

Figure 1 Basalt Fiber

Table 1 Physical and mechanical properties of basalt fiber

Properties	Value
Material	Basalt Fiber
Length	6 mm
Diameter	13 µm
Tensile strength	Approximately 4000 MPa
Density	2.650 g/cm^3
Elastic Modulus	80-100 GPa
Service Temperature	Up to 800^{o}C

Table 2 Properties of bitumen 60/70 PEN

Properties	Standards Test	Result	Requirement
Penetration @ 25 °C, dmm	ASTM D5	66	60-70
Softening point, °C	ASTM D36	52.5	49-56
Viscosity @ 135 °C, Pa·s	ASTM D440	0.7	< 3
Ductility Test @ 25°C, cm	AASHTO T51-86	112	≥ 100
Density @ 15 °C, g/cm^3	ASTM D70	1.038	-
Loss on heating @163°C, %	MS124	0.12	≤ 0.2

Table 3 Physical and mechanical properties of aggregates

Properties	Standards Test	Result	Requirement
Water Absorption (%)	MS30	0.93	≤ 2
Aggregate Crushing Value (%)	BS 812-110	19	≤ 25
Flakiness Index (%)	MS30	23	≤ 25
Polished Stone Value	MS30	53	≥ 40
Soundness (%)	AASHTO T104	6.8	≤ 12
Abrasion Loss (%)	ASTM C131	16.1	≤ 25

2.2 Mix Design

The asphalt mixtures were prepared in accordance with the Malaysian Public Works Department (JKR) Standard Specification for Road Works, Section 4: Flexible Pavement (JKR/SPJ/2008-S4) [35], as summarized in Table 4. The aggregate fractions were proportioned to achieve the AC14 gradation specified in JKR/SPJ/2008-S4. Hydrated lime was added to the mix at 2% as an anti-stripping agent. The Marshall Mix Design Method was used to obtain the optimum bitumen content (OBC). During the assessment, the OBC design was determined in accordance with the criteria specified by the Malaysian Public Works Department including the requirement for Marshall stability, flow, voids in total mix (VTM), and voids filled with bitumen (VFB), ensuring that all asphalt mixtures complied with the relevant Malaysian Public Works Department specifications prior to performance evaluation.

Table 4 Gradation Limits for Asphaltic Concrete, Wearing Course AC14

Sieve Size (mm)	Gradation Limit (%)	Percentage Passing (%)
20.0	100	100
14.0	90-100	95
10.0	76-86	81
5.0	50-62	56
3.35	40-54	47
1.18	18-34	26
0.425	12-24	18
0.150	6-14	10
0.075	4-8	6
Pan	2	2

2.3 Wheel Tracking Test

This study used the Hamburg Wheel-Tracking machine to evaluate the rutting resistance of compacted asphalt mixtures under simulated traffic and moisture conditions. Cylindrical compacted samples with a diameter of 150 mm were prepared at an air void content of 7.0 ± 0.5%. Prior to testing, the compacted samples were preconditioned in water at 50°C for 45 minutes. Samples were tested while submerged in the water and maintained at 50°C to simulate the moisture exposure. Testing continued until the rut depth met the failure criteria or until 20,000 passes. Key parameters measured include the rut depth and the number of passes to failure, which are critical in assessing the durability and quality of asphalt pavements. Figure 2 shows the wheel tracking machine and sample setup for the test. This test was conducted in accordance with AASHTO T324 [36]. To further evaluate the asphalt mixture's resistance to permanent deformation under repeated loading, the wheel tracking slope (WTS) or rutting slope can be determined using Equation 1, as specified in BS EN 12697-22 [37] for comparative evaluation of the deformation rate.

$$WTS= (d_{LC1}-d_{LC2})/LCR \times 1000 \quad (1)$$

where WTS is the wheel tracking slope in mm per 1000 cycles, d_{LC2}, d_{LC1} is the rut depth after a range of load cycles (mm), and LCR is the load cycle range (LC_1- LC_2). WTS is significant for evaluating rutting potential, which reflects continued deformation under creep conditions. A lower WTS value indicates that the mixture has better rutting resistance and a lower potential to deform under applied load cycles.

2.4 Marshall Stability and Flow Test

The Marshall stability test evaluates the maximum load-carrying capacity of the asphalt mixture, while the corresponding flow value provides an indication of deformation at the maximum load. The samples were preconditioned in a water bath at 60 °C for 30-40 minutes prior to testing, in accordance with ASTM D6927 [38]. According to the specification, the minimum stability value is 8 kN, and the acceptable flow range is 2-4 mm. Figure 3 shows the equipment setup for the Marshall test and the Marshall samples used.

2.5 Moisture Damage Evaluation

Moisture susceptibility is a critical factor that affects the long-term durability of asphalt pavements. In this study, the resistance of the samples to moisture was measured using Indirect Tensile Strength (ITS) and the Tensile Strength Ratio (TSR) in accordance with AASHTO T283 [39]. For each mixture type, two subsets comprising a total of six samples were prepared at an air-void content of 7.0 ± 0.5% and tested for indirect tensile strength at 25°C under both wet and dry conditions. This approach provided a comparative assessment of tensile strength loss due to moisture conditioning. Samples for dry ITS were placed in a water bath at 25°C for 2 hours before testing. For wet ITS samples, preconditioning was performed using the modified Lottman method, where the samples were partially saturated with water (70% saturation), frozen for 24 hours, and then thawed at 60°C. The samples were tested at a displacement rate of 50 mm/min, and the indirect tensile strength value was calculated using Equation 2.

$$ITS= 2000P/(\pi Dt) \quad (2)$$

where ITS is the indirect tensile strength (kPa), P is the applied load at failure (N), D is the sample diameter (mm), and t is the sample thickness (mm). The TSR is calculated by taking the ratio of wet ITS to dry ITS. According to the specification, a minimum TSR of 80% is typically recommended to ensure acceptable resistance to moisture damage in asphalt mixtures. A lower TSR value indicates weak adhesive bonding between the bitumen and aggregate, which could lead to stripping and early pavement failure. Figure 4 shows the equipment setup for the indirect tensile strength test and the sample conditioning process prior to testing.

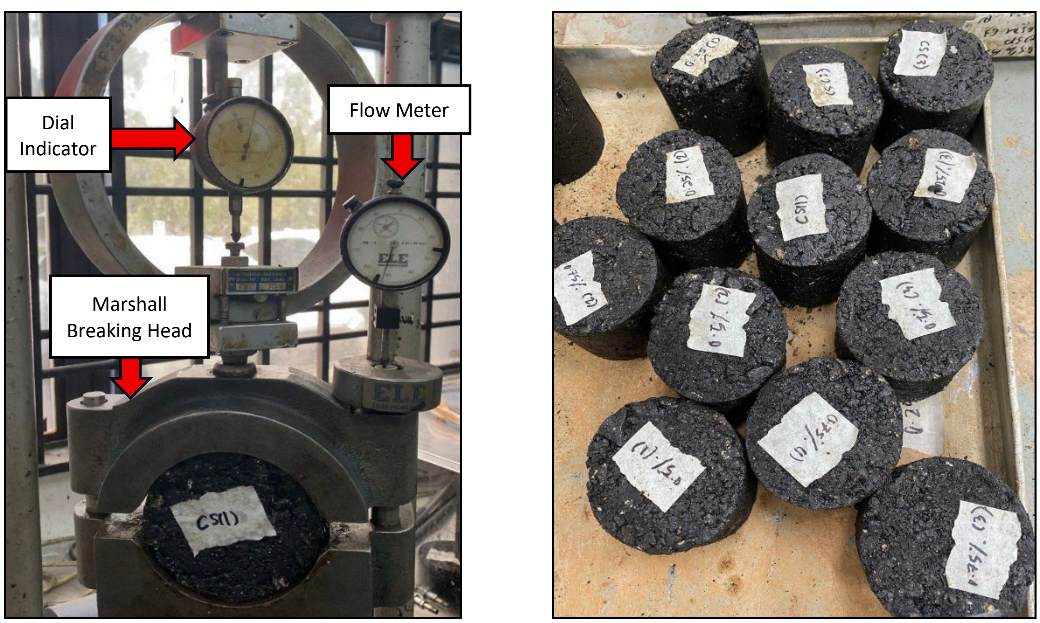
2.6 Cantabro Test

The Cantabro test was used to assess the cohesion and abrasion resistance, or particle loss, of compacted asphalt mixtures. This test was conducted according to the procedure as specified in ASTM D7064 [40]. Although this test was originally developed for open-graded asphalt mix, it can also be applied to dense-graded asphalt mix to provide an overview of aggregate-binder adhesion, cohesion, and the internal stability of the modified mix.

Figure 5 shows the Cantabro machine used in this study. The compacted asphalt sample was placed in the Los Angeles abrasion machine without the steel balls, and the machine was rotated at 300 revolutions. The percentage of mass loss was then calculated to quantify the abrasion resistance. A lower abrasion-loss percentage indicates good aggregate-binder bonding and greater resistance to raveling. In general, there is no official limit provided for Cantabro loss in dense-graded asphalt, since this test is not routinely conducted for dense asphalt mix. However, based on the overall observations reported for conventional dense-graded asphalt mixtures, Cantabro loss values below approximately 10% were observed for several mixtures exhibiting relatively good durability performance [41,42]. Therefore, the 10% value used in this study serves only as a comparative reference rather than a formal specification limit.

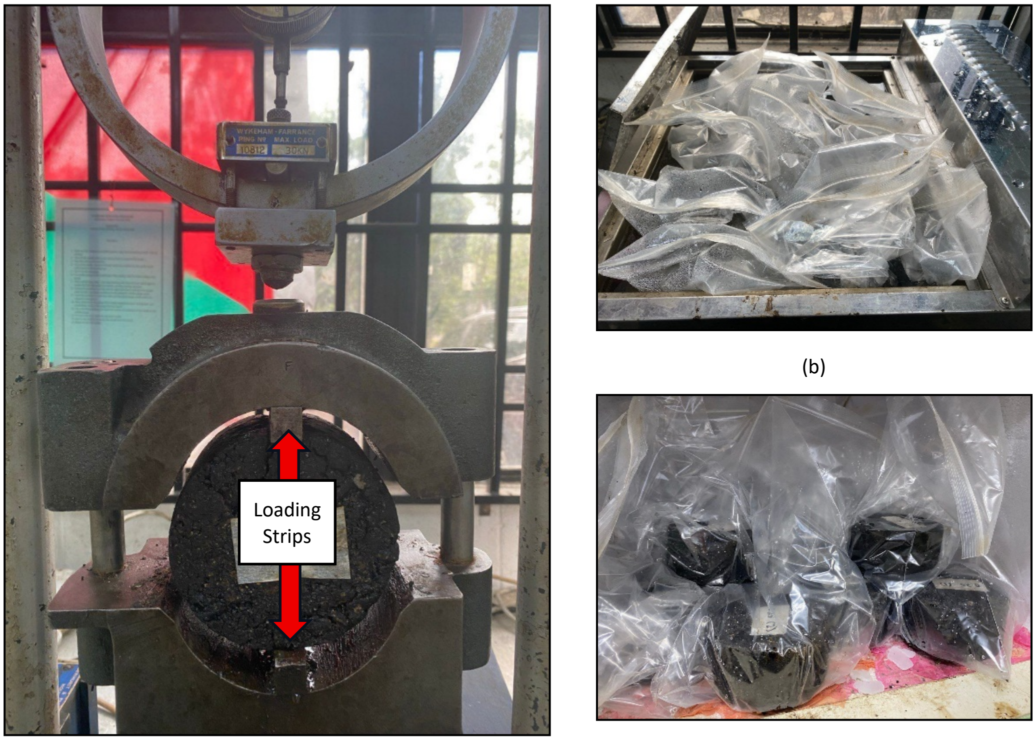
(a) (b)

Figure 2 (a) Wheel Tracking Machine and (b) sample setup



(a) (b)

Figure 3 (a) Marshall Machine Setup and (b) Marshall samples



(a) (b) (c)

Figure 4 (a) Indirect Tensile Strength Machine Setup, (b) sample conditioning, and (c) freezing

Figure 5 Cantabro Machine

3.0 RESULTS AND DISCUSSION

Details of the findings are discussed as follows:

3.1 Optimum Bitumen Content

The OBC was determined using the control asphalt mixture without basalt fiber in accordance with the Malaysian Public Works Department Standard Specification for Road Works [35] which specifies the Marshall mix design criteria for AC14 asphalt mixture. The samples were prepared with varying bitumen contents ranging from 4.0% to 6.0% with 0.5% increments. Main parameters such as Marshall stability, flow, bulk density, voids in aggregate filled with bitumen (VFB), and Voids in Total Mix (VTM) were evaluated. Table 5 summarizes the findings for OBC and Marshall properties for the verified samples. From the table, bitumen content of 5.0% was identified as the OBC. At this binder content, the mixture achieved a satisfactory balance of Marshall properties and volumetric requirements in accordance with the JKR specification.

After establishing an OBC for the control asphalt mixture, the same binder content was adopted for all asphalt mixtures containing basalt fiber. Therefore, 5.0% was chosen as the design binder content for all mixture types fabricated for subsequent testing and performance evaluation. This is to ensure that the observed differences in mechanical performance and durability were primarily associated with the incorporation of basalt fiber rather than variations in bitumen content. Additionally, this could isolate the reinforcement effect of basalt fiber, showing that the changes in measured performance originate from the fiber-mastic interactions rather than the binder richness.

3.2 Marshall Properties

The results of Marshall stability, flow, and stiffness of the samples with varying basalt content are presented in Figure 6. At the minimum required stability of 8 kN and stiffness of 2 kN/mm, all the asphalt mixtures produced meet the specification. In the flow results, only 0.25% of the BF samples exceeded the acceptable range of 2-4 mm, while the others remained within the specified limits. The stiffness of this sample also decreased compared to conventional asphalt, potentially reducing its load-bearing capacity. The addition of 0.5% basalt fiber has increased stability to a maximum of 17.0 kN, with a flow value of 3.6 mm. Furthermore, the moderate flow value combined with high stability and stiffness indicates good flexibility without the sample being too soft. At a 0.75% fiber content, the asphalt exhibits the highest stiffness of 6.5 kN/mm; however, with a flow approaching the lower limit of 2 mm, this indicates reduced flexibility and a potential for brittleness, especially when subjected to constant fatigue or temperature cycles. Overall, the addition of basalt fiber has improved the Marshall properties of the asphalt mixture. Adding less fiber (0.25%) results in lower stiffness, while adding too much (0.75%) causes excessive stiffness, increasing the tendency of brittle failure. Therefore, adding 0.5% basalt fiber appears to provide the best balance of stability, stiffness, and acceptable asphalt mixture flow.

The observed improvement in Marshall properties can be attributed to the reinforcing mechanism of basalt fiber within the bitumen-aggregate matrix. During mixing, the basalt fibers become randomly distributed throughout the asphalt mastic, forming a three-dimensional reinforcing network that enhances the interfacial bonding between the bitumen and aggregates. This network improves stress transfer within the mixture and helps distribute the applied load more uniformly, thereby increasing the load-bearing capacity and resistance to permanent deformation. In addition, the rough surface texture and high tensile strength of basalt fibers contribute to improved mechanical interlocking with the asphalt mastic, limiting aggregate movement under loading. However, excessive fiber content may reduce mixture workability and promote fiber agglomeration, resulting in non-uniform fiber dispersion and localized stress concentrations that can adversely affect mixture flexibility and overall performance [25,30]. Zhao et al. [43] also reported an increase in Marshall stability at the optimum basalt dosage, with an increment of 19.6%. Similar findings were observed in other studies, where basalt fiber enhances stability even in high reclaimed asphalt pavement (RAP) mixtures [26] and in porous asphalt [23].

Table 5. OBC and verified samples

Parameter	Bitumen content (%)	Verified Samples	PWD Specification
Stability	4.5 @ max	12 kN	>8 kN
Bulk specific gravity	5.3 @ max	2.340	-
Flow	4.8 @ 3 mm	3 mm	2-4 mm
VFB	5.2 @ 75%	74%	70-80%
VTM	5.2 @ 4%	4.2%	3-5%
Selected OBC		5.0%	

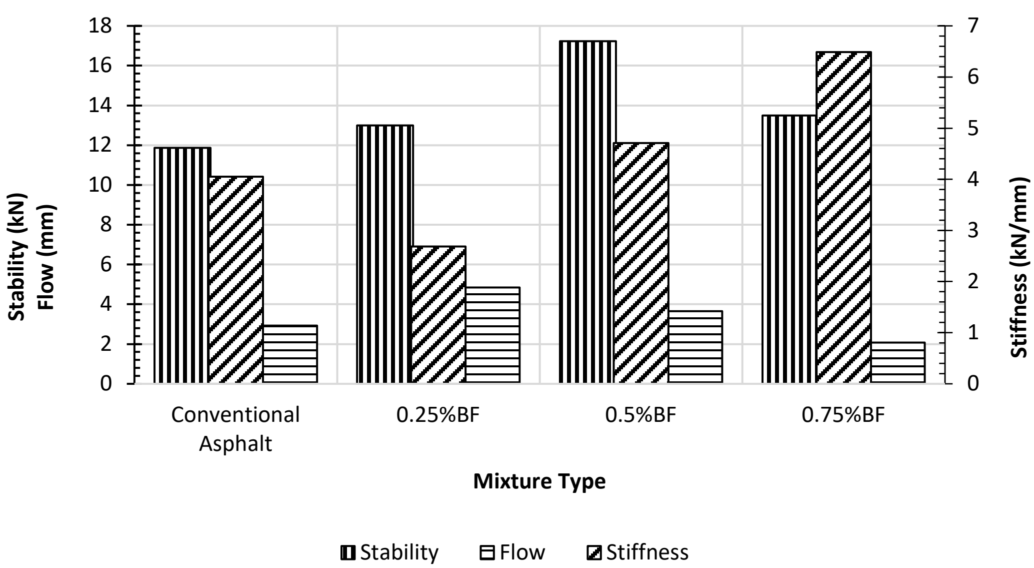
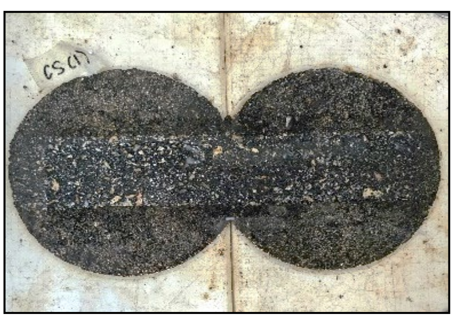


Figure 6 Marshall stability, flow, and stiffness of samples with varying basalt content

3.3 Rutting Resistance

Figure 7 shows the rut depth and cross-section of the tested samples containing basalt fiber at 0%, 0.25%, and 0.5% after the wheel-tracking test. During testing, the rut depth of the samples was monitored until 20,000 passes were completed. It should be noted that all samples were prepared with consistent air void content to avoid the effect of density variation on the differences in rut depth. The plot of rut depth versus applied load cycles is shown in Figure 8, where lower rut depths indicate better rutting resistance. The figure shows a gradual increase in rut depth with increasing number of passes, with the most rapid deformation occurring in the initial 1000 passes due to the post-compaction consolidation state. The trend clearly shows that the control sample without basalt fibers has the highest rutting as the cycles progressed, with a final rut depth exceeding 5.0 mm. This indicates that the absence of basalt fibers caused a lower resistance to permanent deformation under repeated loading. The addition of basalt fiber significantly improved rutting resistance as observed for asphalt containing 0.25% and 0.5% basalt fiber. The sample containing 0.5% basalt fiber exhibited the best mix, with the least total rut depth of approximately 4 mm. The reduced rut depth is consistent with Zhao et al. [43] and Qin et al. [44], who observed that basalt fiber-reinforced asphalt mixtures exhibit better rutting resistance. By reinforcing the asphalt mastics, the fibers enhance deformation resistance under repeated loading, thereby supporting the reduction of rutting potential in this study [27,28]. On the other hand, the sample with 0.75% showed higher rutting potential than the 0.5% sample throughout the cycles. Although the addition of more fibers is expected to provide greater resistance, at 0.75%, this deviation may have resulted from fiber agglomeration, which affects compaction and fiber dispersion. Wu et al. [25] also highlighted that fiber dispersion is a critical factor in rutting resistance as its homogeneity influences the rheological behavior, particularly at higher fiber content. Further study on the mixing time and method could improve the preparation of fiber-modified asphalt samples. In this study, the WTS was derived from the linear portion of the rut depth vs. load cycles graph, typically between 5,000 and 20,000 cycles. Figure 9 shows the result of WTS and total rut depth for asphalt samples with varying basalt fiber content. The changes in WTS behavior were compared across two stages: initially, between 5,000 and 10,000 cycles, and later, between 10,000 and 20,000 cycles. By examining the total rut depth, the addition of basalt fibers has enhanced rutting resistance, with samples containing 0.5% basalt fibers exhibiting the best performance. When comparing the WTS values obtained between 5,000 and 10,000 cycles, the addition of 0.75% basalt fiber showed the lowest rutting rate at 0.086 mm/1000 cycles, compared to conventional asphalt at 0.145 mm/1000 cycles and 0.095 mm/1000 cycles for 0.5% BF. A similar trend was observed for the slope beyond 10,000 loading cycles, where the mixture containing 0.75% basalt fiber exhibited a lower rutting rate of 0.039 mm/1000 cycles than the 0.5% basalt fiber mixture, indicating improved resistance during the creep stage. However, despite the lower WTS values, the higher total rut depth indicates that greater deformation may have occurred during the initial consolidation stage and that the improvement was not sustained throughout the entire loading process. This indicates that a higher basalt fiber content may influence early-stage deformation during consolidation, leading to a higher final rut depth. In contrast, mixtures with lower fiber content exhibited relatively higher deformation rates at extended loading durations, reflecting reduced resistance during the creep stage. Nevertheless, all fiber-modified mixtures demonstrated lower final rut depths than the conventional asphalt, confirming the beneficial role of fiber in enhancing rutting resistance.



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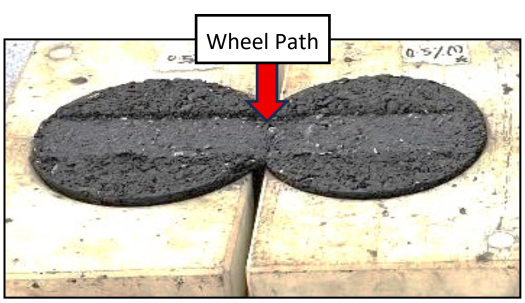

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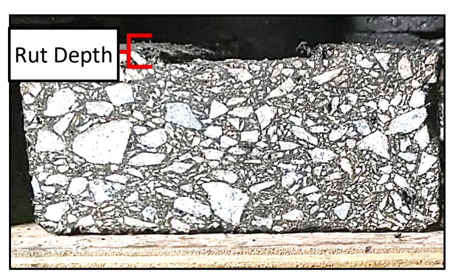

(d)

Figure 7 Wheel Tracking Test sample for (a) conventional asphalt, (b) 0.25% BF, (c) 0.5% BF, (d) sample cross-section

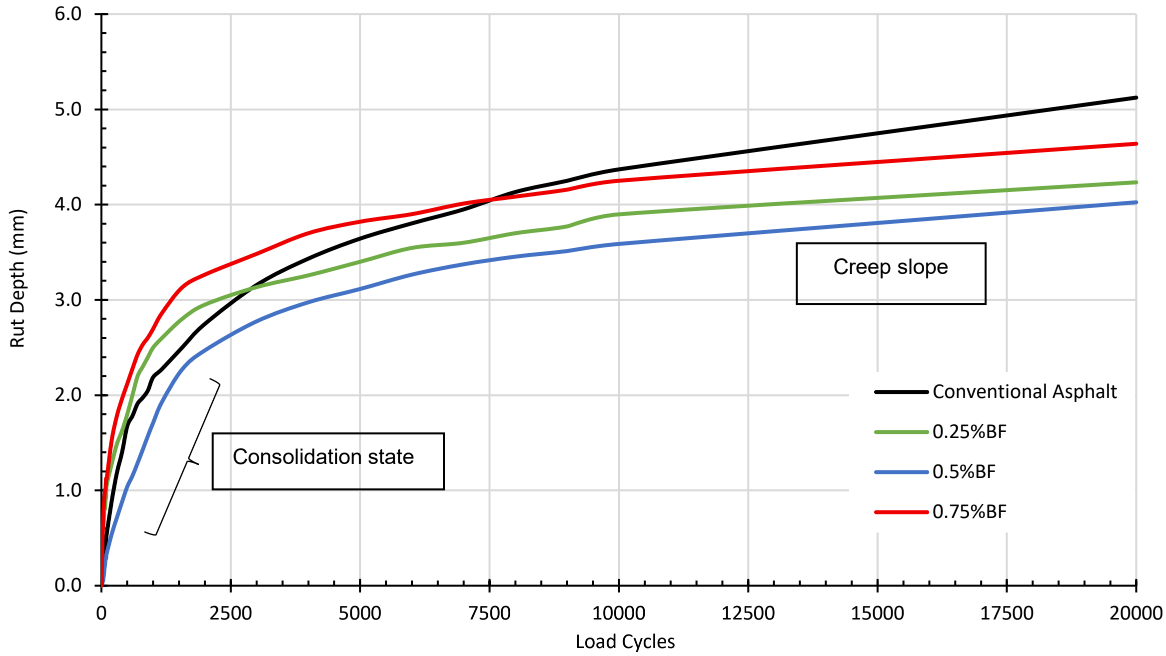

Figure 8 Relationship between Rut Depth (mm) and Load Cycles

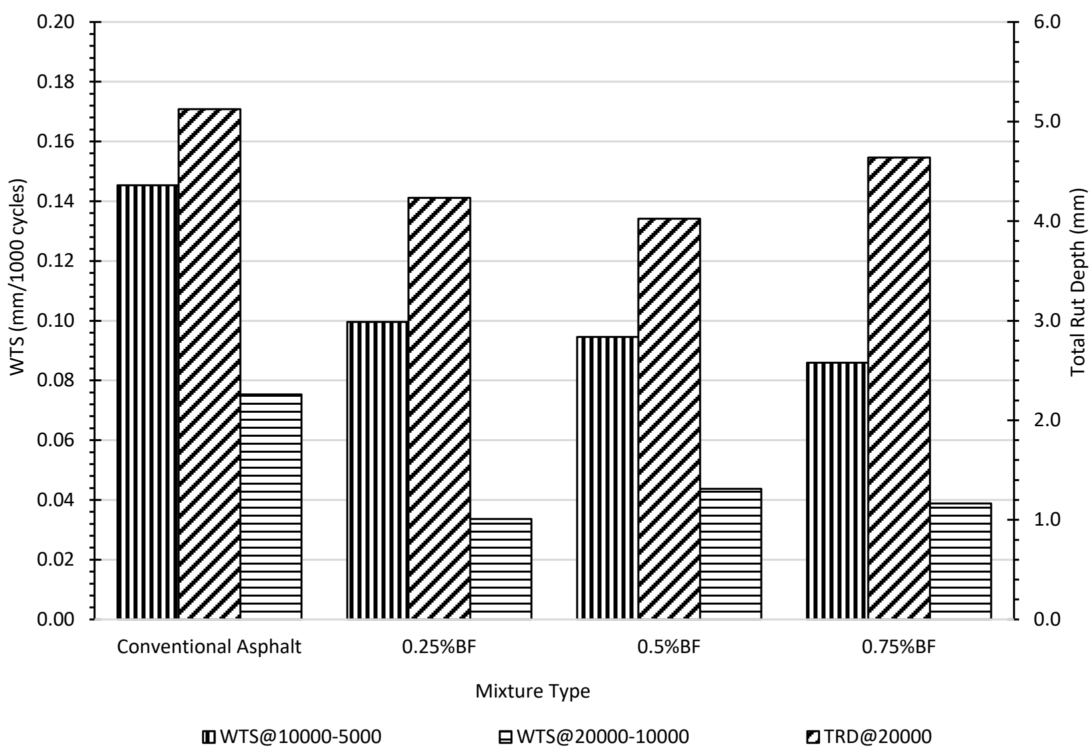

Figure 9 Rutting performance of samples with varying basalt fiber content

3.4 Moisture Susceptibility

The moisture susceptibility evaluation is a critical aspect in assessing basalt fiber's potential to improve asphalt durability under wet conditions. Figure 10 presents the dry and wet indirect tensile strength (ITS) and tensile strength ratio (TSR) for asphalt mixtures with varying basalt fiber contents. The conventional asphalt exhibited a reduction in ITS after-moisture conditioning, resulting in a TSR of 0.80, which represents the minimum acceptable threshold. The incorporation of basalt fiber generally improved moisture resistance, as reflected by higher TSR values across all modified mixtures. The 0.25% BF mixture showed an increase in both dry and wet ITS, indicating enhanced tensile capacity and moisture resistance. For the 0.5% BF mixture, although the absolute ITS values were lower compared to the conventional mixture, the retained strength after conditioning remained acceptable, resulting in a TSR of 0.83. This indicates that moisture resistance was maintained despite the reduction in absolute tensile strength, suggesting that the presence of basalt fiber helped maintain tensile integrity under moisture exposure. The fiber-reinforced structure may restrict microcrack propagation and improve stress transfer.

The 0.75% BF mixture recorded the lowest dry and wet ITS values at 0.78 MPa and 0.74 MPa, respectively. However, the high TSR value at 0.95 indicates effective strength retention after conditioning. This behavior may be associated with changes in internal structure or fiber distribution [44] at higher fiber contents, which requires further investigation. This observation is consistent with Wang et al. [22], who found that basalt fiber mixtures performed better under freeze-thaw cycles, showing enhanced moisture resistance. Another study by Sun et al. [45] also found that basalt fibers enhance toughness, thereby improving water damage resistance in the mixture compared to conventional asphalt.

3.5 Abrasion Loss

The Cantabro test evaluates the durability and cohesion of the conventional and modified asphalt mixtures under mechanical abrasion. The Cantabro sample after testing is shown in Figure 11. Figure 12 shows the result of abrasion loss for samples with varying basalt content. Overall, all mixtures exhibited abrasion loss below the adopted comparative reference value of 10%, indicating relatively good cohesion and resistance to material loss under the test conditions. In particular, the 0.25% BF mix has the highest abrasion loss among all variations, at 5.3%. This shows that adding small amounts of basalt fibers has resulted in slightly lower cohesion in the sample compared to other mixtures. However, samples with 0.5% BF showed the highest abrasion resistance, with a 2.5% loss. This suggests that, at this concentration, basalt fibers contribute to the micro-reinforcement within the asphalt mixture, improving the interlocking between the matrix and aggregate and thereby reducing particle dislodgement.

For samples with 0.75% BF, the abrasion loss was comparable to that of samples with 0.5% BF, indicating better abrasion resistance than conventional asphalt. This finding is supported by Çetin & Oral [23], who found that basalt fiber reduced abrasion loss in porous asphalt mixtures, suggesting better asphalt durability. Although the abrasion loss resistance remains decent, the slight increment suggests that excess fiber content may lead to fiber agglomeration or ‘clumping’ and potentially introduce localized weak points due to poor fiber dispersion [46]. Therefore, a proper mixing method and characterization of the internal structure are recommended for further studies to assess the internal reinforcement mechanism of the modified mixtures. This involves evaluating fiber orientation and embedding within the asphalt matrix, which are outside the scope of this study. Overall, samples with 0.5% basalt fibers are shown to be the optimal fiber reinforcement, as they improve cohesion and aggregate retention under abrasion.

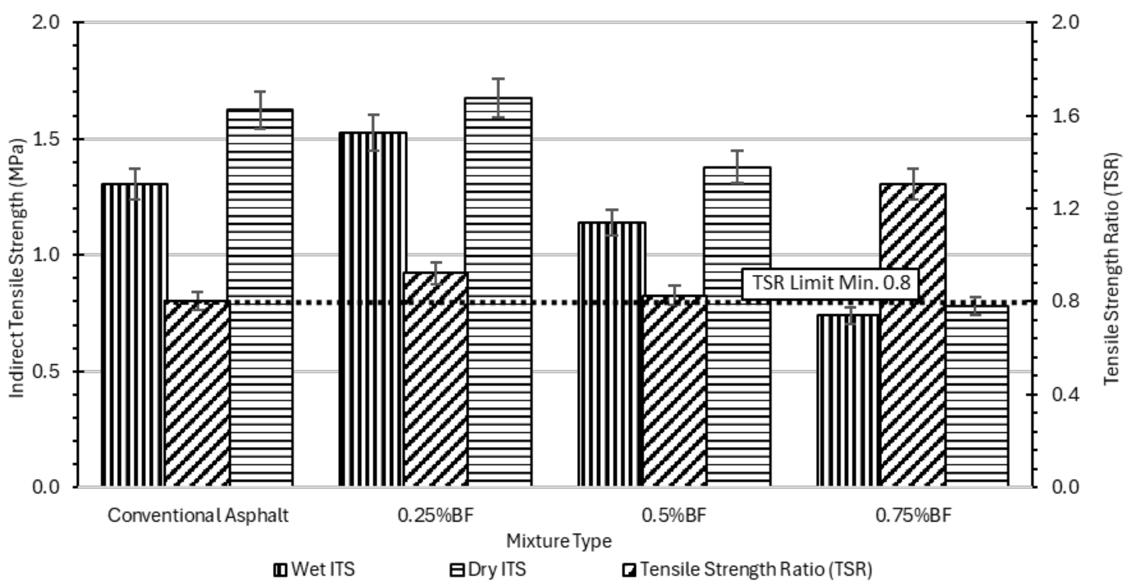

Figure 10 Tensile strength ratio for samples with varying basalt content

Figure 11 Cantabro sample after testing

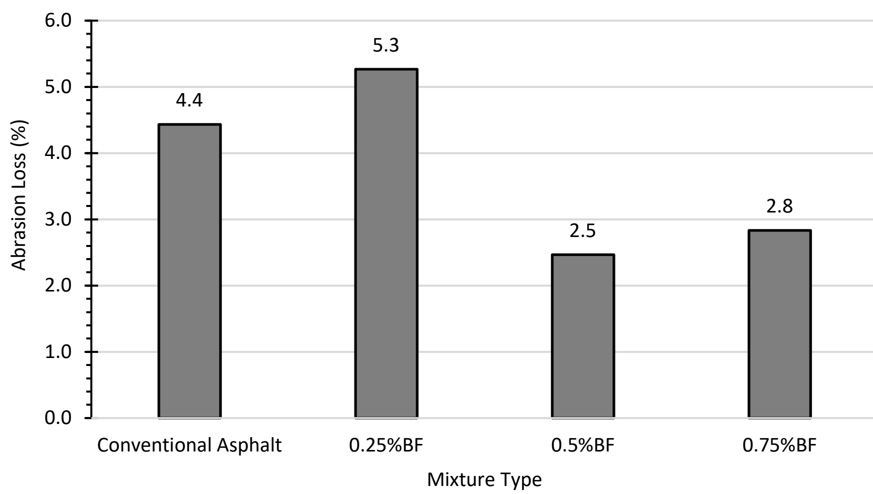

Figure 12 Abrasion loss for samples with varying basalt fiber content

3.6 Comparative Analysis of Test Results

In this study, the optimum basalt fiber content was defined as the dosage that satisfies specification requirements and provides the most balanced improvement across stability, rutting resistance, moisture susceptibility, and abrasion durability, rather than maximizing a single indicator. A comparative analysis was conducted to provide an overall assessment of asphalt mixture performance by simultaneously considering multiple mechanical and durability indicators. Each laboratory test represents a different performance aspect; therefore, a qualitative comparative ranking approach was adopted to facilitate interpretation of the relative performance of the mixtures rather than to establish an absolute or statistically weighted optimization. Table 6 summarizes the relative ranking of the mixtures based on rutting resistance, abrasion loss, Marshall stability, and moisture resistance. In this approach, the ranking is used as an interpretive tool to visualize performance trends across different test parameters, enabling better comparison between mixtures with varying basalt fiber contents. Figure 13 further illustrates this relative distribution, where lower overall ranking values indicate better relative performance trends. The results indicate that the incorporation of basalt fiber generally enhanced the mechanical and durability performance of the dense-graded asphalt mixtures compared to the conventional mixture. This finding is consistent with Cai et al. [47], who reported that basalt fibers create additional interlocking within the asphalt matrix, thereby improving its resistance to repeated loading. Among the tested variations, the mixture containing 0.5% basalt fiber demonstrated consistently strong performance across key indicators, particularly in rutting resistance, Marshall stability, and abrasion durability, while still maintaining acceptable moisture resistance. This suggests that the 0.5% basalt fiber mixture achieved a balanced improvement across multiple performance aspects. Although the 0.75% basalt fiber mixture exhibited a higher TSR, its lower absolute tensile strength, combined with comparatively inferior rutting and abrasion performance, indicates that excessive fiber content may adversely affect mixture homogeneity and deformation behavior. Similarly, while the 0.25% basalt fiber mixture showed improved moisture resistance, its slightly higher Marshall flow value might compromise deformation resistance under traffic loading. Overall, the comparative analysis highlights that the mixture containing 0.5% basalt fiber provides the most balanced performance when multiple mechanical and durability requirements are considered together. This is supported by

Çetin and Oral [23], despite differences in mixture type and gradation, as it can promote effective fiber dispersion within the asphalt matrix, leading to improved resistance to deformation and material degradation.

Table 6 Relative ranking of mixtures based on mechanical and durability performance

Properties	Rating (*Highest Performance* → *Lowest Performance*)			
	1	2	3	4
Total Rut Depth	4.0 mm (0.5% BF)	4.2 mm (0.25% BF)	4.6 mm (0.75% BF)	5.1 mm (Conv. Asphalt)
Abrasion Loss	2.5% (0.5% BF)	2.8% (0.75% BF)	4.4% (Conv. Asphalt)	5.3% (0.25% BF)
Stability	17.0 kN (0.5% BF)	13.5 kN (0.75% BF)	13.0 kN (0.25% BF)	12.0 kN (Conv. Asphalt)
TSR	0.95 (0.75% BF)	0.92 (0.25% BF)	0.83 (0.5% BF)	0.80 (Conv. Asphalt)

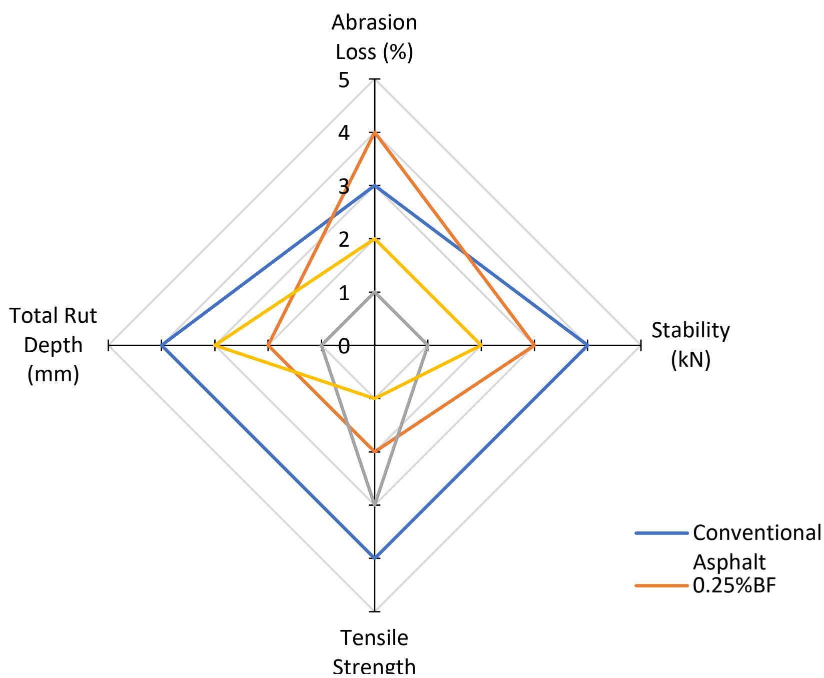

Figure 13 Relative performance ranking across mechanical and durability indicators

4.0 CONCLUSIONS

This study investigated the effect of incorporating basalt fibers into dense-graded asphalt mixtures of AC14. Based on the overall performance of the evaluated parameters, the addition of 0.5% basalt fiber into the dense-graded asphalt mixture provided the most balanced performance by improving Marshall stability, rutting resistance and abrasion durability while maintaining acceptable moisture resistance. This suggests that an appropriate fiber content can effectively reinforce the asphalt mixture whereas excessive fiber content may affect the mixture homogeneity and reduce the effectiveness of reinforcement due to potential non-uniform fiber distribution or fiber agglomeration. Increasing fiber content does not necessarily lead to proportional performance improvement. Therefore, these findings emphasize the importance of selecting an appropriate fiber content for mixture design.

Overall, the findings also suggest that basalt fiber has potential as a reinforcing agent for asphalt pavement applications, offering enhanced mechanical performance and durability. However, this study was limited to laboratory-scale evaluations and did not investigate the internal microstructure or fiber distribution within the asphalt matrix. Therefore, future research is recommended to incorporate microstructural characterization to better understand the fiber dispersion and reinforcement mechanisms. This is important to further validate the effectiveness of basalt fiber as a reinforcing agent in asphalt mixtures.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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