Laboratory Evaluation of Asphalt Mixture Performance Using Composite Admixtures of Lignin and Glass Fibers

Ahmed Khater 1,2,*, Dong Luo 1,*, Moustafa Abdelsalam 1,2, Yanchao Yue 1,*, Yueqin Hou 1,*, and Mohamed Ghazy 2

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Abstract: Moisture damage and low-temperature cracking are common distresses experienced by road pavement. Different types of modifiers, such as fibers, can be used to improve the quality of asphalt pavements. In this paper, lignin and glass fiber were selected as additives to enhance the water- and low-temperature stability of the asphalt mixtures. The main objective of this study was to evaluate the composite effects of adding lignin fiber and glass fiber to a bituminous mix using experimental methods. The Marshall immersion, freeze–thaw splitting, and three-point bending tests were applied to evaluate the efficiency of lignin fiber (and/or) glass fiber modified asphalt mixes with regard to moisture damage and low temperature. Four kinds of asphalt mixes, namely, the control asphalt mix (C), lignin fiber modified asphalt mix (L), glass fiber modified asphalt mix (G), and a composite of lignin fiber and glass fiber modified asphalt mix (LG) were evaluated. The experimental results showed that with the addition of 0.30% lignin fiber and 0.30% glass fiber the water stability, low-temperature stability, and quality of bituminous mix were improved significantly. With lignin fiber, the asphalt mixtures showed better resistance to thermal cracking, while glass fiber resulted in greater moisture susceptibility. The composite admixture was more effective than either lignin or glass fiber in modifying the asphalt performance. This clarifies the great beneficial effect of using the composite mixture in the asphalt mixtures industry.

Keywords: asphalt mixture; moisture susceptibility; low-temperature stability; composite mixture; lignin fiber; glass fiber

1. Introduction

Asphalt pavement is a kind of composite material that comprises aggregate, air voids, filler, and asphalt mastic. Asphalt tends to be soft in hot weather and brittle during cold conditions. It is the most common paving type for highways and airport pavements worldwide due to its service performance [1–3]. Asphalt pavement possesses characteristics such as flexibility, skid resistance, stability, and durability under climate changes, as well as high resistance to moisture damage, low noise, and a good ability to adapt to deformation of the subgrade. It can easily be reused and maintained [4]. High traffic volume and loading intensity, construction errors, and environmental conditions as well as thermal cracking have a negative impact on maintenance costs, service life, and pavement performance, leading to undesirable defects such as freeze–thaw cycles and thermal cracking at low temperatures [5,6].

Water damage has been deemed one of the main and most harmful problems in asphalt pavements in recent times [7]. The durability and stiffness of asphalt pavements are affected by moisture penetration (through cracks on the surface layer of asphalt mixtures [8]) and temperature, leading to distresses such as shoving, stripping, and potholes [9].
Several tests have been employed to estimate the water stability performance of bituminous mixes [10]. In this study, two test methods, Marshall immersion and freeze–thaw splitting, were carried out to assess the moisture susceptibility of bituminous mixes. Low-temperature thermal cracking is common form of distress in pavement structures [11], as low temperatures induce thermal tensile stresses in cold winter climates [12]. Transverse cracks are the most common mode of failure in asphalt pavements, as low temperatures have an undesirable effect on the integrity and continuity of the pavement, and reduce the adhesion force between the asphalt and aggregate. They begin in the upper layer of the asphalt pavement and then spread and expand downwards with time, allowing water penetration in the asphalt layer to fill these cracks [13]. Several previous studies evaluated the low-temperature properties of a bitumen mix [14–16]. In this study, the three-point bending test was selected to evaluate the behavior of bituminous mixes at low temperature.

Placing additives such as rubber powder, polyethylene, and basalt fiber in bituminous mixes is one of the most popular techniques used in past studies to extend the lifetime of asphalt pavements, improving their performance and resulting in a good economic advantage. The authors of these studies proved that these additives had a very good effect on the rutting performance of bituminous mix, although the improvement was not significant with respect to low-temperature and water stability, and it is very difficult to improve all properties of bituminous mixes at the same time using a single additive [17,18]. Therefore, researchers began to consider double-adding admixture technology [19,20].

Hence, a number of studies have recognized the effect of fibers to modify the water stability and thermal cracking resistance of bituminous mixes [5,8,21]. There are different kinds of fibers and in this paper, two kinds of fibers, namely, lignin fiber and glass fiber, were selected to enhance the characteristics of a bituminous mix under different moisture and climate conditions. This study aimed to explore the compound effects of adding lignin and glass fiber simultaneously on performance with regard to the water and low-temperature stability of the asphalt mix.

Lignin fiber has flocculent structures, a rough surface, high resistance to heat, and a large specific surface area. Its flocculent structures increase the absorption of bitumen [22]. Thus, the thermal properties and dispersion of bitumen improved when increasing the content of lignin, resulting in increased bitumen content, cohesion, fatigue life, viscosity, and tensile strength, in addition to delayed fracture of pavement asphalt and also an improved anti-aging capability of the asphalt layer [23]. The short lignin fibers prevent the development of small cracks around them. Furthermore, the bonding force between aggregate and asphalt binder is increased as a result of the toughness of lignin fiber.

Glass fiber is synthetic with high tensile strength, and its Young’s modulus is nearly 70 GPa. Using glass fiber for modifying asphalt mixtures results in improved stability, durability, and ductility due to its high mechanical properties [24]. Moreover, it increases the flow value and resistance to crack propagation in the mixture [25]. At low temperatures, glass fiber can resist the cracks of the pavement as it has a potential resistance towards crack initiation [25].

A considerable amount of literature has been published on the effects of adding lignin fiber [19,20,26–31] and glass fiber [32–41] to asphalt mixtures. With respect to the composite-reinforcing material (polymers, lignin fiber, and other chemical additives with bitumen) used in a study by Zhen et al. [19], tensile strength, tensile strain, ratio of immersion residual stability, and tensile strength ratio (TSR) were improved significantly as compared to the control mixture. In a study prepared by Tuya [26], a laboratory performance evaluation was conducted to analyze the impact of adding lignin fiber with rubber in asphalt mixtures. It was found that increasing the content of lignin fiber to 0.25% improved the low-temperature resistance and TSR, but when the content of the fiber reached 0.30%, the TSR was reduced. According to the conclusion drawn by Zhen et al. [20] with respect to bituminous mixtures modified with composite modifiers (anti-rutting agent with lignin fibers), lignin fiber solely was responsible for the improvement of water stability and the thermal cracking of the asphalt mixture. In another effort by Xiong et al. [28], it was discovered that lignin fiber...
could improve the resistance to low-temperature cracking, but the TSR of asphalt mixture modified with lignin fiber was the lowest. In related research, Thanh et al. assessed the water stability of stone matrix asphalt (SMA) [30]. The results showed that residual stability was enhanced by adding lignin fiber (at a percentage of 0.30%) because of its good adhesion. In addition, Xu et al. [29] indicated that lignin fibers increased the ultimate flexural strength and strain of fiber-reinforced asphalt concrete (FRAC). In contrast, the TSR of the base mixture after freezing–thawing was higher before the freezing–thawing of FRAC. In other research, Manoj Shukla et al. [36] found that adding glass fiber to asphalt mixture delayed the appearance of cracks and improved the TSR by 5%. The results of indirect tensile and freeze–thaw tests of hot mix asphalt mixtures using electrical glass fiber and scraps as reported by Pyeong and Kim [33] revealed that indirect tensile strength and TSR were twice that of the control mix. In another study carried out by Guo et al. [39] on a compound of diatomite and glass fiber selected to modify the bituminous mix, the results demonstrated that the tensile strength was not affected by adding diatomite and glass fiber, but there was a good impact on the tensile strain, hence mitigating the propagation of the micro-cracks. Recent research by Morea and Zerbino [32], showed that adding more than 0.4% glass macro-fibers resulted in enhanced maximum stress. In other research, Khabiri and Alidadi [40] studied the performance of asphalt mixture modified with glass and carbon fibers. The results confirmed an improvement in crack resistance as a result of glass fiber enhancing the cohesion of the bituminous mixtures. Luo et al. [42] presented a review paper on the effect of adding lignin or glass fiber to asphalt mixes, and concluded that the overall performance of asphalt mixture could not be modified by adding a single admixture, as lignin fiber improves the low-temperature cracking, glass fiber improves the high temperature performance, and both types of fibers have a good impact on moisture susceptibility. Finally, Yue et al. [43], evaluated the behavior of asphalt mixes modified with diatomite or lignin fiber and determined that diatomite improved high temperature performance, but the low-temperature crack resistance was improved by the addition of lignin fiber.

It has been demonstrated in several literature reviews that adding lignin fiber or glass fiber to asphalt mixtures of different bitumen grades can improve performance with respect to moisture susceptibility and resistance to low-temperature cracking. It is quite difficult to improve the overall performance of bituminous mixtures to an optimal level with one type of additive. Consequently, different additives with multiple modifications can be used to improve certain characteristics of the bituminous mixture. Moreover, past studies mainly concentrated on a single additive for modification, but little attention has been given to composite admixtures. Hence, research remains at a preliminary stage.

2. Materials

2.1. Asphalt

In this paper, AH-70 bitumen was selected for a heavy traffic loading asphalt type, based on the specifications of Chinese JTG F40-2004 [44]. Table 1 summarizes the characteristics of the selected bitumen in this study.

| Item                     | Penetration (250°C, 100 g, 5 s) (0.1 mm) | Penetration Index (PI) | Softening Point (R&B)/°C | Ductility (15°C) (cm) | Density (15°C) (g/cm³) | Thin-Film Oven Test (TFOT) | Mass Loss/% | Residual Penetration Ratio/% | Ductility (15°C)/cm |
|--------------------------|------------------------------------------|------------------------|--------------------------|----------------------|------------------------|---------------------------|-------------|-----------------------------|-------------------|
| Value                    | 76                                       | −0.95                  | 47                       | 134                  | 1.034                  | 0.043                     | 63.40       | ≥61                         | ≥15               |
| Standard                 | 60–80                                    | −1.0–1.0               | ≥46                      | ≥100                 | -                      | ≤±0.8                     | ≥15         |

Table 1. Properties of the bitumen.
2.2. Admixture

Lignin and glass fibers were selected for the performance tests: lignin fiber was manufactured by Beijing Tiancheng Kentelai Tec. Co., Ltd. (Beijing, China). Glass fiber was manufactured by Taishan Fiber Glass Inc. (Shandong Province, China). Samples of the used lignin and glass fibers are shown in Figure 1. The lengths of lignin and glass fibers were selected based on literature searches and engineering experiences.

Figure 1. Types of fibers used in study: (a) lignin fibers (Fiber 1), (b) glass fibers (Fiber 2).

2.2.1. Lignin Fiber

Lignin fiber is a type of natural complex organic polymer. The dimensions and the basic characteristics of the lignin fiber used are summarized in Table 2 (provided by the manufacturers). It was observed in the literature that the ideal lignin fiber content for asphalt mixtures was 0.2%–0.4% [43]. In this study, a percentage of 0.3% content of lignin fibers for asphalt mixtures was used, as this percentage resulted in greater resistance with respect to water stability and low temperature in previous studies [43].

| Item       | Length (mm) | Specific Area (10^{-3} m^2/gm) | Diameter (mm) | Aspect Ratio (mean) | Density (gm/cm^3) | Melt Temperature (°C) |
|------------|-------------|---------------------------------|---------------|---------------------|-------------------|-----------------------|
| Value      | 1.10        | 118.1                           | 0.045         | 24                  | 1.28              | >200                  |

2.2.2. Glass Fiber

Glass fiber is a kind of inorganic short fiber. Its dimensions and basic characteristics are shown in Table 3 (provided by the manufacturers). In previous studies the amount of glass fiber added was 0.20%–0.60% of asphalt mixture [42]. Glass fiber was added to represent 0.3% of asphalt mixtures, since, as shown in previous studies, this content is more effective in modifying water stability and low-temperature stability [42].

| Item       | Length (mm) | Specific Gravity (g/cm^3) | Color | Softening Point (°C) | Modulus of Elasticity (GPa) | Tensile Strength (MPa) |
|------------|-------------|----------------------------|-------|----------------------|-----------------------------|------------------------|
| Value      | 12          | 2.68                       | White | 860                  | 72                          | 1700                   |

2.3. Aggregate and Gradation

2.3.1. Aggregate and Mineral Filler

The coarse and fine aggregates used were of limestone, which was obtained from an asphalt pavement plant in Xi’an City, Shaanxi Province located in China. The basic properties, such as the Los Angeles abrasion value, apparent relative density value, crushing...
value, and water absorption value were determined. The properties of the coarse and fine aggregates are listed in Tables 4 and 5, respectively, according to specifications [44]. In addition, limestone was used also as the mineral filler; its apparent relative density is 2.577 and the hydrophilic coefficient is 0.773.

Table 4. Properties of coarse aggregate.

| Item | Aggregate Size | Los Angeles Abrasion Value/% | Apparent Relative Density | Crushing Value/% | Water Absorption/% | >9.5 mm Needle and Plate Particle Content/% | <9.5 mm Needle and Plate Particle Content/% |
|------|----------------|-----------------------------|---------------------------|-----------------|-------------------|---------------------------------------------|---------------------------------------------|
| Standard |                | ≤30                         | ≥25                       | ≤25             | ≤3                | ≤15                                        | ≤15                                        |
| Measured  | 5–10 mm        | 15.1                        | 2.723                     | 9.2             | 0.85              | -                                          | 3.28                                       |
|          | 10–20 mm       | 13.2                        | 2.726                     | 9.9             | 0.37              | 6.53                                       | -                                          |

Table 5. Properties of fine aggregate.

| Item | Apparent Relative Density | Sand Equivalent/% | Mud Content (Less than 0.075 Content)/% |
|------|---------------------------|-------------------|-----------------------------------------|
| Standard | >2.5                     | >60               | -                                       |
| Measured  | 2.692                    | 82                | 16.78                                   |

2.3.2. Mix Gradation

AC-16 gradation was used in the test. The gradation values of the mix design (AC-16) used are plotted in Figure 2, and the selected gradation was within the limits.

Figure 2. Aggregate gradation of asphalt mixture (AC-16).
3. Experimental Plan

3.1. Sample Preparation

The following four different asphalt mixtures were used to evaluate performance with regard to moisture susceptibility and low-temperature cracking resistance,

- The control asphalt mixture (without additives) (C)
- The lignin fiber (0.3% of the asphalt mix weight) modified asphalt mix (L)
- The glass fiber (0.3% of the asphalt mix weight) modified asphalt mix (G)
- The composite modified asphalt mix (lignin fiber (0.3% of the asphalt mix weight) + glass fiber (0.3% of the asphalt mix weight)) (LG)

3.2. Determination of the Optimum Asphalt Content

Asphalt mixtures act as a composite material through the addition of lignin fiber and glass fiber that makes its structure more complex. The optimum asphalt content (OAC) of AC-16 for the base and modified mixtures was calculated using the Marshall stability test. According to the standard specification [44], the Marshall compaction machine was used for the preparation of the asphalt samples, using 75 blows for each side (top and bottom) of the specimens [16]. Samples were formed according to the standards of Marshall. Each group consisted of four identical samples (the diameter and the height of each sample were 101.6 mm and 63.5 ± 1.3 mm, respectively) [45].

3.3. Mixing of Asphalt Mixture

There are two common techniques used for mixing additives in bituminous mixtures: the dry method and the wet method. The dry method is the most commonly used for fibers as it is the easiest to apply and can achieve the best distribution of fiber in the mixture; it is also generally used in fieldwork [46]. The dry method was adopted for this study. First, the aggregates were heated for about four hours at 175 °C. Then, by using the automatic mixer, the aggregates were mixed for 90 s, and then fiber was added and mixed for 90 s (for the composite mix 90 s were used for lignin fiber and then another 90 s for glass fiber). This was followed by the addition of optimum bitumen content for another 90 s at a temperature range of 160–170 °C to allow for good spread. Finally, the mineral powder was mixed for another 90 s [20].

3.4. Asphalt Mixture Performance Tests

3.4.1. Water Stability Performance

Marshall Immersion Test

The Marshall immersion or immersion compression test was conducted to estimate the water damage resistance of the bituminous mixes by computing the residual Marshall stability ratio (MSR) [47]. Two duplicate groups of specimens, each consisting of three specimens, were set up; the diameter and the height of each specimen were 101.6 mm and 63.5 ± 1.3 mm, respectively. The first group was immersed in water at 60 °C for 30 min while the other was immersed in water at 60 °C for 48 h. Marshall stabilities were determined based on the standard requirements [48]. Thus, the MSR was computed using the following equation [49]:

\[ MSR = \frac{MS_2}{MS_1} \times 100\% \]  

where MSR is the ratio of residual stability, \( MS_2 \) is the Marshall stability after 48 h of water immersion, and \( MS_1 \) is the Marshall stability of the fresh mixture after 30 min of water immersion.

Freeze–Thaw Splitting Test

The freeze–thaw splitting test was also applied to estimate the water stability performance of bituminous mixes by evaluating the freeze–thaw strength ratio (TSR) specified by Chinese standard JTG E20-2011 [48]. Two identical groups, each group with three identical
cylindrical samples were equipped. The diameter and the height of each sample were 101.6 mm and 63.5 mm, respectively. The first group was put under pressure (98.3–98.7 kPa) for 15 min, then cured in water at 25 °C for 20 min. After this, the specimens were wrapped with 10 mL of water in a plastic refill and refrigerated at −18 °C for 16 h. They were then put in a water bath at 60 °C for 24 h. Next, this group of frozen–thawed samples and the second group of fresh samples were placed in a water bath at 25 °C for 2 h to reach a constant degree of temperature, and a split tensile strength test was conducted in the two groups with a loading rate of 50 mm/min, based on the requirement AASHTO T283 [50]. The TSR can be obtained as follows [49]:

\[
TSR = \frac{R_{T2}}{R_{T1}} \times 100
\]

(2)

\[
R_T = \frac{0.006287P_T}{h}
\]

(3)

where TSR is the tensile strength ratio (%), \(R_{T2}\) is the splitting strength of frozen–thawed samples (MPa), and \(R_{T1}\) is the splitting strength of fresh samples (MPa). \(P_T\) is the indirect tensile loading at failure (N); \(h\) is the sample height (mm).

3.4.2. Low-Temperature Performance Test

To estimate the performance of low-temperature stability of the bituminous mix, the three-point bending beam test was conducted on three identical small beams with dimensions of 250 × 35 × 30 mm cutting from a compacted asphalt mixture slab to assess the tensile behavior by evaluating the bending strength and maximum tensile strain using MTS 810 [51]. The beam was placed in the fixed temperature cabinet at −10 °C [48] for one hour before testing; the test was performed with 50 mm/min loading speed. The concentrated load was placed at the mid-span of the beam sample until it broke. Figure 3 shows the loading and breaking of the beam. The displacement at the midpoint of the beam as well as the maximum load is obtained. The maximum flexural stress and the maximum flexural strain were computed as follows [44,49]:

\[
R_B = \frac{3LP_B}{2bh^2}
\]

(4)

\[
\varepsilon_B = \frac{6hd}{L^2}
\]

(5)

where \(R_B\) is the maximum flexural stress (MPa), \(L\) is the span length of the beam (200 mm), \(P_B\) is the ultimate load when failure occurs (N), \(b\) is the width of the beam (30 mm), \(h\) is the height of the beam (35 mm), \(\varepsilon_B\) is the maximum flexural strain (µε), and \(d\) is the deflection of mid-span when the failure occurs (mm).

Figure 3. The loading and breaking of the beam.
4. Results and Discussion

A summary of the results of the Marshall stability test is shown in Table 6. In addition, summary of the results of the Marshall immersion, freeze–thaw splitting, and low-temperature bending tests for the behavior of the studied four different types of asphalt mixes under the effects of water and low temperature are presented in Table 7.

Table 6. Optimum bitumen content for the control and modified mixtures.

| Asphalt Mix Type | Control (C) | Lignin Modified (L) | Glass Modified (G) | Lignin and Glass Modified (LG) |
|------------------|-------------|---------------------|--------------------|---------------------------------|
| Fiber type       | No fiber    | Lignin              | Glass              | (double addition)               |
| Percentage of fiber * (%) | -           | 0.30                | 0.30               | 0.30 + 0.30                     |
| OAC (%)          | 4.25        | 4.7                 | 4.4                | 4.6                             |
| C: control asphalt mixture; L: asphalt mixture modified with lignin fiber; G: asphalt mixture modified with glass fiber; LG: asphalt mixture modified with double addition of lignin and glass fiber; OAC: optimum asphalt content. * Fiber content as a percentage of asphalt mixture weight.

Table 7. Experimental results of different asphalt mixtures. MS: Marshall stability; MSR: Marshall stability ratio; $R_{T1}$: splitting strength of fresh samples (MPa); $R_{T2}$: splitting strength of frozen–thawed samples (MPa); TSR: tensile strength ratio; C: control asphalt mixture (without additives); L: lignin fiber modified asphalt mix; G: glass fiber modified asphalt mix; LG: composite modified asphalt mix (lignin fiber + glass fiber).

| Asphalt Mixture Type | Marshall Immersion Test Results | Freeze–Thaw Splitting Test Results | Low-Temperature Cracking Test Results |
|----------------------|---------------------------------|------------------------------------|-------------------------------------|
|                      | $MS_1$ (kN) | $MS_2$ (kN) | MSR (%) | $R_{T1}$ (MPa) | $R_{T2}$ (MPa) | TSR (%) | Bending Stress (MPa) | Bending Strain (µε) |
| C                    | 10.89      | 9.29       | 85.3    | 0.684        | 0.544        | 79.51   | 8.20                 | 2086.10             |
| L                    | 10.57      | 9.52       | 90.0    | 0.729        | 0.602        | 82.58   | 9.77                 | 2601.66             |
| G                    | 10.16      | 9.67       | 95.1    | 0.747        | 0.649        | 86.82   | 9.70                 | 2484.40             |
| LG                   | 10.80      | 10.67      | 98.8    | 0.765        | 0.675        | 88.22   | 10.37                | 3104.60             |

4.1. Results and Discussion of Marshall Stability Test

The results of the optimum asphalt content of AC-16 asphalt mixes are listed in Table 6 and indicated in Figure 4. The OAC increased by 0.45, 0.15, and 0.35% with the addition of lignin, glass, and composite mixture, respectively, compared to the control. The addition of fibers led to an increase in bitumen content [52]. The asphalt mixture modified with lignin showed the highest optimum bitumen content, followed by the composite asphalt mixture, the glass fiber modified asphalt mixture, and the control asphalt mixture, respectively. This result can be attributed to the different specific surface areas of the fibers and their bitumen absorption characteristics. However, the glass fiber had lower specific surface areas and bitumen absorption compared to the lignin fiber, and hence has the lowest optimum bitumen.
The addition of fibers led to an increase in bitumen content [52]. The adhesion between asphalt and aggregate, resulting in water damage to the bituminous asphalt mix modified with glass fiber, as the adhesion force between the aggregate and asphalt film more difficult. On the other hand, samples were compacted only 50 times for each side, which fact that the samples were compacted 75 times for each side, reduces the quantity of free asphalt. Due to the specific surface areas and the air voids of the mixture compared to glass fiber.

Discussion of Moisture Susceptibility Tests

4.2. Results of Water Stability Tests

4.2.1. Marshall Immersion Test

The Marshall immersion test was used to estimate the moisture susceptibility of the asphalt mix. The MSR was determined from experimental data of the Marshall immersion test. The Marshall stability values (MS1 and MS2) and the MSR values of the different asphalt mixes are presented in Table 7 as indicated in Figure 5. The results revealed that the MSR improved by 4.7, 9.8, and 13.5% for asphalt mixtures modified by lignin fiber, glass fiber, and composite (LG), respectively, when compared to the control.

Figure 4. Relationship between OAC for different asphalt mixtures.

Figure 5. Results of the Marshall immersion stability test.
4.2.2. Freeze–Thaw Splitting Test

The freeze-thaw splitting test was also selected to assess the moisture susceptibility of the asphalt mixture. The average tensile strengths ($R_{T1}$ and $R_{T2}$) and average TSR of the different modified and unmodified asphalt mixtures are listed in Table 7 and presented in Figure 6. It was found that the TSR values of the mixture of lignin fiber, glass fiber, and composite mixture increased by 3.07, 7.31, and 8.71%, respectively, in comparison with the control.

![Figure 6. Results of the freeze–thaw splitting test.](image)

4.2.3. Discussion of Moisture Susceptibility Tests Results (Marshall Immersion and Freeze–Thaw Splitting)

Both tests results revealed that the water stability performance of the bituminous mixes improved. The bituminous mix modified by a composite admixture was more effective than the bituminous mix that was only modified with glass fiber or lignin fiber. Furthermore, the bituminous mix modified with glass fiber was better than that modified with lignin fiber.

There are several possible explanations for this result. For example, the water stability performance of the bituminous mix can be determined by many factors such as air voids in the asphalt mixture, mineral aggregate and its interaction with asphalt, and the thickness of asphalt film. Undoubtedly, water can penetrate the aggregate, which reduces the adhesion between asphalt and aggregate, resulting in water damage to the bituminous mix.

The relationship between MSR and TSR with different types of asphalt mixtures is shown in Figures 5 and 6, respectively. The results indicated that the residual stability ratio (MSR) was higher than the indirect tensile strength ratio (TSR). This variance in the results between the Marshall immersion test and freeze–thaw splitting test is due to the fact that the samples were compacted 75 times for each side, reducing its porosity to 3%–5% in the Marshall immersion test, and thus making the process of water penetration between aggregate and asphalt film more difficult. On the other hand, samples were compacted only 50 times for each side, with porosity of 7% in the freeze–thaw splitting test.
The parameter values of the modified asphalt mixes with glass and lignin fibers were better than those of the control asphalt mixture, as these fibers have a high ability for asphalt absorption, increasing the thickness of the asphalt film on mineral aggregates, reducing the space between mixtures, and reducing the quantity of free asphalt. Due to the rise in the content of the asphalt internal structure with the addition of glass and lignin fibers, the adhesion force between the bitumen binder and aggregates increased, hence improving the resistance of shear and stability of mixtures and enhancing the water-resistance of the modified bituminous mix. Moreover, the MSR and TSR of bituminous mixes modified with glass fiber were better than those modified with lignin fiber, as the mixture modified with lignin fiber was more difficult to compact than the mixture modified with glass fiber. In addition, the lignin fiber increased the air voids of the mixture compared to glass fiber.

4.3. Results and Discussion of Low-Temperature Three-Point Bending Test

The bending test was applied to assess the effects of lignin and glass fiber on the low-temperature cracking resistance of the bituminous mix. The bending stress and bending strain were computed as listed in Table 7 and the results plotted in Figure 7a,b. The results demonstrate that the lignin fiber and glass fiber additives improve the ultimate bending tensile strength and the failure strain of modified asphalt mixtures, as shown in Figure 7a,b, respectively. From the results, it can be concluded that the bending tensile strength and maximum tensile strain of asphalt mixtures improved by 19.1% and 24.7%, respectively, with the addition of lignin fiber, and by 18.3% and 19.1%, respectively, with the addition of glass fiber as compared to control. Moreover, the composite additive improved the ultimate bending tensile strength and failure strain by 26.5% and 48.8%, respectively. The low-temperature stability of the bituminous mixes was enhanced by adding lignin and glass fiber.

The composite admixture used in this study showed better improvement in the bending stress as well as bending strain. Both lignin fiber and glass fiber showed improvements in low-temperature stability. However, the lignin fiber showed better improvement in flexural stress and strain.

The reasons for these can be clarified as follows. When temperatures begin to drop, the asphalt binder can withstand low-temperature tensile stress by filling between aggregates, which leads to increased bonding. However, it can only resist until a certain low temperature, after which the asphalt binder cannot resist the extreme tensile stress and thermal cracks begin to emerge.

Adding lignin and glass fibers can enhance the cracking resistance of asphalt mixes, as it has a large specific surface area. The viscosity of asphalt was increased due to the absorption of fiber that led to the enhancement of the interface adhesion strengths. Simultaneously, the OAC was increased after using fibers (as indicated in Table 6), which resulted in an improvement in the flexibility of the bituminous mix. Asphalt mixture modified with lignin fiber had higher anti-cracking resistance than that with the glass fiber, though the bituminous mix modified with a composite mixture had the best low-temperature performance. The main reason is that lignin fiber has a larger specific surface area for asphalt absorption and asphalt stabilization, as well as the highest OAC asphalt contents to improve the cracking resistance and flexibility, as extra asphalt films are formed to improve the function of filling and healing in the micro-cracks between aggregates. In addition, the shear strength of the asphalt mix can be enhanced by lignin fiber, as it can improve the friction angle and cohesive force of bitumen [19]. At the same time, glass fiber can disperse the tensile stress of asphalt mortar and prevent micro-cracks in asphalt mortar failure strain, so it can also enhance the deformation of the bituminous mix. Thus, using fibers is very beneficial as an anti-cracking measure, as it can improve the strength of asphalt mixes at low temperatures. Additionally, it can increase the toughness of the asphalt mixes. It can enhance the resistance of stress and deformation by load transmitting and bridging phenomenon since fibers act as a bridge to delay increasing the cracks in the asphalt mixes by spreading through both sides of the micro-cracks [53]. Thus, the
composite action of lignin and glass fibers had the greatest effect on low-temperature performance of the asphalt mixture.

Figure 7. Results of cracking resistance in the low-temperature test. (a) The tensile strength of asphalt mixtures. (b) The tensile strain of asphalt mixtures.

5. Conclusions

In this study, the moisture susceptibility and low-temperature stability of lignin fiber (and/or) glass fiber modified asphalt mixtures were experimentally evaluated. The results
indicated that adding either lignin or glass fiber or a composite mixture of both to asphalt mixes can improve resistance to water damage and low-temperature cracking, hence providing better pavement properties as compared to ordinary pavement. Both lignin fiber and glass fiber were added at a percentage of 0.3% to the AC-16 mixture. Based on the results from the Marshall immersion test, freeze–thaw splitting, and low-temperature bending tests, which were applied to assess the behavior of the studied asphalt mixtures before and after adding fibers, the main conclusions are as follows:

- The optimum bitumen content of the mixtures obtained from the Marshall stability test increased by adding lignin and glass fibers because the fiber has a high absorption of bitumen due to its large specific surface area.
- The MSR, TSR, maximum tensile strength, and strain of asphalt mixtures were enhanced by the addition of lignin and glass fibers. Lignin and glass fibers significantly improved the moisture susceptibility and low-temperature resistance.
- Lignin fiber had a greater effect on the bending strength and ultimate bending strain compared to glass fiber due to its large specific area and absorption effect; however, the influence of glass fiber on improving the water stability performance was more significant than that of lignin fiber.
- The asphalt mixture reinforced with composite admixture showed significant improvements with respect to moisture susceptibility and low-temperature stability as compared to the other mixtures.

In summary, pavement construction using composite technology will have a good impact on enhancing the service life and the overall performance of asphalt mixes as compared to the usage of single additives.

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**Abbreviations**

The following abbreviations were used in this manuscript:

- **C** Control asphalt mix
- **L** Lignin fiber modified asphalt mix
- **G** Glass fiber modified asphalt mix
- **LG** Composite of lignin fiber and glass fiber modified asphalt mix
- **TSR** Tensile strength ratio
- **SMA** Stone matrix asphalt
- **FRAC** Fiber-reinforced asphalt concrete
- **PI** Penetration index
- **TFOT** Thin film oven test
- **O.A.C** Optimum asphalt content
- **MSR** Optimum asphalt content
- **MS₂** Marshall stability after 48 h of water immersion
References

1. Zhang, Z.; Jia, M.; Jiao, W.; Qi, B.; Liu, H. Physical properties and microstructures of organic rectorites and their modified asphalts. Constr. Build. Mater. 2018, 171, 33–43. [CrossRef]

2. Jafarifar, N.; Pilakoutas, K.; Bennett, T. Moisture transport and drying shrinkage properties of steel–fibre-reinforced-concrete. Constr. Build. Mater. 2014, 73, 41–50. [CrossRef]

3. Park, P.; El-Tawil, S.; Park, S.Y.; Naaman, A.E. Cracking resistance of fiber reinforced asphalt concrete at –20 °C. Constr. Build. Mater. 2015, 81, 47–57. [CrossRef]

4. Qin, X.; Shen, A.; Guo, Y.; Li, Z.; Lv, Z. Characterization of asphalt mastic reinforced with basalt fibers. Constr. Build. Mater. 2018, 159, 508–516. [CrossRef]

5. Chen, H.; Xu, Q. Experimental study of fibers in stabilizing and reinforcing asphalt binder. Fuel 2010, 89, 1616–1622. [CrossRef]

6. Abiola, O.; Kupolati, W.; Sadiku, E.; Ndambuki, J. Utilisation of natural fibre as modifier in bituminous mixes: A review. Int. J. Pavement Eng. 2018, 19, 930–936. [CrossRef]

7. Sun, Z.H.; Yang, G.F.; Wang, T.B.; Wang, Z.S. Research on Evaluation Index of Water Stability for Asphalt Mixtures. In Advanced Materials Research; Trans Tech Publications Ltd.: Stafa-Zurich, Switzerland, 2013; pp. 2724–2728.

8. Mashaan, N.S.; Ali, A.H.; Koting, S.; Karim, M.R. Performance evaluation of crumb rubber modified stone mastic asphalt pavement in Malaysia. Adv. Mater. Sci. Eng. 2013, 2013. [CrossRef]

9. Yusoff, N.I.M.; Bream, A.A.S.; Alattug, H.N.; Hamim, A.; Ahmad, J. The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures. Constr. Build. Mater. 2014, 72, 139–147. [CrossRef]

10. Wang, X.; Qiu, Y.J.; Xue, S.Y.; Yang, Y.; Zheng, Y. Study on durability of high-modulus asphalt mixture based on TLA and fibre composite modification technology. Int. J. Pavement Eng. 2018, 19, 24–36. [CrossRef]

11. Wu, J.; Hong, R.; Gu, C. Influence of fiber type on low-temperature fracture performance of presawed asphalt mixture beams. Adv. Mater. Sci. Eng. 2018, 2018. [CrossRef]

12. Pszczola, M.; Jacewski, M.; Rys, D.; Jaskula, P.; Szydlowski, C. Evaluation of asphalt mixture low-temperature performance in bending beam creep test. Materials 2018, 11, 100. [CrossRef] [PubMed]

13. Rys, D.; Judycki, J.; Pszczola, M.; Jacewski, M.; Mejlan, L. Comparison of low-temperature cracks intensity on pavements with high modulus asphalt concrete and conventional asphalt concrete bases. Constr. Build. Mater. 2017, 147, 478–487. [CrossRef]

14. Judycki, J. A new viscoelastic method of calculation of low-temperature thermal stresses in asphalt layers of pavements. Int. J. Pavement Eng. 2018, 19, 24–36. [CrossRef]

15. Shen, J. Pavement Performance of Asphalt and Asphalt Mixture; People’s Transportation Press: Beijing, China, 2001.

16. Tan, Y.; Zhang, L.; Xu, H. Evaluation of low-temperature performance of asphalt paving mixtures. Cold Reg. Sci. Technol. 2012, 70, 107–112. [CrossRef]

17. Kim, S.; Lee, S.-J.; Yun, Y.-B.; Kim, K.W. The use of CRM-modified asphalt mixtures in Korea: Evaluation of high and ambient temperature performance. Constr. Build. Mater. 2014, 67, 244–248. [CrossRef]

18. Attaelmanan, M.; Feng, C.P.; Al-Haddidy, A. Laboratory evaluation of HMA with high density polyethylene as a modifier. Constr. Build. Mater. 2011, 25, 2764–2770. [CrossRef]

19. Fu, Z.; Shen, W.; Huang, Y.; Hang, G.; Li, X. Laboratory evaluation of pavement performance using modified asphalt mixture with a new composite reinforcing material. Int. J. Pavement Res. Technol. 2017, 10, 507–516. [CrossRef]

20. Fu, Z.; Dang, Y.; Guo, B.; Huang, Y. Laboratory investigation on the properties of asphalt mixtures modified with double-adding admixtures and sensitivity analysis. J. Traffic Transp. Eng. (Engl. Ed.) 2016, 3, 412–426. [CrossRef]

21. Sengoz, B.; Agar, E. Effect of asphalt film thickness on the moisture sensitivity characteristics of hot-mix asphalt. Build. Environ. 2007, 42, 3621–3628. [CrossRef]

22. Pan, T. A first-principles based chemophysical environment for studying lignins as an asphalt antioxidant. Constr. Build. Mater. 2012, 36, 654–664. [CrossRef]

23. Gao, D.-Y.; Xia, D.; Li, H.-G.; Tang, J.-Y. Experimental Study on Effects of Cellulose Fiber on the Pavement Performance of OGFC. J. Zhengzhou Univ. (Eng. Sci.) 2008, 3.
24. Abtahi, S.M.; Sheikhzadeh, M.; Hejazi, S.M. Fiber-reinforced asphalt-concrete—a review. *Constr. Build. Mater.* 2010, 24, 871–877. [CrossRef]
25. Najd, A.; Chao, Z.; Ying, G. Experiments of fracture behavior of glass fiber reinforced asphalt concrete. *J. Chang. Univ. (Nat. Sci. Ed.)* 2005, 25, 28–32.
26. Tuya, H. The road performance of lignin and rubber powder composite modified asphalt mixture. *Highw. Eng.* 2014, 39, 170–175.
27. Xu, Q.; Zhao, L.H.; Zhao, J. Research on Performance of Basalt Fiber-Enhanced SMA. In *Advanced Materials Research;* Trans Tech Publications Ltd.: Stafa-Zurich, Switzerland, 2011; pp. 4323–4327.
28. Xiong, R.; Fang, J.; Xu, A.; Guan, B.; Liu, Z. Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete. *Constr. Build. Mater.* 2015, 83, 44–52. [CrossRef]
29. Xu, Q.; Chen, H.; Prozzi, J.A. Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. *Constr. Build. Mater.* 2010, 24, 2003–2010. [CrossRef]
30. Thanh, D.V.; Feng, C.P.; Long, L.H. Analysis of high temperature stability and water stability of SMA mixture using orthogonal experiments. *Int. J. Civ. Struct. Eng.* 2011, 2, 635–647.
31. Zheng, Z.R.; Zhao, C.; Zhao, Y.F.; Song, P. Influence of Double-Doped Admixtures on Asphalt Mixture Performance. In *Advanced Materials Research;* Tech Publications Ltd.: Stafa-Zurich, Switzerland, 2012; pp. 329–333.
32. Morea, F.; Zerbino, R. Improvement of asphalt mixture performance with glass macro-fibers. *Constr. Build. Mater.* 2018, 164, 113–120. [CrossRef]
33. Yoo, P.J.; Kim, T.W. Strengthening of hot-mix asphalt mixtures reinforced by polypropylene-impregnated multifilament glass fibres and scraps. *Constr. Build. Mater.* 2015, 41, 415–420. [CrossRef]
34. Muftah, A.; Bahadori, A.; Bayomy, F.; Kassem, E. Fiber-Reinforced Hot-Mix Asphalt: Idaho Case Study. *Transp. Res. Rec. J. Transp. Res. Board* 2017, 2633, 98–107. [CrossRef]
35. Park, K.-S.; Yoo, P.-J.; Ohm, B.-S.; Choi, J.-Y.; Lim, J.-K. A study on plastic deformation resistance test between glass fiber reinforced asphalt and modified SMA mixture. In Proceedings of the 18th International Conference Road Safety on Five Continents (RSCC 2018), Jeju Island, South Korea, 16–18 May 2018.
36. Shukla, M.; Tiwari, D.; Sitaramanjaneyulu, K. Performance characteristics of fiber modified asphalt concrete mixes. *Int. J. Pavement Eng.* *Asphalt. Technol.* 2014, 15, 38–50. [CrossRef]
37. Sadeghnejad, M.; Arabani, M.; Taghipoor, M. Predicting the impact of temperature and stress on the glashphalt mixtures’ rutting behavior. *Int. J. Pavement Res. Technol.* 2018, 11, 300–310. [CrossRef]
38. Mahrez, A.; Karim, M.R. Rutting characteristics of bituminous mixes reinforced with glass fiber. In Proceedings of the Eastern Asia Society for Transportation Studies the 7th International Conference of Eastern Asia Society for Transportation Studies, Dalian, China, 24–27 September 2007; p. 282.
39. Guo, Q.; Li, L.; Cheng, Y.; Jiao, Y.; Xu, C. Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture. *Mater. Des.* (1980–2015) 2015, 66, 51–59. [CrossRef]
40. Khabiri, M.M.; Alidadi, M. The Experimental Study of the Effect of Glass and Carbon Fiber on Physical and Micro-Structure Behavior of Asphalt. *Int. J. Integr. Eng.* 2017, 8, 1–8.
41. Hua, T. Marshall Stability and Splitting Test of Fiber Reinforced Asphalt Mixture. *Shanxi Transp. Sci. Technol.* 2010, 1, 9–12.
42. Luo, D.; Khater, A.; Yue, Y.; Abdelsalam, M.; Zhang, Z.; Li, Y.; Li, J.; Isley, D.T. The performance of asphalt mixes modified with lignin fiber and glass fiber: A review. *Constr. Build. Mater.* 2019, 209, 377–387. [CrossRef]
43. Yue, Y.; Abdelsalam, M.; Luo, D.; Khater, A.; Musanyufu, J.; Chen, T. Evaluation of the Properties of Asphalt Mixes Modified with Diatomite and Lignin Fiber: A Review. *Mater. Res. 2019, 12, 400.* [CrossRef]
44. Shen, J.; Li, F.; Chen, J. Technical Specification for Construction of Highway Asphalt Pavements (JTG F40–2004); Communication Press: Beijing, China, 2005.
45. Morova, N. Investigation of usability of basalt fibers in hot mix asphalt concrete. *Constr. Build. Mater.* 2013, 47, 175–180. [CrossRef]
46. Abtahi, S.; Hejazi, S.; Sheikhzadeh, M.; Semnani, D. An investigation on the use of textile materials to mechanical reinforcement of asphalt-concrete (AC) structures and analysis of results by an artificial neural network (ANN). *4th Nat. Cong Civ. Eng.* 2008.
47. Pang, L.; Liu, K.; Wu, S.; Lei, M.; Chen, Z. Effect of LDHs on the aging resistance of crumb rubber modified asphalt. *Constr. Build. Mater.* 2014, 67, 239–243. [CrossRef]
48. Research Institute of Highway Management. *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering;* [TG E20-2011]; China Communications Press: Beijing, China, 2011.
49. Shen, J.; Li, P.; Sun, Z. *Ministry of Communications. [T] 052-2000 Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering;* Communications Press: Beijing, China, 2000.
50. AASHTO, T. 283-07. *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage;* American Association of State and Highway Transportation Officials: Washington, DC, USA, 2011.
51. Yin, A.; Yang, X.; Zeng, G.; Gao, H. Fracture simulation of pre-cracked heterogeneous asphalt mixture beam with movable three-point bending load. *Constr. Build. Mater.* 2014, 65, 232–242. [CrossRef]
52. Zhu, Z.-H. Study on the Road Performance of Asphalt Mixture with External Fiber. Master’s Thesis, Chang’an University, Xi’an, China, 2004.
53. Abdelsalam, M.; Yue, Y.; Khater, A.; Luo, D.; Musanyufu, J.; Qin, X. Laboratory Study on the Performance of Asphalt Mixes Modified with a Novel Composite of Diatomite Powder and Lignin Fiber. *Appl. Sci.* 2020, 10, 5517. [CrossRef]