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Research Article

Road Performance and Microscopic Mechanism Analysis of Modified Straw Fiber Asphalt Binder

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In this study, the correlation between the microstructure of straw fibers and the macroscopic properties of asphalt binders is investigated. Penetration, softening point, bending beam rheometer, and toughness tests are performed to investigate the relationship between the pavement properties of fiber asphalt binders and each of the fiber types and contents. Subsequently, a four-component test, SEM, Fourier transform infrared microscopy, and fluorescence microscope tests are performed to analyze the microstructure of the straw fiber and its effect on asphalt properties. The results show that the high-temperature performance and shear resistance of the asphalt binder were enhanced with an increase in the modified straw fiber content. The low-temperature performance and toughness of the asphalt binder were reduced because of excessive fiber, and the recommended fiber content is 1.5%–2.0%. The adsorption capacity of the modified straw fiber for the light components of asphalt increased by 5.4% on average, and the low-temperature creep capacity of asphalt decreased by 9.6%. The surface roughness of the straw fiber increased via modification, and the shear resistance, high-temperature deformation resistance, and stress relaxation ability of the asphalt increased by 23.1%, 6.5%, and 5.7%, respectively. The comprehensive properties of the asphalt binder with modified straw fiber are similar to those of lignin fiber.

1. Introduction

The rapid increase in vehicle loads and the effect of the external environment render asphalt pavements susceptible to rutting, cracks, potholes, and other damages. Research shows that asphalt mixtures mixed into fibers can effectively improve their resistance to deformation, cracking, spalling, and other damages [1–3]. Crop straws are produced widely in China, and approximately 20% of the straw is not fully utilized [4, 5]. To improve the resource utilization rate of straw, researchers have extensively investigated straw fiber technology for asphalt pavements. Li et al. [6] found that cotton straw powder can effectively improve the toughness, viscoelasticity, and rheology of asphalt. Liu et al. [7] concluded that cotton straw fiber can effectively improve its high-temperature stability, low-temperature crack resistance, and water stability. Li et al. [8] discovered that corn straw fiber exerted the best improvement effect on the high-temperature performance of asphalt binders. Chen et al. [9] concluded that an appropriate amount of corn straw fiber can improve the road performance of asphalt mixes and can be used to replace lignin fiber. These studies provided the preparation methods of straw fiber and the feasibility of the application of cotton straw fiber and corn straw fiber in asphalt binder and mixture, but the improvement effect of straw fibers on asphalt binder remains to be improved.

In previous studies, the macroscopic properties of fiber-reinforced asphalt binders and mixtures have been widely investigated. However, studies regarding the microstructure of straw fibers and their effect on macroproperties are few. Therefore, the chemical modification of corn and cotton straw fibers was innovatively carried out in this study, and the effects of the modified straw fibers on the pavement performance of asphalt binders were comprehensively investigated from macroperspectives and microperspectives. The modification treatment can change the microstructure of the fibers, which is beneficial to the shear resistance, high-temperature deformation resistance, and stress relaxation ability of the asphalt binder. Herein, theoretical support for the macroscopic properties exhibited by straw fiber asphalt binders is provided and expounded, and the optimal range of modified straw fibers is proposed. The flowchart of the research is shown in Figure 1.

2. Materials and Methods

2.1. Straw Fiber Production. In this study, corn and cotton straws from Shandong Province, China, were selected as raw materials. The straw fibers were prepared via mechanical crushing and treated with a NaOH solution to obtain modified straw fibers (see Figures 2 and 3). The specific process is as follows:

First, leaves, ears, nodes, and other debris were removed from the straw surface. The corn and cotton straws were soaked in water for 4 h and 7 d, respectively. Second, the corn straw pith was removed, and the rind was cut into strips measuring 10 ± 2 mm in length. The cotton straw was cut into strips measuring 10 ± 2 mm in length. Third, the corn and cotton straws were comminuted for 2 and 3 mins, respectively, using a crusher at a rotational speed of 30000 r/min. Finally, the comminuted straw fibers were sieved using the standard square hole sieve of 0.3 mm and 1.18 mm to obtain normal straw fibers.

The process performed to modify the corn and cotton straw fibers is as follows: First, normal corn and cotton straw fibers were soaked in a 5% NaOH solution for 30 mins. Subsequently, the residual NaOH solution on the surface of the fibers was washed. Next, the modified straw fibers were dried in an oven to a constant weight.

2.2. Fiber Performance Testing. In this study, corn and cotton straw fibers were investigated and compared with lignin fibers, and the appearance and shape of the fibers are shown in Figure 4. The properties of the fibers were tested based on the Chinese specifications (JTT 533-2020). The results are presented in Table 1.

2.3. Asphalt Performance Testing. In this study, 70# asphalt was used. Its basic performance was tested based on the Chinese specification (JTG E20-2011). The results are presented in Table 2.

2.4. Filler Performance Testing. The physical properties of the filler used in this study are shown in Table 3.

2.5. Fiber Asphalt Binder Preparation. In this paper, the high-speed shear machine was used to prepare fiber asphalt binder at 140°C. Firstly, the machine speed was adjusted to 2000 r/min for 10 mins, and the fibers and filler were slowly added to the asphalt. Fiber content was 1.5%, 2%, and 2.5%. The ratio of filler to asphalt was 0.8. Secondly, the machine speed was gradually increased to 5000 r/min to maintain for 40 mins. Finally, the speed of the machine was reduced to 1500 r/min for 10 mins to eliminate the bubbles in the asphalt. A total of 16 groups of asphalt binder were prepared (see Table 4). In this study, the penetration, softening point, toughness, bending beam rheometer (BBR), four components, scanning electron microscopy (SEM), fluorescence microscopy (FM), and Fourier transform infrared (FTIR) spectroscopy tests were carried out.

2.6. Macroscopic Test. In this study, penetration, softening point, toughness, and BBR tests are performed based on the Chinese specification (JTG E20-2011) to investigate the effects of fiber type and content on the pavement performance of asphalt binders. The test results are used to evaluate the shear resistance, high-temperature deformation resistance, low-temperature rheology, and viscosity of the modified straw fiber asphalt binder.

The prepared fiber asphalt binder sample was poured into a metal container of $\Phi 55\,\mathrm{mm} \times 35\,\mathrm{mm}$, and the penetration test was carried out by a LHZR-111 penetrometer. A cone needle was used instead of a standard needle to overcome the discreteness of the penetration data [10, 11]. The penetration is the depth of a 153.2 g cone needle vertically penetrating the asphalt sample within 25°C and 5 s. Using the penetration results, the shear strength can be calculated via the following equation:

$$\tau = \frac{981 m \cos^2 (\alpha/2)}{\pi h^2 \tan (\alpha/2)}, \quad (1)$$

where τ is the shear strength (kPa); m is the penetration quality, g; h is the penetration (mm); and α is the needle cone angle, 30°.

The softening point test was carried out by the ring and ball method. Firstly, the sample ring was placed on the sample base plate coated with the isolating agent. Secondly, the fiber asphalt binder was poured into the sample ring. Then the steel ball was placed in the center of the sample ring. The size of the sample ring is $\Phi 15.9\,\mathrm{mm} \times 2.38\,\mathrm{mm} \times 5.35\,\mathrm{mm}$. The diameter and mass of the steel ball are $\Phi 9.55$ mm and 3.5 g, respectively. The softening point is the temperature at which the steel ball penetrates the sample and contacts the metal plate.

In this paper, the SYD-0624 asphalt toughness tester was used to test the toughness at a tensile speed of 500 mm/min. Firstly, the asphalt binder with a mass of 50 g was poured into the preheated sample container. Secondly, the tensile hemispherical head was rapidly immersed in the asphalt binder sample. Finally, the asphalt binder sample is placed in a 25°C constant temperature water bath for 1.5 h before the test.

Firstly, the asphalt binder was poured into the rectangular test mold, and the internal size of the test mold is $127\,\mathrm{mm} \times 6.35\,\mathrm{mm} \times 12.7\,\mathrm{mm}$. Secondly, the test piece was placed in a −6°C water bath for 5–10 min, and then the test mold was removed. Finally, the test piece was put into

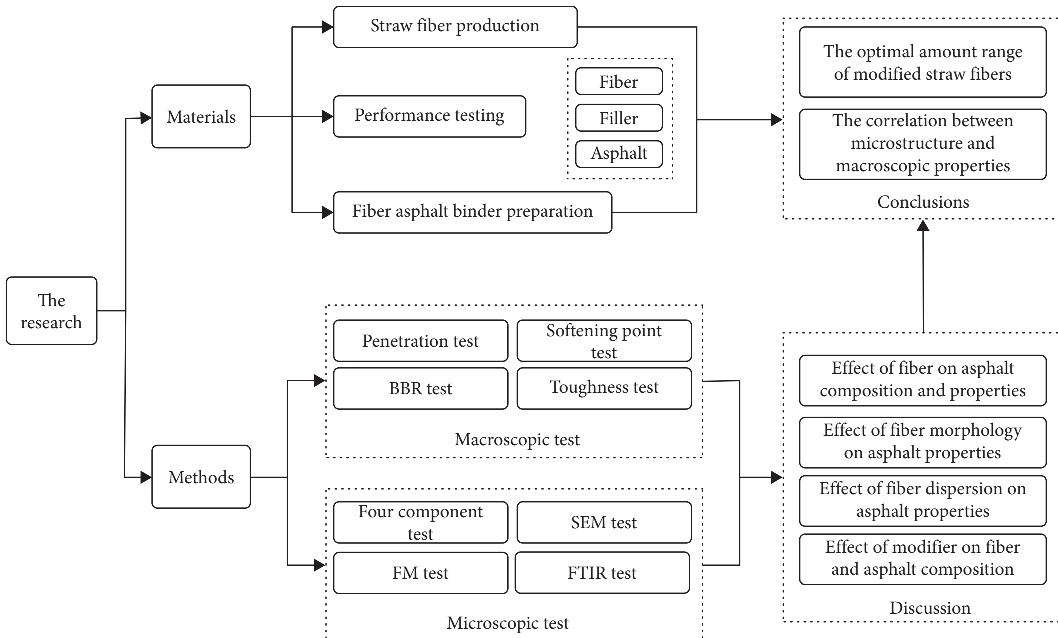


Figure 1: Flowchart of the research.

Figure 2: Production and modification process of corn straw fiber.

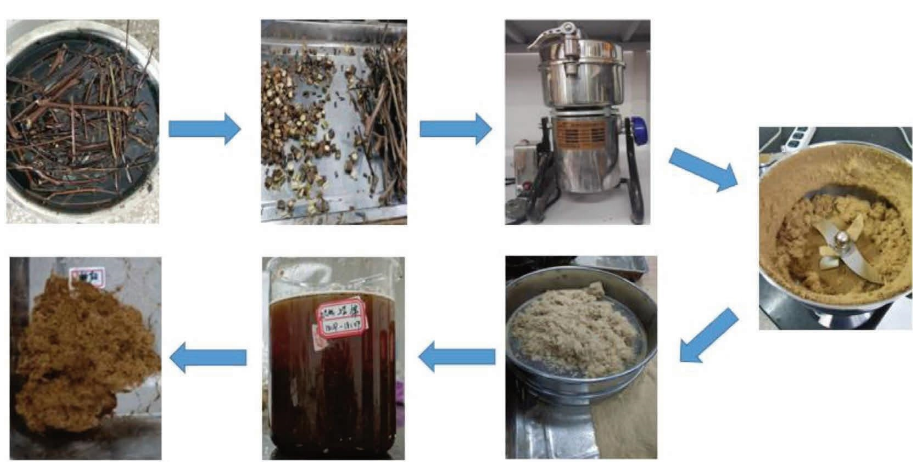


Figure 3: Production and modification process of cotton straw fiber.

Table 1: Physical properties of fibers.

Fiber type	Color	Average length (mm)	pH	Oil absorption rate (multiple)	Thermal weight loss (%)	Ash content (%)
Corn straw fiber	Yellow	3.8	7.06	5.71	7.3	5.4
Modified corn straw fiber	Light yellow	3.8	8.35	7.69	5.6	5.8
Cotton straw fiber	Brown	3.2	6.5	6.3	9.0	4.8
Modified cotton straw fiber	Light brown	3.2	7.97	7.82	5.5	5.2
Lignin fiber	Light gray	<5	8.4	8.13	5.6	18.7
Technical requirements	—	≤6	7.5 ± 1	7 ± 2	≤6	≤23

(a) (b) (c) (d) (e)

Figure 4: Appearance of fibers. (a) Corn straw fiber. (b) Cotton straw fiber. (c) Modified corn straw fiber. (d) Modified cotton straw fiber. (e) Lignin fiber.

Table 2: Physical properties of 70# asphalt.

Parameter	Value	Technical requirements
Penetration (25°C) (mm)	69	60–80
Softening point (°C)	47.1	$\nless 46$
Ductility (5 cm/min, 10°C) (cm)	29	$\nless 15$
Ductility (5 cm/min, 15°C) (cm)	≥150	$\nless 100$
Density (g/cm^3)	1.027	Actual test
Flash point (°C)	269	$\nless 260$
Solubility (%)	99.7	$\nless 99.5$

Table 3: Physical properties of filler.

Parameter		Value	Technical requirements
Apparent density (t/m^3)		2.785	$\nless 2.50$
Particle size range (%)	<0.6 mm	100	100
	<0.15 mm	94.6	90–100
	<0.075 mm	85.3	75–100
Water content (%)		0.32	$\ngtr 1$
Hydrophilic coefficient (%)		0.43	<1
Appearance		No agglomerates	No agglomerates

Table 4: The composition of samples.

No.	Composition	The total sample numbers
1	0.8% corn straw fiber + 44.1% filler + 55.1% asphalt	27
2	1.1% corn straw fiber + 44.0% filler + 54.9% asphalt	27
3	1.4% corn straw fiber + 43.8% filler + 54.8% asphalt	27
4	0.8% modified corn straw fiber + 44.1% filler + 55.1% asphalt	27
5	1.1% modified corn straw fiber + 44.0% filler + 54.9% asphalt	27
6	1.4% modified corn straw fiber + 43.8% filler + 54.8% asphalt	27
7	0.8% cotton straw fiber + 44.1% filler + 55.1% asphalt	27
8	1.1% cotton straw fiber + 44.0% filler + 54.9% asphalt	27
9	1.4% cotton straw fiber + 43.8% filler + 54.8% asphalt	27
10	0.8% modified cotton straw fiber + 44.1% filler + 55.1% asphalt	27
11	1.1% modified cotton straw fiber + 44.0% filler + 54.9% asphalt	27
12	1.4% modified cotton straw fiber + 43.8% filler + 54.8% asphalt	27
13	0.8% lignin fiber + 44.1% filler + 55.1% asphalt	27
14	1.1% lignin fiber + 44.0% filler + 54.9% asphalt	27
15	1.4% lignin fiber + 43.8% filler + 54.8% asphalt	27
16	44.4% filler + 55.6% asphalt	27

a constant temperature water bath that reached the test temperature and kept there for 60 min before the test. The low-temperature performance of the asphalt binder was evaluated based on the stiffness (S) and creep rate (m) obtained when it was loaded for 60 s, and the test temperatures were −6°C, −12°C, and −18°C. The lower the S value and the higher the m-value of the asphalt binder, the higher the creep and relaxation ability [12].

2.7. Microscopic Test. In this study, the contents of the four components of fiber asphalt were determined using a rod thin-layer chromatography analyzer to quantitatively evaluate the adsorption of the fibers in the asphalt components, based on a fiber content of 2% [13]. To determine the reasons contributing to the change in the adsorption capacity of the modified straw fibers and the effects of the latter on the macroscopic properties of asphalt, SEM tests were performed on the straw fibers. The magnification was 100× and 1000× [14].

The dispersion of fibers in asphalt must be observed, as it significantly affects the viscosification and toughening effects of the fibers [15]. In this study, fluorescence microscopy (FM, Axioscope 5) was performed to observe the modified straw fiber and lignin fiber asphalt binders.

The effect of NaOH solution on the compositions of the straw fibers and asphalt binder was investigated by FTIR. Because different types of functional groups have different infrared light absorption frequencies, their positions on the spectrogram are different. The composition of a material at the atomic level can be obtained based on its position. The vibrational frequency absorption bands of most organic and inorganic functional groups appear in the midinfrared region; therefore, the scan range selected was 400–4000 cm^{-1}.

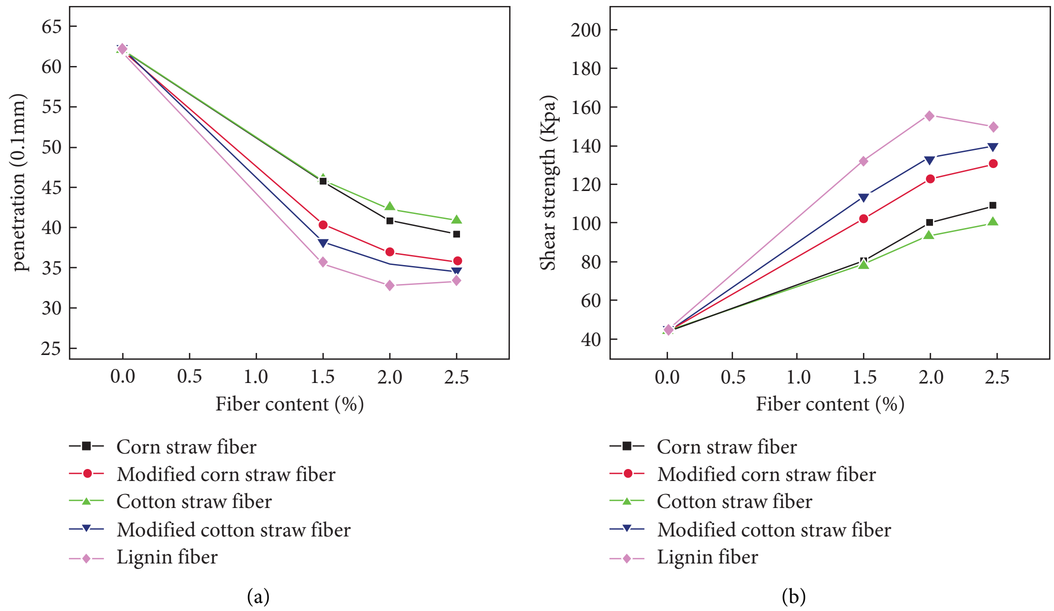


Figure 5: Effect of fiber content on (a) penetration and (b) shear strength of asphalt binder.

3. Results

3.1. Shear Resistance. Figure 5 shows that as the fiber content increased, the penetration decreased, and the shear strength increased. When the straw fiber content exceeded 2%, the slope of the penetration and shear strength curve decreased, indicating a diminishment in the improvement effect of excessive fiber on the shear resistance of the asphalt binder. The shear strength of the modified straw fiber asphalt binder was 23.1% higher than that of the normal straw fiber, which suggests that the modified treatment can improve the shear resistance of the binder. When the lignin fiber content exceeded 2%, the penetration of the asphalt binder began to increase, and the shear strength began to decrease.

3.2. High-Temperature Resistance to Deformation. Figure 6 shows that as the fiber content increased, the softening point increased continuously. When the fiber content exceeded 2%, the increase rate decelerated, indicating a diminishment in the improvement effect of excessive fiber on the high-temperature deformation resistance of the asphalt binder [16]. The softening point of the modified straw fiber asphalt binder was 6.5% higher than that of the normal straw fiber and higher than that of the lignin fiber, which suggests that the modified treatment might improve the temperature stability of the binder. When the lignin fiber content exceeded 1.5%, the softening point began to decrease.

3.3. Low-Temperature Rheological Property. Figures 7 and 8 show that as temperature decreased, the stiffness of the same type of fiber asphalt binder increased and the creep rate decreased, indicating the high dependence of the fiber asphalt binder on temperature. At low temperatures, the asphalt binder became brittle and hard, and its deformation performance deteriorated. At −6°C, the effect of the fiber content on the S and m values of the asphalt binder was insignificant, and the regularity was unsatisfactory. When the temperature decreased to −12°C and −18°C, the effect of the fiber content on the S and m values of the asphalt binder gradually became more prominent [17].

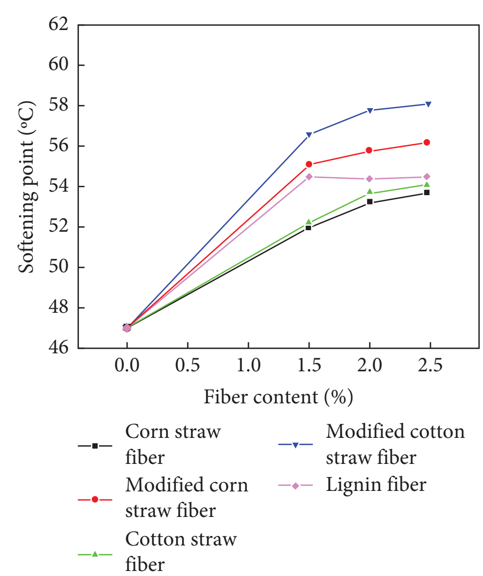


Figure 6: Effects of fiber content and type on softening point of asphalt binder.

The stiffness of the asphalt binder varied in a concave parabolic shape as the fiber content increased and reached a minimum of 1.5% fiber content (see Figure 9), indicating that the asphalt binder exhibits the best creep ability at low temperatures. When the fiber content exceeded 2%, the stiffness increased. At the same fiber content, the stiffness of the modified straw fiber asphalt binder was 9.6% higher than

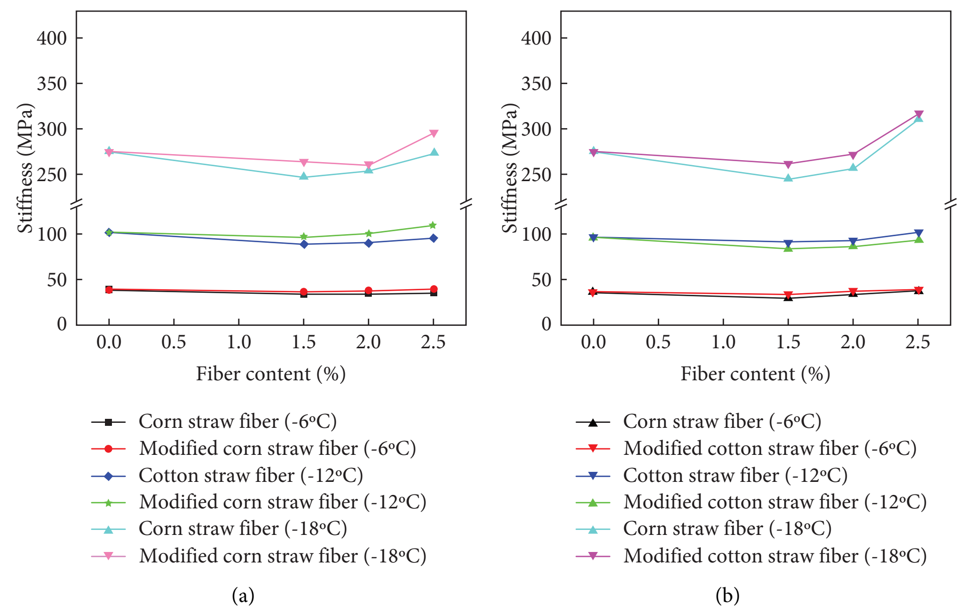


Figure 7: Effects of temperature and fiber content on stiffness of straw fiber asphalt binder. (a) Corn straw fiber. (b) Cotton straw fiber.

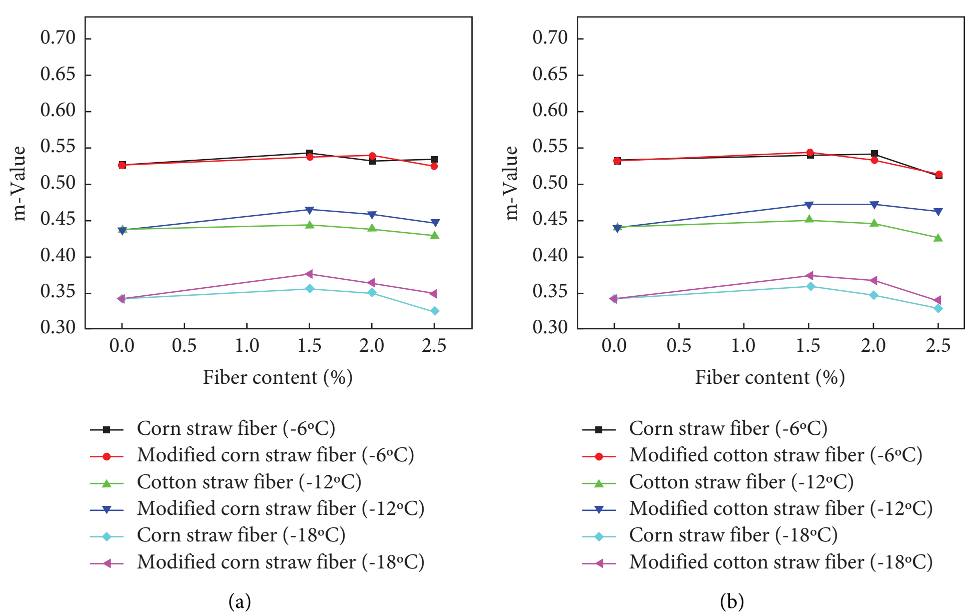


Figure 8: Effects of temperature and fiber content on m-value of straw fiber asphalt binder. (a) Corn straw fiber. (b) Cotton straw fiber.

that of the normal straw fiber but less than that of the lignin fiber. This indicates that the modified treatment can reduce the flexibility of the binder [14].

As the fiber content increased, the m-value of the asphalt binder varied in a convex parabolic shape and reached a maximum when the fiber content was 1.5%, indicating that the asphalt binder demonstrates the highest stress relaxation capacity. When the fiber content exceeded 2%, the m-value began to decrease. At the same fiber content, the m-value of the modified straw fiber asphalt binder was 9.6% higher than that of the normal straw fiber. This suggests that the modified treatment can improve the relaxation ability of the binder [18].

3.4. Toughness and Tenacity. As the fiber content increased, the toughness and tenacity first increased and then decreased (see Figure 10). The toughness and tenacity of the asphalt binder decreased when the fiber content exceeded 1.5%. After modification, the toughness and tenacity of the corn straw and cotton straw fiber asphalt binders increased by an average of 11% and 18%, respectively. This suggests that the modified treatment can improve the toughness and tenacity of the binder.

3.5. Four-Component Test. Based on Table 5, the addition of the fibers changed the contents of the four components of asphalt. Specifically, the amounts of asphaltenes and resins increased, the aromatic content decreased, and the saturated

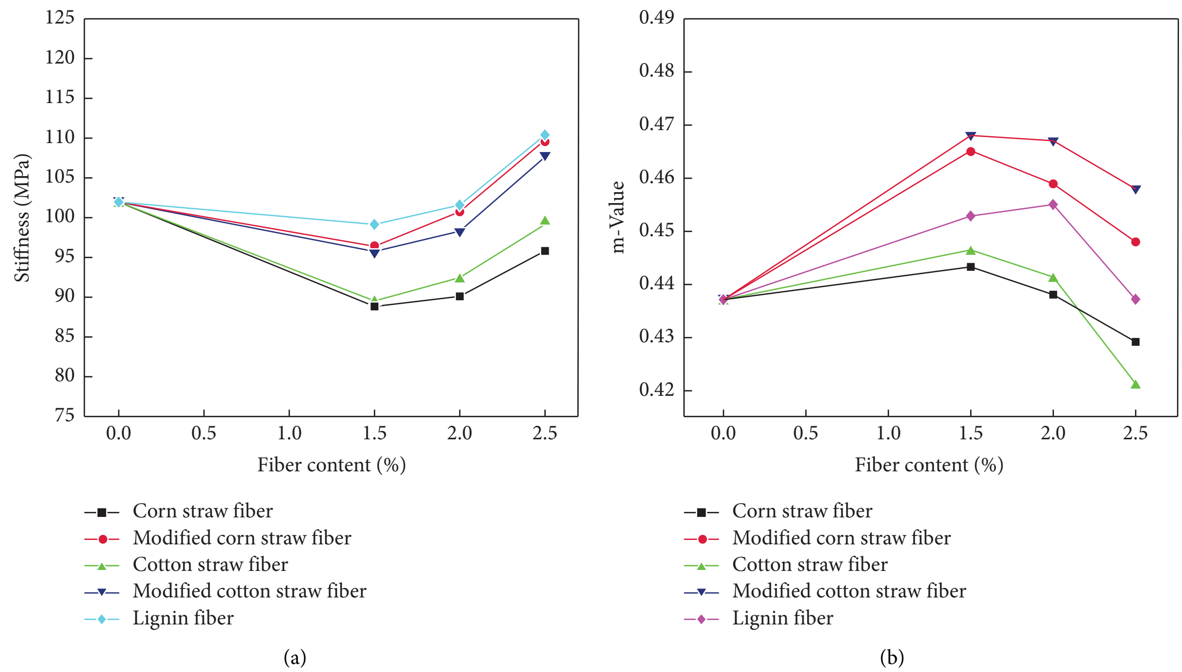


Figure 9: Effects of fiber type and content on stiffness and m-value of asphalt binder at −12°C. (a) Stiffness. (b) m-value.

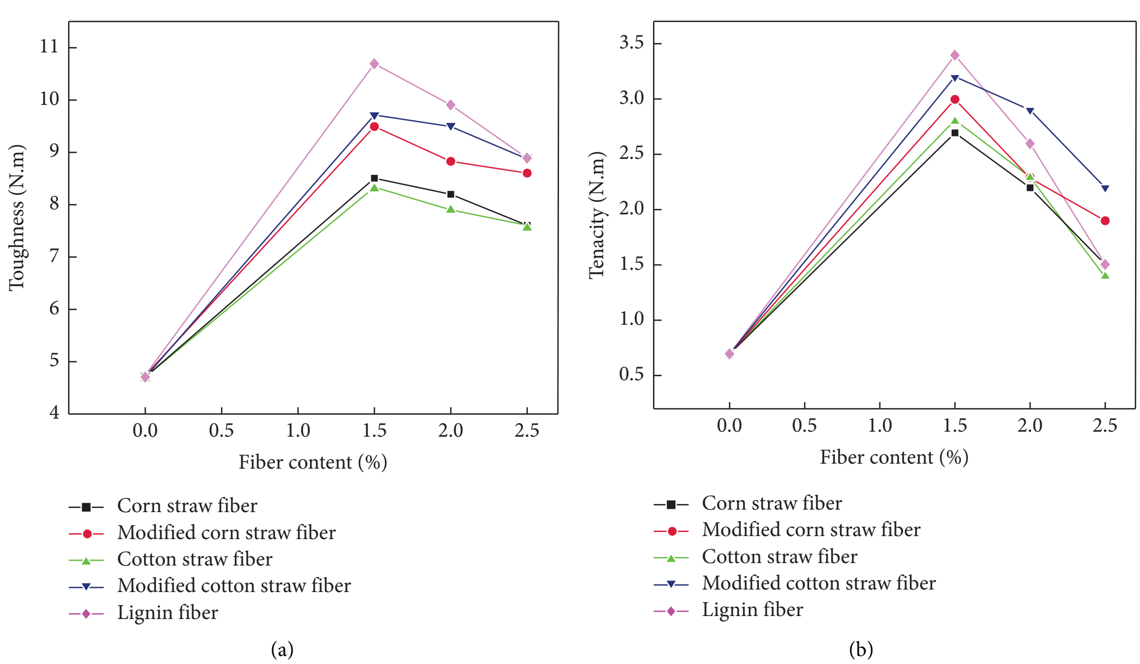


Figure 10: Effects of fiber content and type on (a) toughness and (b) tenacity of asphalt binder.

content remained unchanged. The increasing and decreasing amplitudes of the modified straw fiber asphalt binder were higher than those of the normal straw fiber, and the contents of the four components of the modified straw fiber asphalt binder were similar to those of the lignin fiber.

3.6. SEM Test. The lignin fibers were banded, featured small diameters, and were primarily composed of uniformly distributed single fibers (see Figure 11). The corn straw fibers were cylindrical and included both single and bundled fibers, and their diameters were different. The cotton stalk fibers were cylindrical, featured large diameters, and were primarily composed of uniformly distributed bundled fibers. After modification, the straw fibers crimped, some bundled fibers were separated into single fibers, and the diameter decreased.

Based on Figure 12, cavities were present on the surface of the lignin fiber, and irregular cavities were present on the surface of the corn and cotton straw fibers. After

Table 5: Changes in four components of straw fiber asphalt binder.

Fiber type	Four components (%)				Increase (%)		Decrease (%)	
	A_s	R	A_r	S	A_s	R	A_r	S
Modified corn straw fiber	13.65	27.08	40.94	18.33	1.85	6.48	6.96	0.27
Asphalt	11.8	20.6	47.9	18.6				
Normal corn straw fiber	12.4	25.28	43.83	18.49	0.6	4.68	4.07	0.06
Asphalt	11.8	20.6	47.9	18.6				
Modified cotton straw fiber	13.8	27.4	40.54	18.26	2	6.8	7.36	0.34
Asphalt	11.8	20.6	47.9	18.6				
Normal cotton straw fiber	12.56	25.34	43.56	18.54	0.76	4.74	4.34	0.11
Asphalt	11.8	20.6	47.9	18.6				
Lignin fiber	13.68	27.01	40.78	18.53	1.88	6.41	7.12	0.07
Asphalt	11.8	20.6	47.9	18.6				

A_s: asphaltenes; R: resins; A_r: aromatics; S: saturates.

modification, the longitudinal grooves on the surface of the corn straw fiber deepened and widened, and the surface roughness increased. Meanwhile, the surface cavities of the modified cotton straw fiber increased, and the tubular structure of the fibers collapsed.

3.7. FM Test. The asphalt binder shown in Figure 13(a) contains only asphalt and filler, and the asphalt matrix did not indicate fluorescence under the fluorescence microscope; therefore, the region in black indicates the asphalt, and the green fluorescent points to the filler. The uniform distribution of the green fluorescent points indicates that the mineral powder is highly compatible with asphalt [19].

The short green fluorescent lines in Figures 13(b) and 13(c) indicate the modified straw fibers. As shown, they were well dispersed and their lengths were uniform, indicating the good dispersion of the modified straw fibers in the asphalt binder. As shown in Figure 13(d), the lignin fibers agglomerated and had different lengths, indicating that the dispersibility of the lignin fibers in the asphalt binder was not comparable to that of the modified straw fibers.

3.8. FTIR Test. The characteristic peaks of the two fibers appeared in the same positions (see Figure 14), indicating that their compositions were similar. The common absorption peaks of the two fibers are listed in Table 6 [20].

Based on Figure 15(a), the characteristic peak positions of the five fibers were the same, and only the intensity of the absorption peaks of the straw fiber changed. After modification, the absorption peaks lowered to approximately 2894 and 1730 cm^{-1}, and the continuous vibrational absorption peaks near 1640 and 1515 cm^{-1} weakened. The absorption peaks of the lignin fibers at 3427, 1041, 2894, and 1515 cm^{-1} were higher than those of the other fibers.

Meanwhile, the positions of the absorption peaks of the five fiber asphalt binders and the asphalt binders were similar (see Figure 15(b)). The modified straw fiber asphalt binder did not indicate any new absorption peaks.

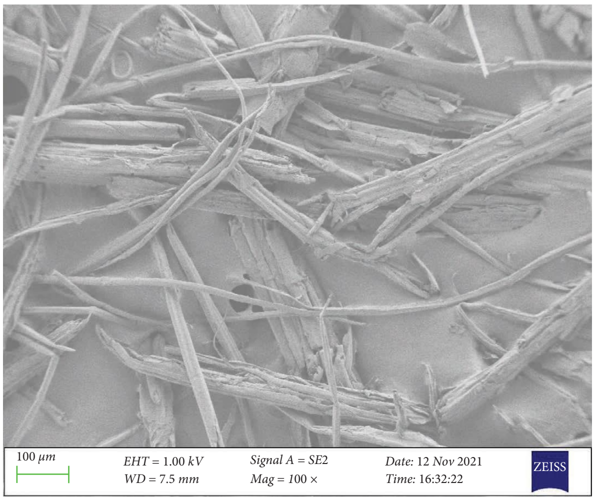
4. Discussion

4.1. Effect of Fiber on Asphalt Composition and Properties. The proportions of light components in the asphalt binder, corn straw fiber, cotton straw fiber, and lignin fiber asphalt binder are 67.24%, 62.32%, 62.10%, and 59.19%, respectively, as listed in Table 5. This shows that the straw fiber can absorb light components in asphalt, but its adsorption capacity is lower than that of the lignin fiber. After adding the modified corn and cotton straw fibers, the proportions of light components in the asphalt binder were 59.27% and 58.80%, respectively, which suggests that the modified straw fiber can increase the adsorption of light components.

The heavy components increased and some light components decreased in the four components of asphalt after the addition of the fibers. This is attributable to the thermal-oxidative ageing caused by high-speed shearing at high temperatures during the preparation of fiber asphalt binder. Some of the light components were converted into resins, whereas the resins were converted into asphaltenes. However, the decrease in light components was also due to the incorporation of the fibers. Compared to the heavy components, the light components have a higher diffusion coefficient and are more easily adsorbed on the surface of the fibers.

As the fiber adsorption capacity increased, the free asphalt in the asphalt transformed into structural asphalt, which exhibited limited fluidity and lower brittleness. In addition, excessive fibers in asphalt lapped easily into a network structure, which further deteriorated the low-temperature creep behavior of asphalt. Therefore, the low-temperature deformation performance of the modified straw fiber asphalt binder was worse than that of the normal straw fiber asphalt binder; hence, excessive addition of the fiber should be avoided [21–23].

4.2. Effect of Fiber Morphology on Asphalt Properties. The diameters of the three fibers shown in Figure 11, from large to small, are ranked as follows: lignin fiber < cotton straw fiber < corn straw fiber. The smaller the diameter of the fiber,



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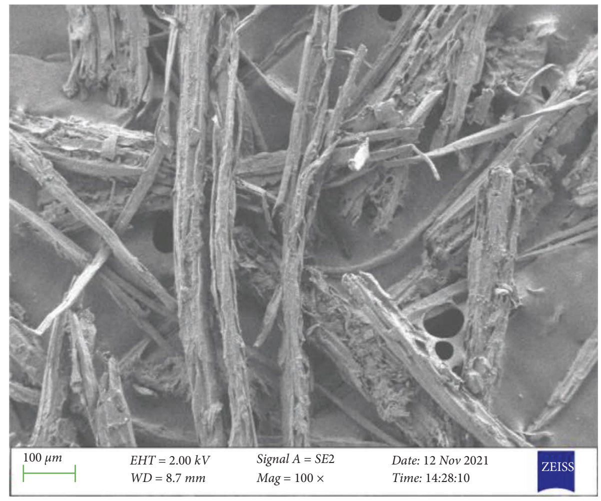

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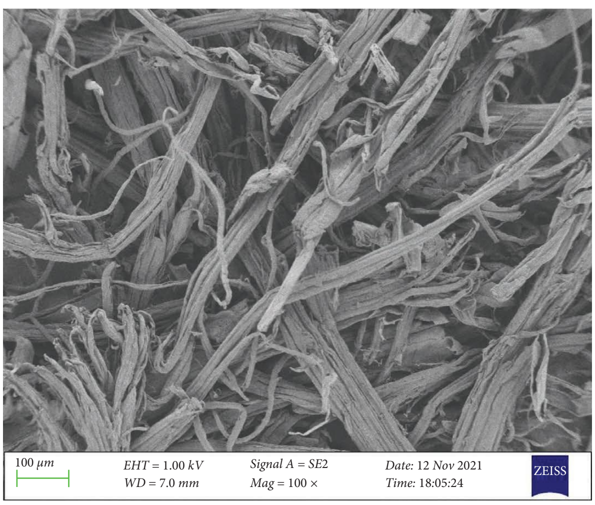

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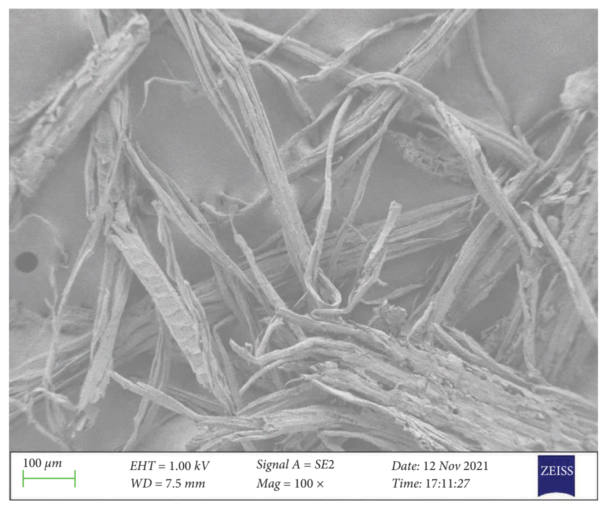

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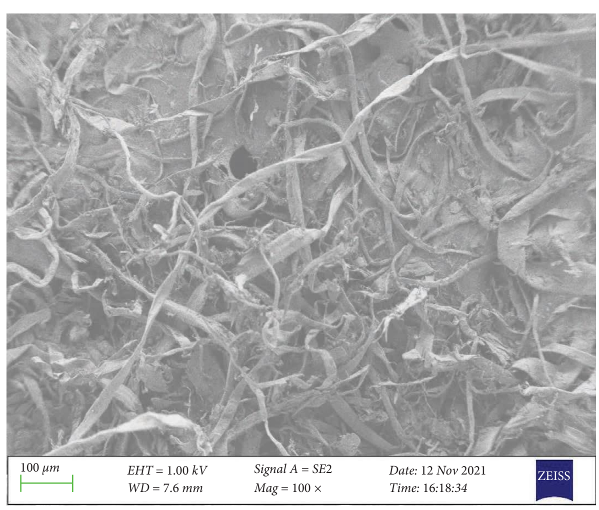


(e)

Figure 11: Microscopic view of fiber at 100x. (a) Corn straw fiber. (b) Cotton straw fiber. (c) Modified corn straw fiber. (d) Modified cotton straw fiber. (e) Lignin fiber.

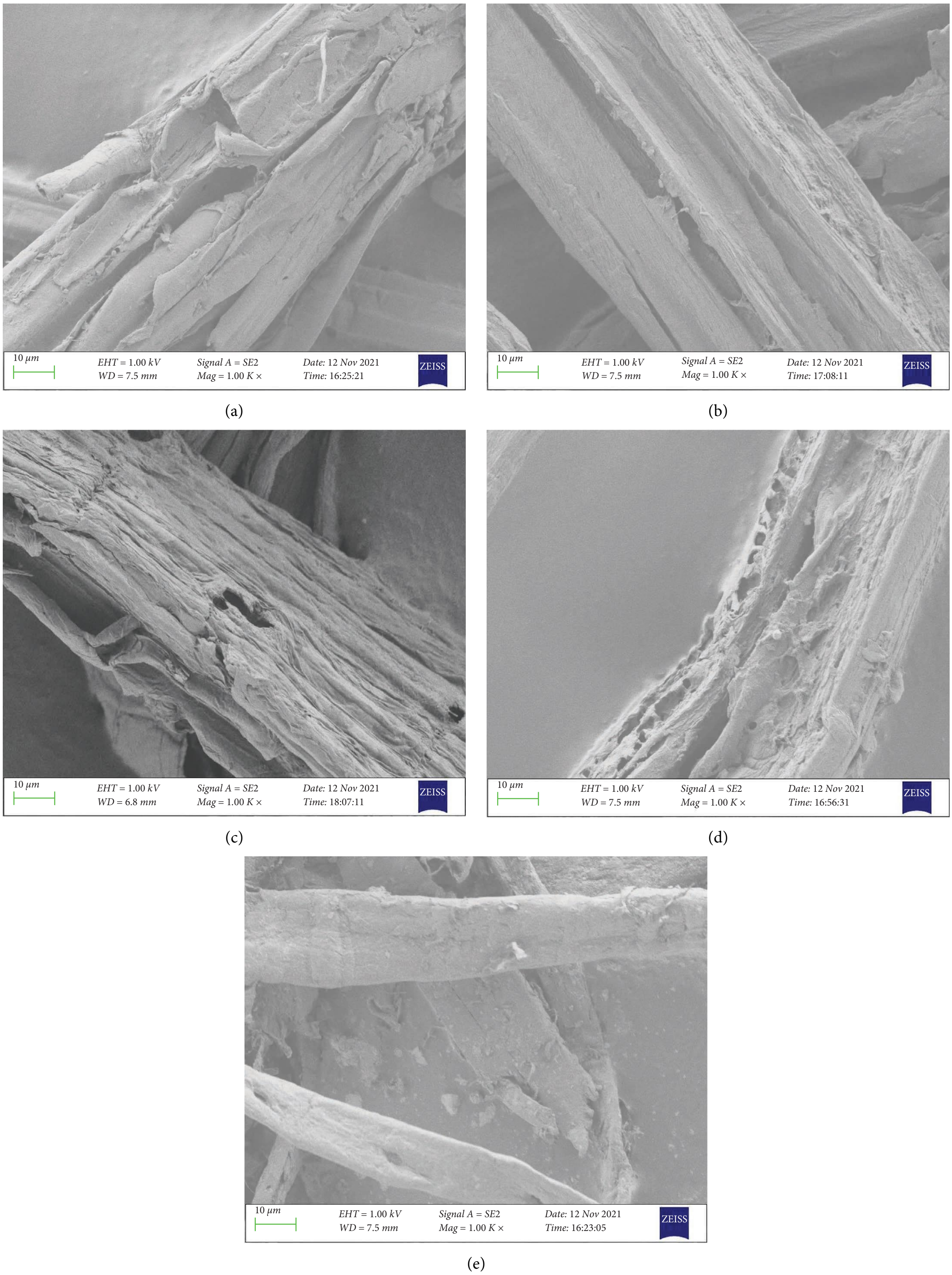
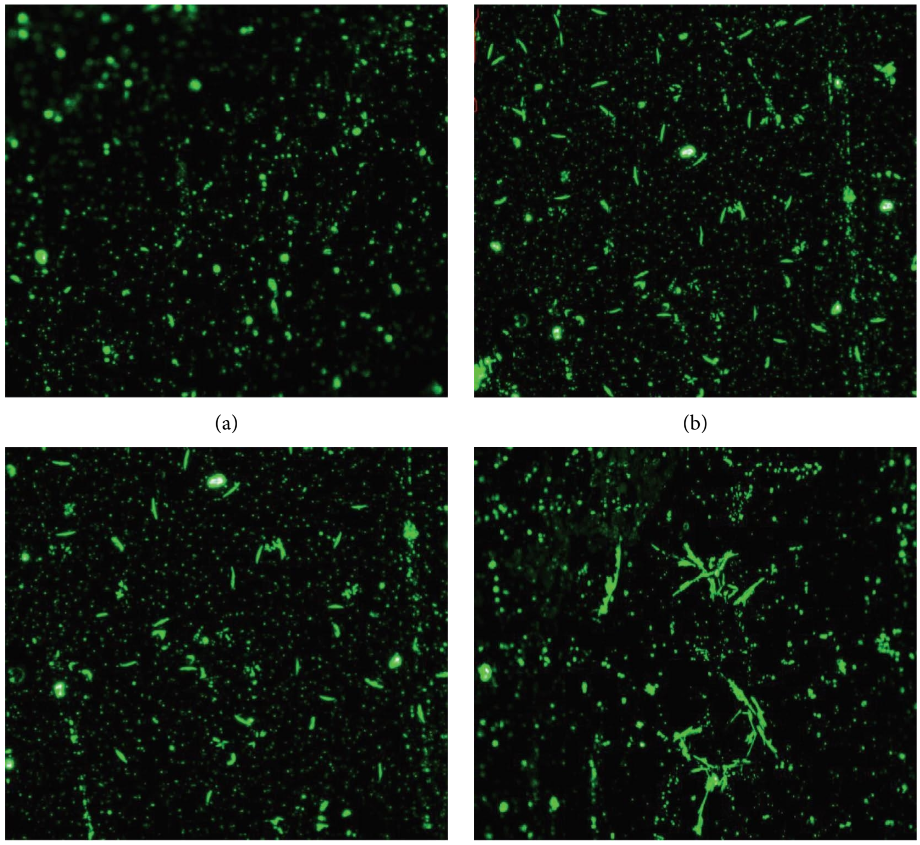


Figure 12: Microscopic view of fiber at 1000x. (a) Corn straw fiber. (b) Cotton straw fiber. (c) Modified corn straw fiber. (d) Modified cotton straw fiber. (e) Lignin fiber.



(a) (b)

(c) (d)

Figure 13: Fluorescent micrographs of asphalt and fibrous asphalt binder. (a) Asphalt binder. (b) Modified corn straw fiber asphalt. (c) Modified cotton straw fiber asphalt. (d) Lignin fiber asphalt.

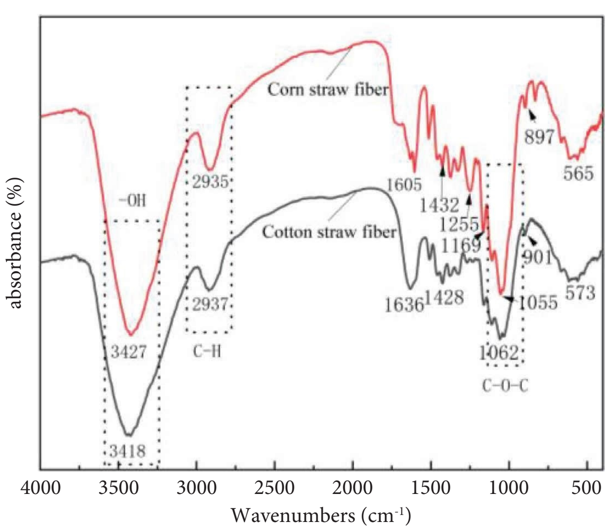


Figure 14: Infrared spectra of straw fiber.

the smaller the length-to-diameter ratio, which results in a larger contact area between the fiber and asphalt as well as higher absorption of asphalt by the fiber [24, 25].

The NaOH solution removed hemicellulose, pectin, waxy, and other unstable components; consequently, the adhesion stress in the fiber bundle decreased, the single fibers were dispersed, and the surface roughness of the straw fiber increased. Therefore, the adsorption capacity of the modified straw fiber exceeded that of normal straw fibers [9, 26, 27]. In addition, the increased number of cavities and grooves on the fiber surface can enhance the interaction between the fibers and asphalt.

Macroscopically, fibers with a high adsorption capacity can increase the viscosity and consistency of the asphalt binder as well as improve its shear strength and softening point [28]. Therefore, the shear resistance and high-temperature deformation resistance of the modified straw fiber asphalt binder exceeded those of the normal straw fiber asphalt binder. The retardation in the surface roughness of the modified straw fiber was better than that of the normal straw fiber, which was more conducive to the dissipation of the internal stress of the asphalt binder. However, excessive fibers affected the retardation between the fibers and that of the asphalt. Therefore, the stress relaxation capacity of the modified straw fiber asphalt binder exceeded that of the normal straw fiber asphalt binder, and an appropriate amount of fibers should be added.

4.3. Effect of Fiber Dispersion on Asphalt Properties. The straw fibers were well dispersed, and their lengths were uniform (see Figure 13), indicating that the screening steps in the fiber production process effectively controlled the length of

Table 6: Common absorption peaks of two types of straw fibers.

Wavenumber (cm^{-1}) Corn straw fiber	Cotton straw fiber	Functional group	Polymer
3427	3418	O-H stretching	Mostly cellulose
2935	2937	C-H stretching	Mostly hemicellulose
1605	1636	C=C stretching	Mostly lignin
1055	1062	C-O vibrations	Cellulose and hemicellulose
897	901	β-D-glucoside bond vibrations	Mostly cellulose
3427	3418	O-H stretching	Mostly cellulose
2935	2937	C-H stretching	Mostly hemicellulose

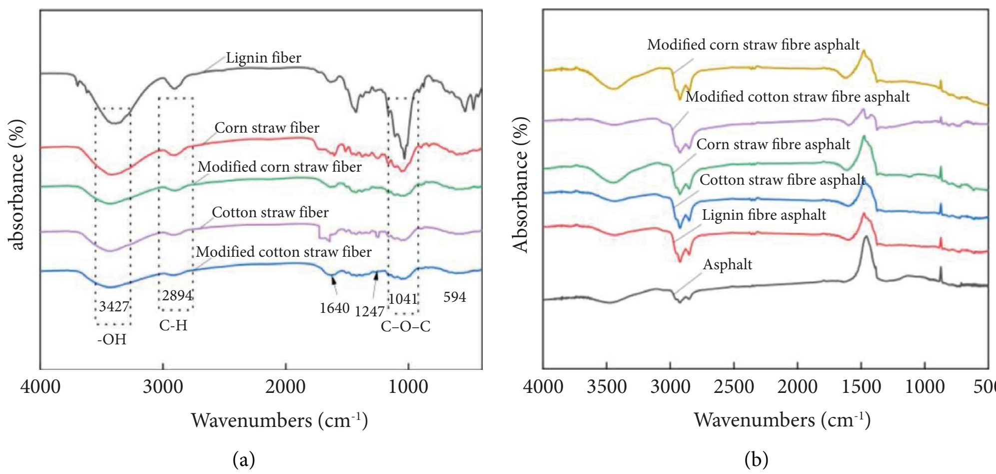


Figure 15: Comparative infrared spectra of (a) straw fiber and (b) asphalt binder.

the straw fibers. The lignin fibers agglomerated because their length (≤6 mm) exceeded that of the modified straw fibers (≤4 mm). As the fiber content increased, the penetration of the asphalt binder decreased, the softening point increased, and the performance improved. When the fiber content exceeded 2%, the fibers became entangled and were dispersed unevenly in the asphalt binder. At this time, the fiber could not fully exert its viscosification and toughening effects. Because the straw fibers were short, they agglomerated less as compared with the lignin fiber when the amount of straw fibers was excessive. Therefore, the performance improvement of the straw fiber decreased, but the performance of the lignin began to deteriorate.

4.4. Effect of Modifier on Fiber and Asphalt Composition. The absorption peaks at 3427 and 3418 cm^{-1} were similar in intensity (see Figure 14), indicating that the cellulose content of the two fibers was similar. The absorption peak at 2935 cm^{-1} was stronger than that at 2937 cm^{-1}, indicating that the hemicellulose content of the cotton straw fiber was slightly higher than that of the corn straw fiber. The absorption peak at 1605 cm^{-1} was significantly stronger than that at 1062 cm^{-1}, indicating that the lignin content of the cotton straw fiber was higher than that of the corn straw fiber. As the lignin content determines the stiffness and brittleness of the fiber, the cotton straw fiber, after being physically crushed, was slightly harder, whereas the corn straw fiber was softer [29].

Meanwhile, the characteristic peak positions of the five fibers were the same (see Figure 15(a)), indicating that the NaOH solution affected only the fiber composition. The absorption peak lowered to approximately 2894 and 1730 cm^{-1}, indicating that the hemicellulose content decreased and the hydrophilicity of the fibers weakened, which increased the water damage resistance of the asphalt mixture [30]. The continuous vibrational absorption peaks near 1640 and 1515 cm^{-1} lowered, indicating that the lignin content decreased and the tensile strength of the fibers increased, which increased the crack resistance of the asphalt mixture [31].

Figure 15(b) shows that no new functional groups or absorption peaks were generated in the asphalt binder after the addition of the fibers, indicating that the interaction between the straw fiber and asphalt binder was primarily physical [32]. Similarly, the modified straw fiber asphalt binder showed no new absorption peaks, indicating the absence of a chemical reaction between the residual NaOH solution on the surface of the straw fiber and the asphalt. Therefore, the physical adsorption action of the modified straw fiber was the same as that of the lignin fiber.

5. Conclusions

In this study, the effects of fiber type and content on the properties of asphalt binders were investigated based on the softening point as well as penetration, BBR, and toughness tests. Additionally, the effects of straw fibers on the properties of asphalt binders were investigated via a four-component test, SEM, FTIR spectroscopy, and FM tests. The following conclusions were obtained:

(1) Owing to the addition of modified straw fibers, the softening point of the asphalt binder increased and the penetration decreased. However, the stiffness of the asphalt binder increased, and the m-value and the toughness decreased when excessive fiber was added. Therefore, the recommended content of modified straw fiber was 1.5%–2.0%.

(2) After modification, the adsorption capacity of the straw fiber for the light components of asphalt increased and was similar to that of the lignin fiber, which increased the stiffness of the asphalt binder and decreased the creep performance at low temperatures.

(3) Owing to the NaOH solution, the surface roughness and the ability of the straw fibers to absorb asphalt improved. The creep rate, shear strength, and softening point of the asphalt binder increased, and the stress relaxation, shear resistance, and high-temperature deformation resistance improved.

(4) Compared with the lignin fiber, the modified straw fiber was more evenly dispersed in the asphalt binder. After the modified straw fiber was added, no new functional groups were generated in the asphalt binder. Furthermore, the modified straw fiber showed only physical adsorption on asphalt, which was also exhibited by the lignin fiber.

Data Availability

The table data used to support the findings of this study are included within the article. The image data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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