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Factors Influencing the Rheological Characteristics of Modified Corn Stalk Fiber Asphalt Mortar

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ABSTRACT

As the demand for sustainable and environmentally friendly road construction materials increases, corn stalk fiber modified with NaOH is a promising candidate due to its renewable and eco-friendly nature. This study employs an orthogonal experimental design to optimize the investigation of multiple factors (corn stalk fiber length, content, and modifier concentration) in the experiments, ensuring that the effects of different factors on the high and low temperature performance of asphalt binder can be independently estimated. Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests were conducted. The bonding between fiber and asphalt was analyzed by infrared spectroscopy, and the action mechanism of fiber in asphalt was revealed from a microscopic perspective by scanning electron microscopy and fluorescence microscopy. Evidently, the concentration of modifier is the main factor affecting the rheological properties of fiber asphalt mortar. Considering the influence of various factors on the rheological properties of modified corn stalk fiber asphalt mortar, the optimal modifier concentration is 7%, the fiber length is 6mm, and the content is 1.5%. After adding modified corn stalk fiber, the asphalt mortar did not produce new characteristic peaks, and the fiber and asphalt were mainly bonded by physical action. The large surface roughness of the modified corn stalk fiber determines its good adsorption capacity, which is conducive to increasing the bonding force of the asphalt. Fibers with a large aspect ratio are easy to bridge with each other, restraining the expansion of cracks and thus enhancing the crack resistance of the mortar.

Keywords: Road engineering, Corn stalk fiber, Asphalt mortar, Orthogonal test, Rheological properties.

INTRODUCTION

With the rapid development of China 's economy, the increase of traffic volume and vehicle load leads to the frequent occurrence of asphalt pavement diseases and the shortening of service life, which makes the transportation industry face great challenges, such as traffic congestion, energy consumption and environmental pollution. (Tang et al., 2017; Sun et al., 2023; Cheng et al., 2023; Wu et al., 2022; Chen et al., 2020). Therefore, it is necessary to modify the existing asphalt to improve the performance of asphalt pavement. Numerous studies and engineering applications confirm that using basalt, glass, and polyester, among other fibers, as additives in asphalt mortar helps in adsorbing asphalt and decelerating the development of cracks, thus enhancing the capabilities of asphalt paving for roads (Li et al., 2022; Cui et al., 2022; Chen et al., 2023; Zhang et al., 2023; Guo et al., 2020;

Kumar et al., 2023). However, these fibers are high-energy-consuming materials, which does not comply with the Chinese low-carbon development strategy.

As a green, environmentally friendly, and renewable material, corn stalk fiber can effectively reduce the utilization of limited resources and increase road service times; thus, it is typically applied to the asphalt mixture (Li et al., 2022; Chen et al., 2023). Chen et al. (2019) described the methods for preparing corn stalk fibers physically and chemically, which are added to asphalt; reportedly, corn stalk fibers exhibit superior dispersion uniformity compared with lignin fibers. Li et al. (2019) investigated the optimal preparation process of corn stalk fiber for road use and added it to asphalt mixtures, thus concluding that its high and low temperature properties are superior to those of lignin fiber. Xu et al. (2023) investigated the optimal modification process for corn stalk fiber modified with NaOH and found that the road performance of modified corn stalk fiber is similar to that of lignin fiber. Wang et al. (2023) studied NaOH-modified corn stalk fiber and added it to asphalt; reportedly, with an increase in content, its performance at high temperatures was enhanced, whereas its low-temperature performance decreased. Chen (2021) found that adding modified corn stalk fiber to the SMA-13 asphalt mixture can effectively improve the road performance of the asphalt mixture. Wang et al. (2023) revealed that the doping of modified corn stalk fibers optimally improved the performance of asphalt mortar when compared with the non-doping of corn stalk fibers and doping of normal corn stalk fibers. At present, research on corn stalk fiber is focused primarily on the preparation process of stalk fiber, and on the influence of fiber content on the performance of asphalt mortar and asphalt mixture. However, studies on the high and low temperature rheological properties of corn stalk fiber-asphalt mortar under various influencing factors (fiber content, length, and modifier concentration) are limited.

In order to make better use of corn stalk fiber and improve the high- and low-temperature rheological properties of asphalt mortar, dynamic shear rheological and bending beam rheological tests were conducted on corn stalk fiber asphalt mortar with different fiber contents, lengths, and modifier concentrations *via* an orthogonal experiment. The influence of different factors on the high- and low-temperature rheological properties of modified corn stalk fiber asphalt mortar was investigated.

MATERIALS AND METHODS

Asphalt

The performance of SBS (I-D)-modified asphalt produced by Shandong Expressway Construction Materials Co. according to the Test Procedure for Asphalt and Asphalt Mixture in Highway Engineering (JTG E20-2011), was tested. The results are presented in Table 1.

Table 1. Main technical indicators of asphalt

Test items	Test results	Technical requirements	Test methods
Needle penetration 25℃,100 g, and 5 s (0.1 mm)	55	40–60	T0604-2011
Penetration index (PI)	0.7	≥0	T0604-2011
Softening point (℃)	80.5	≥60	T0606-2011
135℃ kinematic viscosity (pa·s)	1.4	≤3	T0619-2011
5℃ ductility and 5 cm/min (cm)	33	≥20	T0605-2011
Flash point (℃)	248	≥230	T0611-2011
Solubility (%)	99.87	≥99	T0607-2011
25℃ elastic recovery (%)	98	≥75	T0662-2000
Residues after thin-film oven test or rolling thin-film oven test			
Mass variation (%)	–0.180	≤±1.0	T0610-2011
25℃ residual penetration ratio (%)	78	≥65	T0604-2011
Ductility 5℃ (cm)	18	≥5	T0619-2011

Mineral Powder

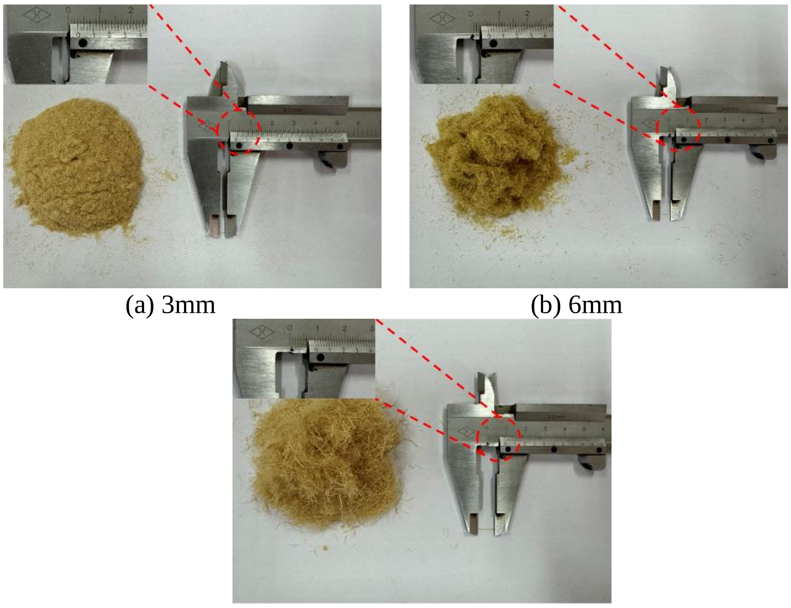
Fine limestone powder was selected, and its main technical indicators are presented in Table 2.

Table 2. Main technical indicators of mineral powder

Test items		Test results	Technical requirements	Test methods
Apparent density (g/cm^3)		2.785	≤ 2.5	T0352-2000
Particle size Range (%)	<0.6 mm	100	100	T0351-2000
	<0.15 mm	94.6	90–100	
	<0.075 mm	85.3	75–100	
Water content (%)		0.32	≤ 1	T0103-1993
Hydrophilic coefficient (%)		0.43	< 1	T0353-2000
Appearance		No agglomerates, no caking	No agglomerates, no caking	—

Preparation and Modification of Corn Stalk Fiber

The preparation process of corn stalk fiber used in this paper is as follows. First, the natural corn stalk fiber is used to remove impurities, such as leaves and ears, on the surface. Second, the corn stalk fiber was cut off and soaked for 4h, and the core was removed. The stalk skin was cut into 8-10 mm segments and crushed by a household high-speed multi-functional pulverizer at 30000 r/min for 2min. Subsequently, the crushed corn stalk fiber was placed in a 50°C ultraviolet electric blast drying oven and dried at constant weight. Finally, 0.3-mm and 0.15-mm round sieves were used for screening, and 3-,6- and 9-mm corn stalk fibers were obtained. The appearance of the corn stalk fibers is shown in Fig. (1), and the technical indicators are shown in Table 3.



(a) 3mm (b) 6mm

(c) 9mm

Figure (1): Modified corn stalk fiber of different lengths

The modification process of modified corn stalk fibers with different concentrations is as follows. Firstly, deionized water and NaOH particles were mixed in different proportions to prepare 3%-, 5%- and 7%-NaOH solutions. The corn stalk fibers of the same mass and different lengths were placed in different concentrations of NaOH solutions. The glass rod was slightly stirred until the surface of the fiber was completely immersed in the alkali solution, and the beaker containing the modified solution was placed in a magnetic stirrer for uniform stirring for 30 min. After the stirring is completed, the modified stalk fiber is filtered out, and the residual alkali solution on the surface of the fiber is washed with deionized water until the fiber PH value is in the range of 6.5-7.5; the fiber was placed in a 50°C ultraviolet electrothermal blast drying oven, and dried to a constant weight to obtain 3%-, 5%-, and 7%- modified corn stalk fibers.The appearance and morphology of corn stalk fiber at different concentrations are shown in Fig. (2), and its technical indicators are shown in Table 3.

(a) 3%

(b) 5%

(c) 7%

Figure (2): Corn stalk fiber with different modification concentrations

Table 3. Main technical indicators of fiber

Test items	**Color**	**Fiber length/mm**	**Ash content/%**	**pH value**	**Oil absorption multiple times**	**Thermal weight loss rate (170°C，2h)/%**
Unmodified corn stalk fiber	Yellow	≤9	5.4	7.06	5.71	7.3
Modified corn stalk fiber	Light yellow	≤9	5.8	8.75	6.3	5.6

It can be seen from Table 3 that the ash content, pH value and oil absorption multiple of the modified corn stalk fiber are better than those of the unmodified corn stalk fiber. The increase in these indicators contributes to promoting the absorption of asphalt components, reducing the degradation of mixture performance caused by acid-base reaction, enhancing the adhesion between asphalt and mineral materials, making the asphalt mixture more compact and stable, thereby improving the overall strength and durability of the road surface. In addition, the reduction in the thermal weight-loss rate of modified corn stalk fiber helps it maintain a more stable structure in a high-temperature environment, making it less likely to decompose and deteriorate. During the high-temperature period in summer, it can effectively reduce road diseases caused by asphalt softening.

Preparation of Fiber Asphalt Mortar

The modified corn stalk fiber mortar samples were prepared using a pure-blade asphalt-shear apparatus, as follows. Before preparation, corn stalk fibers of different lengths, which were treated with different modifier concentrations combined with mineral powder, were dried in a 135℃ oven. Subsequently, to avoid the formation of fiber agglomeration during the preparation of the mortar, the mineral powder and the fiber were dry-mixed for about 2 minutes. Thereafter, SBS-modified asphalt was heated until it was flowing in an oven, the temperature of which was 165 ± 5℃, and low amounts of a uniformly mixed fiber-mineral powder were added to the SBS-modified asphalt in the flow state multiple times. During this period, a glass rod was inserted into the bottom of the asphalt tank, followed by continuous stirring at a constant speed; thus, the fiber-mineral powder mixture was evenly dispersed. After the fiber-mineral powder mixture was fully incorporated, the pure-blade asphalt-shear apparatus was started, and the mineral powder and fiber were uniformly dispersed in the asphalt matrix by shearing at a high speed of 3000 rpm for 30 minutes. Subsequently, the fiber asphalt mortar was stirred at a low speed of 1500 rpm for 20 minutes to eliminate the bubble components generated during the high-speed mixing process of fiber asphalt mortar. As the asphalt mortar is being stirred, the temperature was controlled at 165 ± 5℃ using a heating sleeve. To prevent the occurrence of fiber and mineral powder segregation caused by the long storage time of the mortar, the performance test of the mortar should be completed in minimal time after the preparation of the mortar. In Fig. (3), the preparation procedure is depicted.

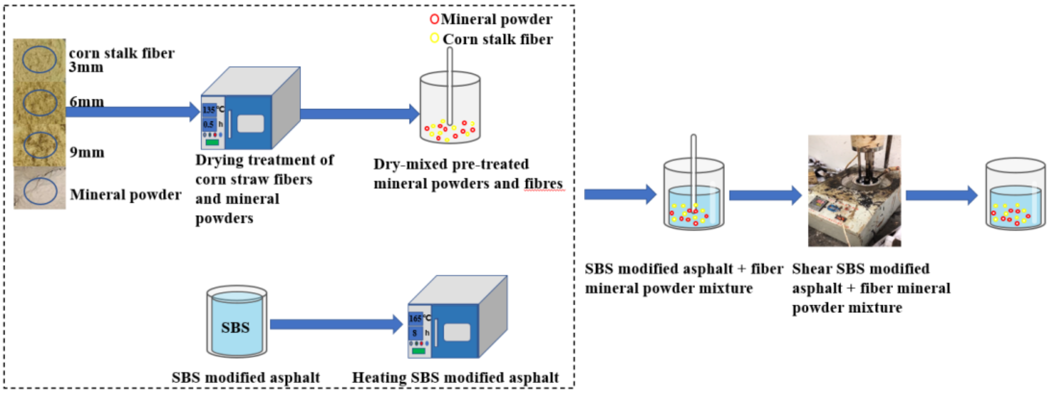


Figure (3): Fiber asphalt mortar preparation flowchart

TEST SCHEME

The test flowchart is shown in Fig. (4).

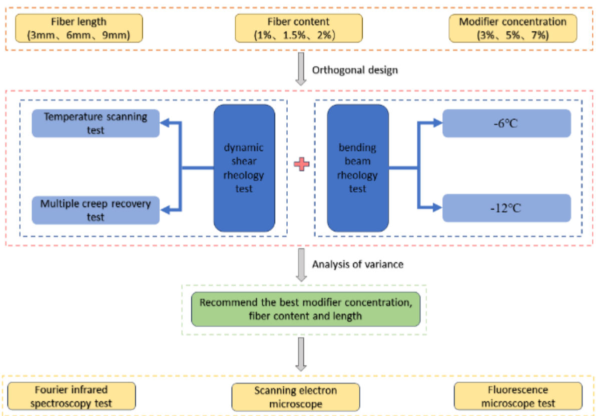


Figure (4): Test flowchart

Orthogonal Design

The influence of three factors; namely, corn stalk fiber length, fiber content, and modifier concentration, on the fiber-asphalt mortar's rheological characteristics was investigated using orthogonal tests. Fiber lengths of 3, 6, and 9 mm were selected in the experiment. The fiber content was 1.0–2.0% (measured by the SBS asphalt weight ratio, and the interval was 0.5%). The concentration of modifier was 3–7% (NaOH was counted in the total mass of the solution, and the interval was 2%). The orthogonal table L_9 (3^4) of three factors and three levels was used to carry out the test. The orthogonal test factor level table is presented in Table 4, and the test plan is presented in Table 5.

Table 4. Factor level table of orthogonal test

Level	Factor A	Factor B	Factor C
	Fiber length (mm)	Fiber content (%)	Modifier concentration (%)
1	3	1	3
2	6	1.5	5
3	9	2	7

Table 5. Orthogonal test schedule

Test number	Test scheme	Fiber length (mm)	Fiber content (%)	Modifier concentration (%)
1	$A_1B_1C_1$	3	1	3
2	$A_1B_2C_2$	3	1.5	5
3	$A_1B_3C_3$	3	2	7
4	$A_2B_2C_3$	6	1.5	7
5	$A_2B_3C_1$	6	2	3
6	$A_2B_1C_2$	6	1	5
7	$A_3B_3C_2$	9	2	5
8	$A_3B_1C_3$	9	1	7
9	$A_3B_2C_1$	9	1.5	3

Dynamic Shear Rheology (DSR) Experiments

Unaged modified corn stalk fiber asphalt mortar was subjected to DSR tests in two modes; namely, temperature scanning and multi-stress repeated creep recovery test (MSCR), using a Gemini IIADS dynamic shear rheometer. According to the data of the National Climate Center, the normal temperature of asphalt pavement in summer in China is 60°C. Under this condition, the values of evaluation index G*/sinδ, unrecoverable creep compliance (Jnr), and creep recovery rate R were analysed to study the influence of different influencing factors on the high-temperature performance of fiber asphalt mortar.

Bending Beam Rheology (BBR) Experiment

The thermal-expansion bending beam rheometer standard device (TE-BBR-SD) bending beam rheometer was employed for the test, and the test temperatures were set as -6ºC, and -12ºC. The stiffness modulus S and stiffness change rate m were used as the evaluation indices of the low-temperature performance of asphalt mortar. According to the T0627 asphalt bending creep stiffness test method in the Highway Engineering Asphalt and Asphalt Mixture Test Specification (JTG E20-2011), the stiffness modulus S and stiffness change rate m values of fiber asphalt mortar under different factors were measured, as follows.

$$S\,(t) = \frac{Pl^3}{4bh^3 v\,(t)} \tag{1}$$

$$m = \frac{a\log S\,(t)}{a\log\,(t)} \tag{2}$$

where S is the creep stiffness modulus (MPa); P is the constant load applied (N); l is the span of asphalt beam (mm); b is the width of the asphalt beam specimen (mm); h is the height of the asphalt beamlet specimen (mm); v is the deflection at the mid-span (mm); and m is the rate of change of creep strength.

FTIR Test

Fourier infrared spectrometer was used to test the chemical functional group information of fiberless asphalt mortar, modified corn stalk fiber asphalt mortar and modified corn stalk fiber. The test frequency is 4 cm^{-1}, and the wave number scanning range is 400-4000 cm^{-1}.

SEM Test

The modified corn stalk fiber was observed by scanning electron microscopy. The scanning voltage was 3.0kV and the current was 5mA.

Fluorescent Fiber Lens Test

A high magnification fluorescence microscope, Axioscope 5, manufactured by Carl Zeiss Microscopes, GmbH, Germany, was used to observe the fiberless asphalt mastic and modified corn stalk fiber asphalt mastic, as well as to analyze the distribution of fibers in the asphalt mastic and the mechanism of action.

RESULTS AND DISCUSSION

Dynamic Shear Rheological Test Results

Dynamic shear rheological tests were carried out on nine groups of modified corn stalk fiber asphalt mortar. The test results are presented in Table 6.

Table 6. Dynamic shear rheology test results

Test no.	G*/sinδ (kPa)	$Jnr_{0.1}$ (kPa^{-1})	$Jnr_{3.2}$ (kPa^{-1})	$R_{0.1}$ (%)	$R_{3.2}$ (%)
1	6.73	0.0105	0.024	91.59	85.30
2	7.49	0.0038	0.0098	94.40	90.19
3	12.36	0.0031	0.0109	95.37	89.68
4	9.01	0.0043	0.0096	93.66	89.75
5	9.10	0.0035	0.0114	94.82	88.76
6	6.72	0.0087	0.0211	93.16	86.51
7	6.78	0.0371	0.0566	77.82	70.27
8	6.19	0.0052	0.0161	95.09	88.40
9	6.42	0.0109	0.0256	90.83	83.34

To determine the influences of three factors on the evaluation indices of the high-temperature rheological properties of corn stalk fiber asphalt mortar, a range analysis of the data listed in Table 5 was carried out, and the calculation results are presented in Table 7.

Table 7. Results of extreme difference analysis of high temperature influencing factors

Index		G*/sinδ (Pa)	$Jnr_{0.1}$ ($kPa^{-1)}$	$Jnr_{3.2}$ (kPa^{-1})	$R_{0.1}$ (%)	$R_{3.2}$ (%)
Range r	Fiber length	3.516	0.010	0.013	3.824	6.590
	Fiber content	1.680	0.006	0.010	4.100	3.603
	Modifier concentration	4.203	0.017	0.021	7.593	7.606

Cheng et al. (2021) and Ma et al. (2022) studied the effects of rice stalk fiber and basalt fiber asphalt mortar's content, length, and powder-to-binder ratio on their performance at high and low temperatures. They found that the powder-binder ratio has the most significant influence on high- and low-temperature performance. With respect to the powder-binder ratio, no relevant research has yet been conducted on the factors that could have a significant influence on the high- and low-temperature performance of asphalt mortar. Therefore, in this study, fiber length, fiber content, and modifier concentration were selected to study the high- and low-temperature properties of fiber asphalt mortar. It can be seen from Table 7 that the concentration of modifier is the main influencing factor of rut factor, unrecoverable creep compliance and creep recovery rate under 3.2 kPa stress level, followed by fiber length and fiber content. At the stress level of 0.1 kPa, the influence order of the three factors on the creep recovery rate is: modifier concentration > fiber content > fiber length. Through the above analysis, it can be seen that different factors have different effects on the creep rate under different stress levels, but the most important factor is still the modifier concentration. On the whole, modifier concentration is the most important factor influencing the high-temperature performance of corn stalk fiber asphalt mortar, followed by fiber length, and then by fiber content. Therefore, within a certain range, the higher the modifier concentration, the longer the fiber length and the higher the fiber content, the more favorable the high-temperature performance of the asphalt mortar.

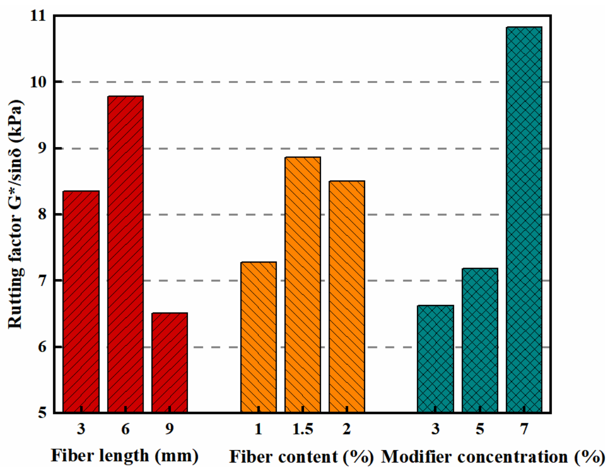


Figure (5): Influence law of each factor on rutting factor G*/sinδ

The G*/sinδ index evaluates the high-temperature rheological properties of different modified corn stalk fiber asphalts. With an increase in G*, the capacity to resist deformation increased. With a decrease in δ, the more elastic the asphalt mortar is and the less prone the material is to permanent deformation. With a decrease in G*/sinδ, the stronger the asphalt pavement's resistance to rutting (Xu et al., 2023; Xu, 2023; Wu, 2022). From Fig. (5), it can be seen that with the increase of modifier concentration, the rutting factor G*/sinδ shows a gradual increase trend. When the modifier concentration is 7%, the rutting factor reaches the maximum value, which is 63.42% and 60.21% higher than that of asphalt mortar with modifier concentration of 3% and 5%, respectively. This shows that the increase of modifier concentration improves the rutting factor of asphalt mortar. Thus, to ensure the high-temperature shear deformation resistance of fiber asphalt mortar, the modifier concentration should not be less than 7%. With the increase of fiber length and fiber content, the rutting factor G*/sinδ increased first and then decreased. When the fiber length is 6mm and the fiber content is 1.5%, the maximum value is obtained, indicating that the fiber length is too long and the content is too high, which has an adverse effect on the high-temperature performance of the asphalt mortar. In order to ensure the high-temperature shear-deformation resistance of fiber asphalt mortar, the recommended fiber length, fiber content and modifier concentration are 6mm, 1.5% and 7%, respectively.

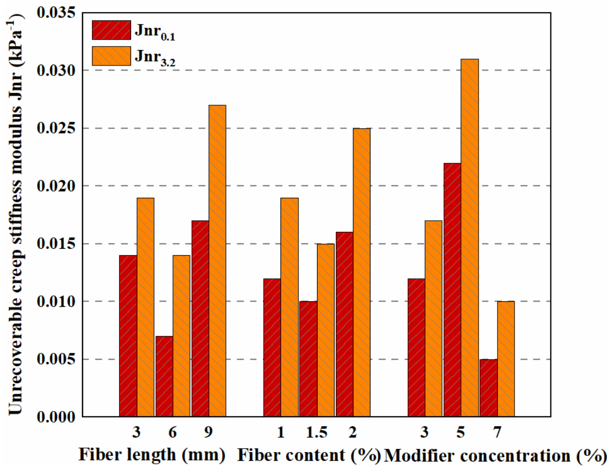


Figure (6): Influence law of each factor on the irrecoverable creep flexibility Jnr

The unrecoverable creep compliance Jnr reflects the non-linear rheological response of asphalt under large stress, and it is in correlation with the anti-rutting performance of the asphalt mixture (Guo, 2022; Chen, 2022; Li et al., 2023). Evidently from Fig. (6), the fiber length and content influenced the irrecoverable creep flexibility in a similar manner. As fiber length and content increase, the unrecoverable creep compliance first decreased and then increased; however, the increase in the fiber length had a significant influence on the increase of unrecoverable creep compliance. This indicates that when the fiber was excessively long, the proportion of elastic delay deformation and viscous deformation of fiber asphalt mortar under stress loading was large, and the degree of deformation recovery was poor after stress unloading. Moreover, the unrecoverable creep compliance of mortar was larger at low modifier concentrations. When the concentration of modifier increased from 5% to 7%, $Jnr_{0.1}$ and $Jnr_{3.2}$ decreased by 77.27% and 67.74%, respectively. In conclusion, considering the value of irrecoverable creep compliance (Jnr), a fiber length of 6 mm, a fiber content of 1.5%, and a 7% modifier concentration represent the optimal combination.

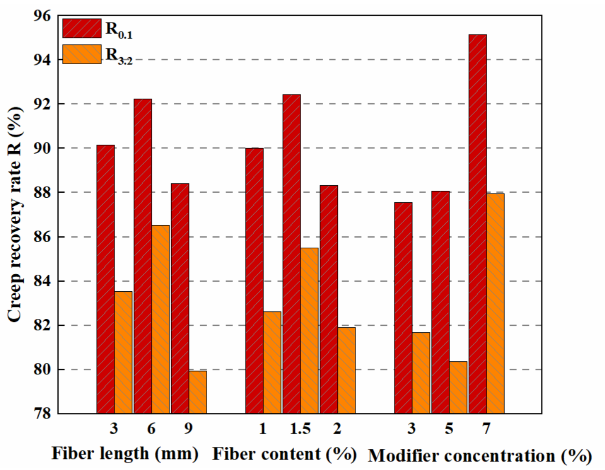


Figure (7): Influence law of each factor on the creep recovery rate R

The deformation recovery capability of asphalt can be indicated by the creep recovery rate. With an increase in the recovery rate, the higher the recovery capacity of asphalt after deformation (Xu et al., 2020; Li, 2020; Zhang et al., 2023) Evidently from Fig. (7), with an increase in the stress level, the creep recovery rate decreased significantly, thus indicating that the size of the external stress effect had a more significant influence on the creep performance of the mortar. For the influence factor of modifier concentration, under the stress level of 0.11kPa, the creep recovery rate increased with an increase in modifier concentration. When the fiber length was 9 mm, the creep recovery rate R value was larger than those of 3 mm and 6 mm. When the fiber content increased from 1.5% to 2.0%, the creep recovery rates $R_{0.1}$ and $R_{3.2}$ decreased by 4.44% and 4.21%, respectively. It can be seen that excessively long fiber length and high fiber content will weaken the creep recovery of mortar.

Bending Rheological Test Results

Rheology tests for bending were performed on nine groups of modified corn stalk fiber asphalt mortar, and the results are presented in Table 8.

Table 8. Bending beam rheological-test results

Test no.	Stiffness modulus (MPa)		Creep rate, m	
	-6° C	-12° C	-6° C	-12° C
1	62.60	169.40	0.511	0.451
2	67.20	175.30	0.543	0.483
3	99.90	245.60	0.536	0.417
4	95.70	213.10	0.531	0.479
5	52.70	186.10	0.503	0.398
6	69.40	205.30	0.529	0.421
7	76.80	193.20	0.506	0.407
8	88.20	287.30	0.517	0.441
9	54.30	148.70	0.561	0.449

It can be seen from Table 8 that as the temperature drops from -6°C to -12°C, the stiffness modulus of the fiber asphalt mortar of the same group of schemes shows an upward trend as the temperature decreases, while the creep recovery rate is the opposite, indicating that the fiber asphalt mortar is sensitive to temperature; at low temperatures, the viscous component of the fiber asphalt mortar increases and the elastic component decreases, resulting in a weakened deformation recovery ability. Among them, the stiffness modulus of groups 8#, 3#, and 4# are all greater than those of the other groups, indicating that when the concentration of the modifier increases, it has a favorable effect on the high-temperature performance of the fiber asphalt mortar, but under relatively low temperatures, it will have an adverse effect on the low-temperature performance of the fiber asphalt mortar.

Range analysis was performed on the test for low-temperature bending results presented in Table 8. The influence of the three factors on the stiffness modulus S and the creep rate m at different temperatures is presented in Table 9.

Table 9. Results of extreme difference analysis of low-temperature influence factors

Index		Stiffness modulus S, (MPa)		Creep rate, m	
		–6 ºC	–12 ºC	–6 ºC	–12 ºC
Range, r	Fiber length	3.97	12.97	0.009	0.018
	Fiber content	4.07	41.63	0.030	0.063
	Modifier concentration	38.07	80.60	0.003	0.013

As demonstrated in Table 9, the concentration of corn stalk fiber modifier had a more significant influence on the strength modulus S and the creep rate m, followed by fiber content. To more comprehensively analyze the effects of three variables on the performance of fiber asphalt mortar at low temperatures, the variation trend of stiffness modulus S and creep rate m with three factors is drawn according to Table 9, as shown in Fig. (8).

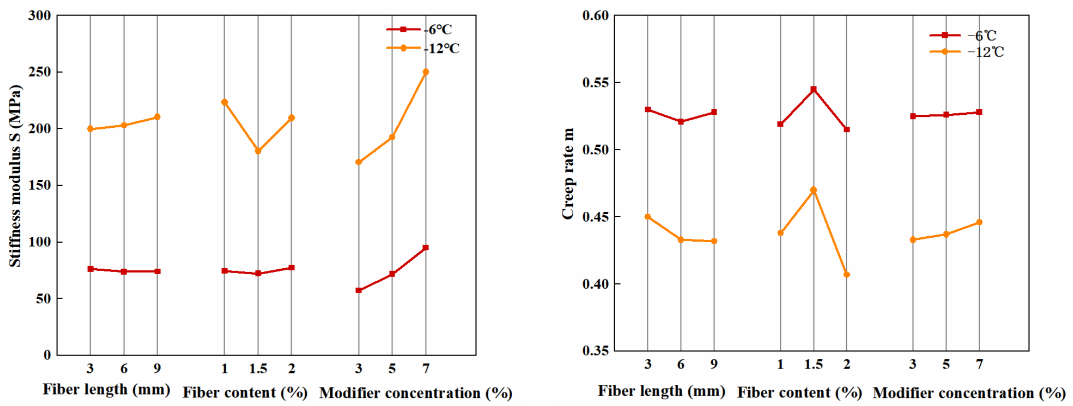


Figure (8): Stiffness modulus (left) and creep rate (right) *versus* different factors influencing low-temperature rheological index

Evidently from Fig. 8., the modifier concentration increased from 3% to 7%, the strength modulus S at -6ºC increased by 25.4% and 68.9%; at -12ºC, the stiffness modulus S increased by 14% and 48%, whereas the creep rate m has a small increase at different temperatures. This indicates that the increase in modifier concentration adversely influenced asphalt mortar's low-temperature performance. Considering asphalt mortar's low-temperature performance, the modifier concentration should not be greater than 7%.

When the test temperature decreased from -6ºC to -12ºC, the variation range of the evaluation index of the mortar's low-temperature rheological characteristics increased, thus indicating that the corn stalk fiber asphalt mortar was sensitive to the change of ambient temperature. The increase of fiber length has little effect on stiffness modulus S and creep rate m. At different temperatures, the stiffness modulus S decreases first and then increases with the increase of fiber content, and the creep rate m increases first and then decreases. Both of them have an inflection point at 1.5% fiber content, indicating that when the fiber content is 1.5%, the low-temperature crack resistance of the modified corn stalk fiber asphalt mortar is the best.

Infrared Spectroscopy Test Results

The blending mechanism of modified corn stalk fiber and asphalt mortar was analyzed by infrared spectroscopy of modified corn stalk fiber, non-fiber asphalt mortar and modified corn stalk fiber asphalt mortar by a Fourier infrared spectrometer. The test results are shown in Fig. (9).

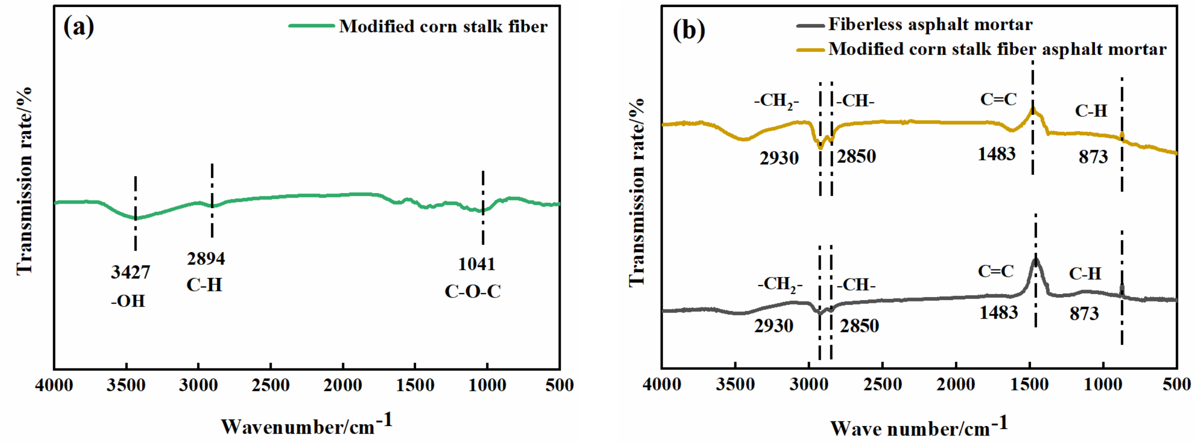


Figure (9): Infrared spectra of fiber and asphalt mortar; (a) Modified corn stalk fiber, (b) Fiberless asphalt mortar and modified corn stalk fiber asphalt mortar

It can be seen from Fig.9 (a) that the broad and strong stretching vibration characteristic peak at 3427cm^{-1} mainly comes from the characteristic peak formed by the stretching vibration of-OH caused by the formation of hydrogen bonds in cellulose and hemicellulose molecules; 2894cm^{-1} is the characteristic peak caused by the anti-symmetric stretching vibration of C-H group in hemicellulose molecule. The characteristic peak at 1640 cm^{-1} is caused by the stretching vibration of C = O on lignin. The characteristic peak at 1041cm^{-1} is the absorption peak of C-O-C asymmetric stretching vibration on carbohydrates. It can be seen that the modified corn stalk fiber is mainly composed of cellulose, hemicellulose and lignin.

From Fig. 9 (b), it can be seen that the fiberless asphalt mortar, in the functional group region, the absorption peaks caused by the C-H stretching vibration of cycloalkanes and alkanes appeared at 2930 cm^{-1} and 2850 cm^{-1}, and the absorption peaks at 2930 cm^{-1} were mainly caused by the symmetric stretching of the methylene group. The appearance at 1483 cm^{-1} is generated by the C=C vibration of the aromatic ring on the benzene ring. In the fingerprint region, a smaller absorption peak caused by the bending vibration of the benzene ring -CH- occurs at 873 cm^{-1}. Combining the functional group area with the fingerprint area, the active groups, such as alkanes, cycloalkanes, amides, aromatic ethers, and sulfoxides, in the asphalt mortar can be obtained. Compared with the modified corn stalk fiber asphalt mortar, it is found that there is no new absorption peak in the fiber asphalt mortar, which indicates that the incorporation of modified corn stalk fiber only produces physical adsorption on the asphalt, and there is no chemical reaction.

SEM and Fluorescence Fiber Mirror Test Results

The SEM image of modified corn stalk fiber is shown in Fig. (10).

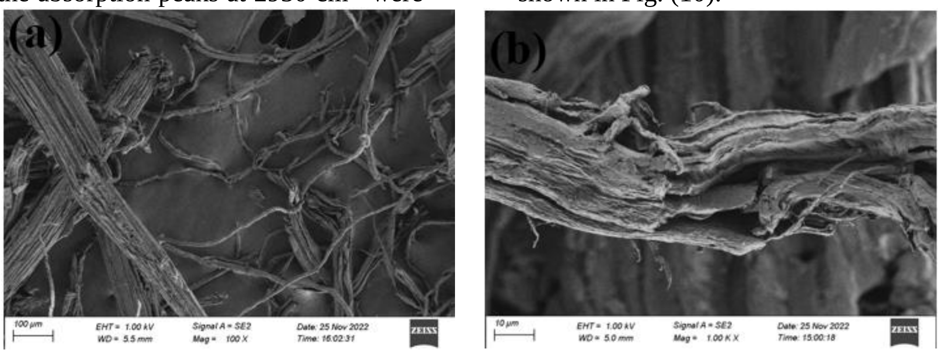


Figure (10): 7%-modified corn stalk fiber; (a) Amplification factor 100μm; (b) Amplification factor 10μm

It can be seen from Fig. (10) that the surface of corn stalk fiber modified by 7% modifier concentration curled up. The number of monofilament fibers increases and the aspect ratio increases. The fibers are entangled with each other. The surface of the individual fiber is rougher and there are pores inside, which is conducive to the adsorption of asphalt and the increase of the bond between asphalt and mineral material.

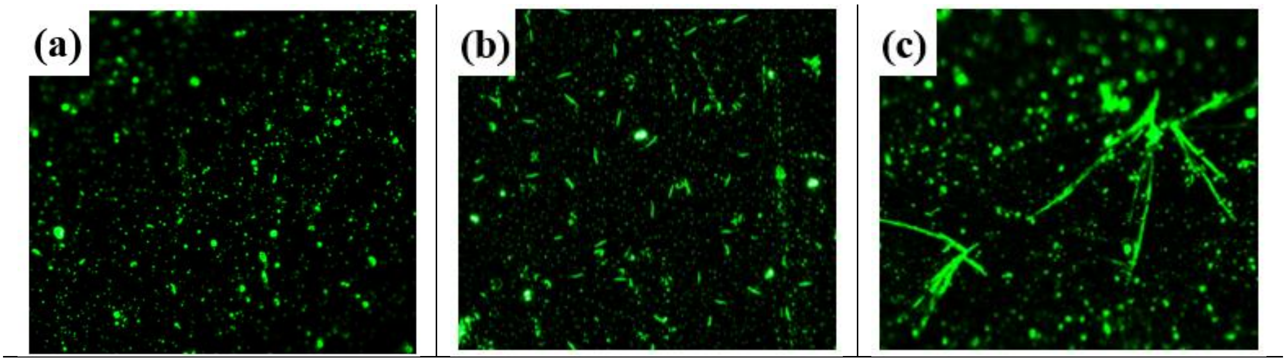


Figure (11): Fluorescence microscope diagram of asphalt slurry; (a) Fiberless asphalt mortar, (b) Modified corn stalk fiber asphalt mortar, (c) Enlarged view of fiber section

Fig. 11 (b) is the asphalt mortar with corn stalk fiber length of 6mm, dosage of 1.5% and modifier concentration of 7%. Compared with Fig.11 (a), it is found that the green fluorescence short line is evenly distributed and well dispersed. This green fluorescence short line is modified corn stalk fiber, indicating that the modified corn stalk fiber is well dispersed in asphalt mortar and has good compatibility with asphalt. Fig.11 (c) shows the enlarged fiber part of modified corn stalk fiber asphalt mortar. It can be found that the modified corn stalk fibers are obviously dispersed and overlapped with each other, which can better play a reinforcing role in the asphalt mortar and make the overall structure of the asphalt mortar more stable.

CONCLUSIONS

By conducting DSR and bending beam rheology (BBR) tests, the influence of corn stalk fiber content, fiber length, and modifier concentration on the high- and low-temperature performances of asphalt mortar was analyzed, and the following conclusions were drawn.

- The concentration of modifier has the most significant effect on the high-temperature stability of corn stalk fiber asphalt mortar. With the increase of modifier concentration, the rutting factor and creep recovery rate show a rapid growth trend, while the irreversible creep modulus is the opposite. Considering its high temperature performance, the concentration of modifier should not be less than 7%.
- Corn stalk fiber asphalt mortar's low-temperature performance is mainly influenced by the concentration of modifier. When the concentration of modifier increases, the modified corn stalk fiber asphalt mortar's stiffness modulus and creep rate increase respectively, and the performance at low temperature decreases. Considering its performance at low temperatures, the concentration of modifier should not be greater than 7%.
- When the fiber content and length increase, the unrecoverable creep compliance and stiffness modulus of corn stalk fiber asphalt mortar decrease first and then increase, whereas the creep recovery rate and creep rate are opposite. The high-temperature rheological properties of asphalt mortar are significantly improved, while the fiber content and length have little effect on the low-temperature performance of asphalt mortar. Considering the high- and low-temperature performance of asphalt mortar, the modifier concentration was determined to be 7%, the fiber length was 6mm, and the fiber content was 1.5%.
- The modified stalk fiber is incorporated into the asphalt, and no new characteristic peaks are generated. The fiber and the asphalt are mainly bonded to each other by physical interaction. Under microscopic conditions, it was observed that the modified stalk fiber was uniformly dispersed in the asphalt and played a role in increasing viscosity, toughening and reinforcing.

Conflict of Interests

The authors declared no known or potential conflict of interests with respect to the research, authorship, and publication of this article.

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