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Unraveling the influence of fibers on aging susceptibility and performance of high content polymer modified asphalt mixtures

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ABSTRACT

High-Content SBS Polymer Modified Asphalt Mixtures (HCPMA) combined with fibers have gained popularity in porous pavement construction due to their superior performance. Although the aging behavior of HCPMA has been extensively studied, the impact of fibers on performance and aging susceptibility remains unclear. This research investigates the influence of two representative fibers (lignin and polyester) on the raveling, cracking, fatigue, and rutting resistance of HCPMA before and after aging using Cantabro loss tests, SCB strength tests, SCB fatigue tests, and Hamburg Wheel-Tracking tests. The results indicate that in the original state, polyester fiber slightly enhances HCPMA performance, while lignin fiber shows limited or even adverse effects on cracking, raveling, fatigue, and rutting resistance. However, both fibers exhibit a more pronounced enhancement effect after short- and long-term aging. FTIR analysis reveals that fiber addition does not significantly impact bitumen oxidation and polymer degradation. The excellent properties of High-Content SBS Polymer Modified Bitumen (HCPMB) in the original state create a "masking" effect that conceals the enhancement effect of fibers, which becomes more evident after long-term aging. Consequently, it is recommended that the performance evaluation and design of open-graded asphalt mixtures containing HCPMB be based on post-aging performance.

1. Introduction

In the past 20 years, styrene-butadiene-styrene (SBS) was most widely used among various bitumen modifiers such as polymers, crumb rubber, chemical additives (e.g. polyphosphoric acid) and recycled vegetable/engine oils, and so forth, which is mainly due to the wide compatibility and excellent tensile strength of SBS polymer [1–5]. The most commonly used SBS modified bitumen contains around 3–4% of SBS polymer by total weight of the binder due to economic reasons. Based on the survey of Habbouche et al., the significant increase in highway traffic volume, and tire pressure axle loads have led to a demand for high-quality bitumen binder that can resist serious distress such as rutting, cracking, and raveling [6]. The wide application of open-graded friction courses and porous asphalt also raised a great demand for high-performance bitumen with both high rheological performance and long-term durability to resist aging and moisture damage [7,8].

Based on these demands, high-content SBS polymer modified bitumen (HCPMB) was developed, which contains 7–8% of SBS

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polymer by weight of the binder. With such a high amount of SBS polymer, the three-dimensional polymer network was formed in the HCPMB, which significantly improved the elasticity, high-temperature stability, and low-temperature cracking resistance of the binder [8–13]. At the mixture level, the superior performance of high-content SBS polymer modified asphalt mixture (HCPMA) has been recognized in many investigations. According to the experience in Florida, USA, the fatigue-based structural coefficient of HCPMA is 0.54, which is higher than the structure coefficient of 0.44 for conventional SBS-modified asphalt mixture [14,15]. Habbouche et al. also verified the structure coefficient (0.54) of the HCPMA coefficient with mechanistic-empirical (ME) analysis [13]. Yan et al. indicated that HCPMA exhibited better stripping, cracking, and rutting resistance compared with conventional SBS-modified asphalt mixture at different aging levels. As for fatigue performance, Molenaar et al. announced that the fatigue life of the HCPMA showed over an order of magnitude increase [16]. In his research, the CARPA 3D modeling analysis showed that the HCPMA pavement had better permanent deformation and fatigue damage resistance even with a 40% reduced pavement thickness [17]. Except for laboratory experiments, the excellent rutting, cracking and fatigue resistance of HCPMA is also validated in the field test at the NCAT test track [18].

As HCPMA contains a higher amount of SBS polymer (7–8%) and the SBS polymer is chemically active due to the unsaturated bond in polybutadiene [19], the HCPMA is vulnerable to aging. Meanwhile, due to the high viscosity of the binder, the HCPMA requires a higher mixing temperature and compaction temperature compared with conventional SBS-modified asphalt mixture [10]. According to the experience of contractors, the mixing temperature of HCPMA is usually 180–190 ℃ and the paving and compaction temperature is around 165–180 ℃ [20,21], which leads to severe short-term aging. Furthermore, HCPMA is commonly used in the open-graded friction course or porous asphalt, which withstands much more serious oxidation aging and moisture damage [22]. Thus, the aging behavior and the durability of HPCMA should be highly emphasized and thoroughly investigated.

In porous asphalt pavement, the fibers are widely employed to improve the resistance of rutting, fatigue, and drain-down [23,24]. The fiber absorbs the free-state bitumen and improves the interfacial adhesion strength. Meanwhile, fiber bridges the aggregates in the asphalt mixture and bears the reallocated stress when cracking occurs, which improves the flexibility and strength of the asphalt mixture [25]. The addition of fiber can also decrease the moisture sensitivity of porous asphalt mixture and decrease the possibility of fatigue and reflective cracking [26]. Furthermore, fibers also increase the optimal bitumen content and air void in asphalt mixture design [27]. In pavement construction, fibers can be classified as synthetic fibers, such as polyester, nylon, and spandex fibers; biological fibers, such as lignin, cotton, jute, and ramie fibers; and inorganic fibers, such as basalt, steel, copper, carbon, glass and silica fibers. Among them, polyester fiber (produced from crude oil) and lignin fiber (produced from natural plants) are the most widely applied in producing durable and high-performance porous asphalt. Putman et al. found that polyester fiber brought more significant improvements in the Stone Mastic Asphalt (SMA) mixture toughness than lignin fiber [28]. It was explained that polyester fiber had better capability in withstanding the stress when cracks occurred during the loading. Abtahi et al. evaluated the influence of different fibers on the performance of OGFC mixtures. The test results supported the idea that lignin fiber could absorb moisture from rain, which led to premature failure [29]. Wu et al. incorporated lignin fiber in reclaimed asphalt mixture[30,31] and found that the addition of lignin fiber improved the rutting resistance, moisture susceptibility, cracking resistance, and durability. From the scanning electron micrographic observation, the bitumen was reinforced by lignin fiber in a 3D structure, which reduces the possibility of the drain-down problem of the bitumen-fiber mastic system [32].

Fibers require more bitumen binders to wrap onto their surface due to higher specific surface area and absorbance of the light component of the bitumen binder [33–35]. In particular, lignin fiber has a loose structure and larger specific surface area, which absorbs a high amount of bitumen binder. However, in the design specification of porous asphalt mixture (ASTM D7064 and NEN 13108–7), the bitumen binder content is mainly determined based on the gradation of the aggregate, and the influence of fiber is not adequately considered. Thus, based on current porous asphalt design specifications, the addition of fibers leads to a variance in bitumen film thickness. Meanwhile, the interaction between the fiber, filler and the bitumen binder mastic system will also influence the diffusion of oxygen and the aging behavior of the asphalt mixture. The long-term performance of porous asphalt pavement is of great significance. However, the influence of fiber on the aging susceptibility of porous asphalt mixture is still not clearly understood.

2. Objective

In this research, the influence of two representative fibers (i.e., lignin fiber and polyester fiber) on the aging susceptibility of HCPMA will be investigated, and the main objectives are:

(1) To evaluate the performance reinforcement effect of lignin- and polyester-fiber on HCPMA.
(2) To evaluate the effect of lignin- and polyester-fiber on the aging susceptibility of HCPMA based on: raveling, cracking and rutting resistance performance.
(3) To gain insight into the influence of lignin- and polyester-fiber on the aging behavior of HCPMA.

3. Materials and methods

3.1. Bitumen and aggregate

In this investigation, a 7.5% linear SBS polymer modified bitumen was used as a representative of high content polymer modified bitumen(HCPMB). The HCPMB was prepared with a shearing machine and a blending machine in the laboratory. The detailed preparation process of HCPMB is described in the previous study, and the preparation process schematic can be seen in Fig. 1[9]. After preparation, the conventional and rheological properties of HCPMB were characterized, and the results are presented in Table 1.

To evaluate the influence of fibers on the performance and aging behaviors of the HCPMA, the lignin fiber, polyester fiber, basalt aggregates, and limestone filler were used to prepare the mixture specimens. The pictorial view of the fibers can be seen in Fig. 2. The physical and mechanical properties of the fibers can be seen in Table 2 and the basic properties of the basalt aggregate and limestone filler can be seen in Table 3.

3.2. Mixture design and preparation

As HCPMA is mainly used in the drainage wearing course, the typical Open-graded Friction Course with 13 mm nominal maximum aggregate sizes (OGFC-13) was investigated in this research. The selected typical OGFC-13 gradation can be seen in Table 3. The air void of HCPMA was controlled at 20%, and the binder content was designed at 4.1% based on ASTM D7064. In order to investigate the influence of fibers on the aging characteristic of the HCPMA, 0.15% of fiber was added to the HCPMA during the mixing process.

In this research, both short-term aging and long-term aging were conducted following the AASHTO R30. The blended loose mixture was placed on a steel pan covered with aluminum foil to prevent the asphalt mixture from sticking to the pan, and the thickness of the asphalt mixture was less than 1 in. (25.4 mm) to ensure the degree and uniformity of aging (Fig. 3). The standard short-term aging temperature of 135 ℃ was not used in this study because it is much lower than the mixing and transport temperature of HCPMA and does not reflect the actual conditions in the field. In this research, the short-term aging was conducted at the compaction temperature of HCPMA (163 ℃) for 2 h to simulate the aging process during the mixing, transportation, and paving stages [36,37]. The mixture was stirred every 60 min to maintain uniformity of aging during this aging process.

Meanwhile, the long-term aging was also conducted according to AASHTO R30 to simulate the aging of HCPMA in the field. After short-term aging, the loose HCPMA was compacted with Superpave Gyratory Compactor (SGC). After cooling down to the environmental temperature, the compacted HCPMA specimens were placed in the oven at a temperature of 85 ℃ for 120 h to simulate the long-term aging of 7–10 years in the filed. The HCPMA specimens were then cooled to environmental temperature for 16 h, and then the long-term aged specimens were prepared for the following tests.

3.3. Test methods

3.3.1. Cantabro loss test

In order to evaluate the raveling resistance of the HCPMA, the Cantabro Loss test was applied in this research. Following the standard of AASHTO TP 108–14, a cylindrical asphalt mixture specimen with a 101.6 mm diameter and a 63.5 mm height was prepared with SGC. It should be noted that specimens prepared with a Marshall hammer were used for the Cantabro Loss test at the beginning. However, after comparing the SGC specimens with the Marshall specimens, it was found that the test variance of SGC specimens is much smaller. Thus, the SGC specimens were selected for the Cantabro Loss test. After preparation, the mixture specimens were cured in a 25 ℃ bath for 20 h and then placed into the Los Angeles abrasion machine. The machine was rotated for 300 revolutions at a speed of 30 rpm at 25 ℃. The percentage of mass loss was calculated to represent the raveling of the asphalt mixture. For each type of mixture, four replicates were conducted.

3.3.2. Semi-circular bending (SCB) strength test

The evaluation of the HCPMA's resistance to cracking was conducted utilizing the SCB strength test, in compliance with AASHTO TP124 guidelines. Subsequent analysis was carried out by leveraging established studies as reference points [38]. Adhering to the methods described in prior research and preparatory practices, cylindrical specimens were shaped using the Superpave Gyratory Compactor, each possessing a height of 135 mm and a diameter of 150 mm. The cylindrical specimen was then sectioned into four semi-circular samples, each with dimensions of 50 mm in height and 150 mm in diameter. A notch was carved into the central bottom of the specimen, measuring 15 mm in length and 1.5 mm in width, thus ensuring the cracking mode. Prior to testing, the mixture specimen underwent a pre-conditioning process in a chamber set at 25 ℃ for a minimum of four hours. The SCB strength test was

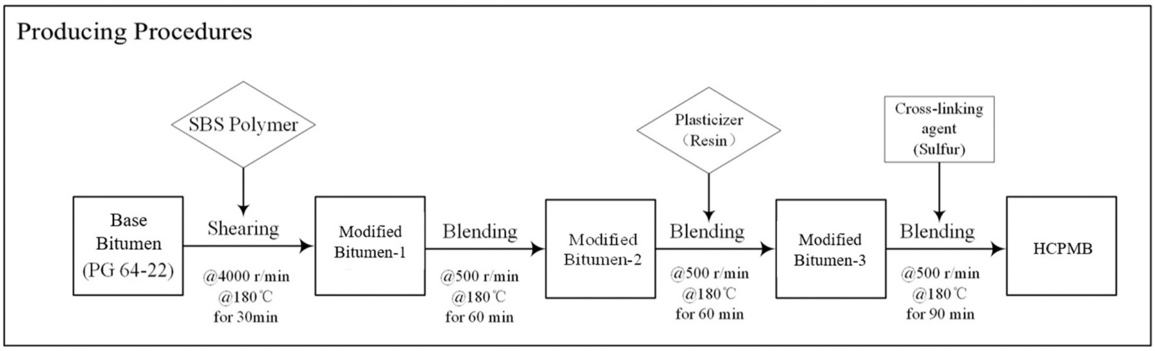


Fig. 1. Preparation Process of HCPMB[9].

Table 1
Conventional and rheological properties of HCPMB.

Parameters	HCPMB
SBS Content	7.50%
Penetration at 25 ℃, 0.1 mm	41
Softening point, ℃	> 100
Ductility at 5 ℃, cm	44.1
135 ℃, Viscosity, Pa·S	5.72
70 ℃ Complex modulus, Pa	5281
70 ℃ Phase angle, °	48
70 ℃ Jnr3.2, kPa^{-1}	0.011
70 ℃ R3.2, %	98.8

Fig. 2. View of lignin fiber and polyester fiber.

Table 2
Physical and mechanical parameters of fibers.

Parameters	Lignin Fiber	Polyester Fiber
Fiber length(mm)	0.8	6
Fiber diameter(μm)	8	20 ± 5
Density(g/cm3)	0.91	1.36
Tensile strength(MPa)	300	≥ 500
Young's modulus (GPa)	30	13.5
Melting point(℃)	260	260
Ignition point(℃)	470	554

Table 3
Aggregate properties and percentage passing of the OGFC-13 gradation.

Sieve size (mm)	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	99.9	92.6	66.3	18.7	13	10.7	9	7.8	7.3	6.9
Combined Bulk Specific Gravity			2.853			Fractured 1 Face (%)			99.2		
Flat & Elongated Particles (%)			10.2			Fractured 2 Face (%)			98.7		
Fine Aggregate Angularity (%)			55.8			Water Absorption (%)			1.213		
LA Abrasion (%)			10.7			Sand Equivalent (%)			72		

subsequently executed at a displacement rate of 50 mm/min and at 25 ℃. Utilizing the force-displacement curve, tensile strength (σ_{max}) and fracture energy (G_f) were computed through the subsequent equations[38].

Tensile strength (σ_{max}) describes the strength of the asphalt mixture, which is calculated with the following Equation:

$$\sigma_{max} = \frac{4.263 \times F_{max}}{D \times t} \quad (1)$$

Where: Fmax is the maximum force in N, D is the diameter of the specimen in mm, and t is the thickness of the specimen in mm. The

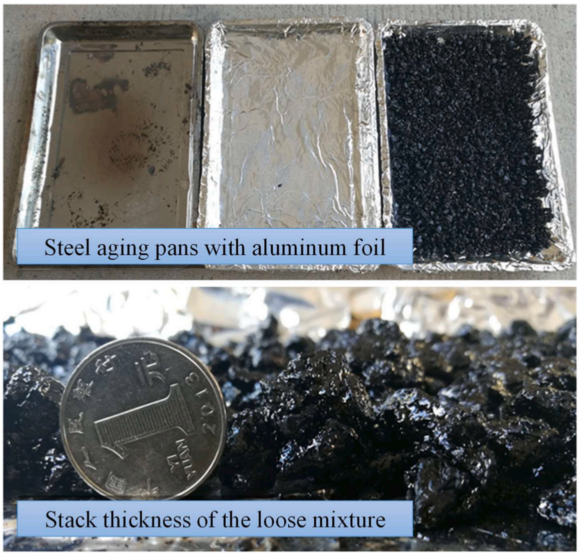


Fig. 3. Schematic diagram of the aging pan and loose HCPMA.

constant 4.263 is derived from the research conducted by Van de Ven et al. [38] with a 3D finite element analysis assuming that the support span is 80% specimen diameter.

Fracture energy (G_f) describes the amount of energy consumed to generate cracks per unit area, as illustrated in Fig. 4, which can be calculated with the following Equation:

$$G_f = \frac{W_f}{A_{lig}} \tag{2}$$

Where W_f (fracture work) is defined as the work done to perform the fracture process, which can be calculated as the area of a force-displacement curve. A_{lig} is the ligament area, calculated as follows:

$$A_{lig} = (W - a) \times T \tag{3}$$

Where W is the height of the specimen in mm, a is the depth of the notch of the specimen in mm, and T is the thickness of the specimen in mm.

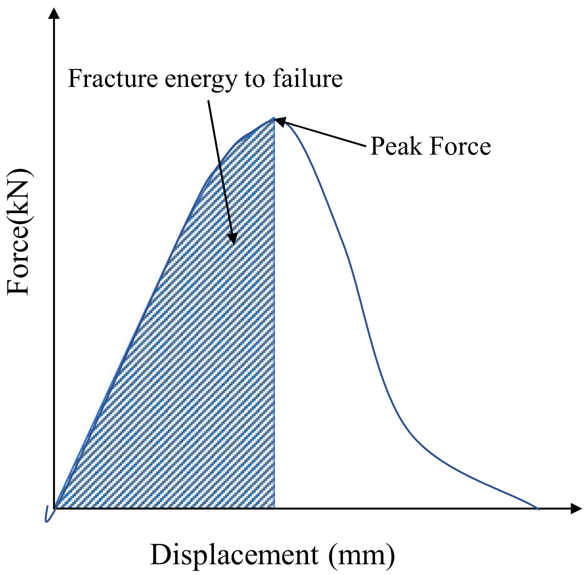


Fig. 4. Fracture energy to failure and fracture energy in the force-displacement curve.

3.3.3. Semi-circular bending (SCB) fatigue test

The fatigue resistance of the HCPMA was evaluated with the SCB fatigue test. According to the literature, the stress control SCB fatigue test is widely used and in this research, four stress amplitudes (stress ratio (σ_{ratio}) of 0.3, 0.4, 0.5, and 0.6) were selected and applied in SCB fatigue tests [40–42]. In this study, the stress level is defined as the ratio of stress amplitude to the tensile strength of the specimen [40]. Before the SCB fatigue test, four replicates were SCB strength test was conducted to obtain their tensile strengths at 15 °C. When the tensile strength was obtained, the stress amplitudes can be calculated with selected stress ratios (0.3, 0.4, 0.5, and 0.6) and applied for SCB applied to the SCB fatigue test. The frequency of the repeated compressive load is 10 Hz, consisting of 0.1 s half-sin load and no rest period under different stress levels. Four replicates of SCB fatigue tests were conducted at 15 °C for each type of HCPMA at each stress level.

3.3.4. Hamburg wheel track (HWT)test

The rutting resistance of the HCPMA was assessed with the HWT test. The HWT test was conducted with a Double Wheel Track device at 60 °C in moisture conditions according to the AASHTO T324–11. Two cylindrical specimens with 150 mm diameter and 62 mm height were loaded in the HWT device as one test sample. The HCPMA specimens were subjected to steel wheels rolling at a speed of 52 passes/min, and a Linear Variable Differential Transformer (LVDT) was utilized to record the relative vertical deformation of the specimens. The test terminates either when the vertical deformation reaches 20 mm, or the specimen experiences 20,000 passes of loads. After the HWT test, a rutting depth-load number curve was generated for each test. The rutting resistance can be characterized by the slope of the creeping stage, and the stripping resistance can be characterized by the slope of the stripping stage. It should be noted that the strip stage is considered only when the slope of the strip stage is twice as much as the creep slope. Two replicates were conducted for each type of HCPMA.

3.3.5. Attenuated Total Reflection (ATR) Fourier Transform Infrared (FT-IR) spectroscopy

In order to characterize the aging degree of bitumen binder extracted from the asphalt mixture, an FT-IR spectrometer equipped with a reflection diamond ATR accessory was used to collect the infrared spectra of the extracted bitumen. In this research, carbonyl, sulfoxide, and trans-polybutadiene functional groups were used to characterize the oxidation of the bitumen and the degradation of SBS polymer [43,44]. In order to semi-quantify the IR absorption peaks, the area of functional peaks was normalized to the total sum of bands areas ($\sum AR_{\tilde{v}}$). The definition of the IR indices are as follows:

$$Carbonylindex: I_{C=O} = AR_{1700} \Big/ \sum AR_{\tilde{v}} \tag{4}$$

$$PolybutadieneIndex: I_{PB} = AR_{965} \Big/ \sum AR_{\tilde{v}} \tag{5}$$

$$SulfoxideIndex: I_{PS} = AR_{1030} \Big/ \sum AR_{\tilde{v}} \tag{6}$$

$$\sum AR_{\tilde{v}} = AR_{1700} + AR_{1600} + AR_{1460} + AR_{1310} + AR_{1030} + AR_{965} + AR_{864} + AR_{814} + AR_{743} + AR_{725} + AR_{700} \tag{7}$$

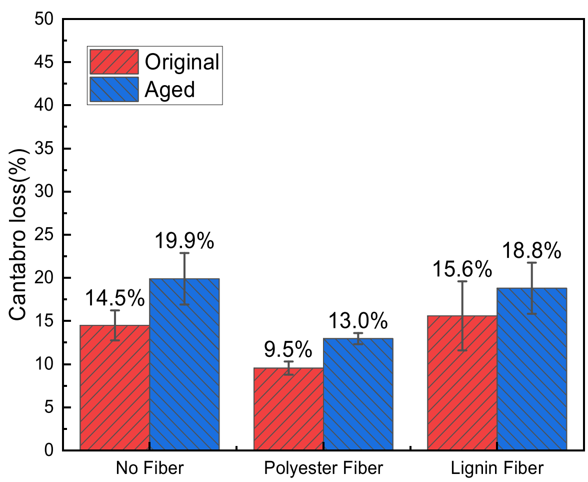


Fig. 5. Influence of fiber on the raveling resistance before and after aging.

4. Results and discussion

4.1. Cantabro loss test results analysis

Fibers can be applied in porous asphalt mixes to absorb asphalt binder in its free state, thus preventing the problem of bitumen binder leakage and improving the interfacial adhesion properties between the asphalt binder and the aggregates. In order to characterize the influence of fibers on the raveling resistance of HCPMAs before and after aging, the Cantabro loss tests were conducted, and the results can be seen in Fig. 5.

In the original state, the addition of polyester fiber resulted in a 5.0% decrease in the Catabro loss ratio, while the addition of lignin fiber led to a 1.1% increase in the Cantabro loss ratio. The addition of polyester mainly plays a role in the mechanical reinforcement due to the network effect, which leads to a decrease in the Cantabro loss ratio [45–47]. While the lignin fiber mainly plays a role in absorbing the bitumen in the free state, the reinforcement effect is very limited [48,49]. In this research, the bitumen content in the HCPMA was 4.1%, and the absorbance of bitumen due to the addition of lignin fiber resulted in a slight decrease in raveling resistance.

After long-term aging, the Cantabro loss ratio of HCPMA without fiber increased by 5.4%. However, the Cantabro loss ratio of the HCPMA with polyester and lignin fiber only increased by 3.5% and 3.2%, respectively. This indicates that adding fibers reduced the aging susceptibility of HCPMA, or that adding lignin and polyester fibers provided a more pronounced strengthening effect.

4.2. SCB strength test results analysis

To investigate the influence of fiber on the cracking resistance of HCPMA before and after aging, the SCB tests were conducted on the HCPMA specimens enhanced with fibers. The tensile strength and fracture energy results of HCPMA specimens before and after aging in the SCB test can be seen in Fig. 6 and Fig. 7, respectively.

As illustrated in Fig. 6, the addition of polyester and lignin fibers improved 525.2 kPa and 155.0 kPa of tensile strength in the SCB test, respectively, which supported the perspective that polyester shows advantages in mechanical properties reinforcement [50,51]. After short- and long-term aging, the tensile strength of HCPMA without fiber increased by 109.1 kPa, which may be due to the increase in stiffness of the binder during the aging process. The tensile strength of HCPMA specimens with polyester and lignin fibers decreased by 280.3 kPa and 55.5 kPa, respectively. However, the tensile strength of HCPMA containing polyester fibers was still higher than that of HCPMA without fibers and those containing lignin fibers. It demonstrated that the addition of polyester fiber still shows advantages in tensile strength even after aging.

The fracture energy is also an important parameter to characterize the cracking resistance of the asphalt mixture in the SCB test. The fracture energy can be calculated according to Eq. (2) and Eq. (3), and the fracture energy results can be seen in Fig. 7.

In the original state, adding polyester fiber led to a 7.5% increase in fracture energy, and adding lignin fiber led to a 6.1% decrease in fracture energy. The decrease in fracture energy of specimens with lignin fiber may be due to the bitumen absorption by lignin fiber and a decrease in bitumen film thickness. In the aged state, the fracture energy of HCPMA specimens with polyester fiber and lignin fiber is 47.0% and 12.3% higher than that of HCPMA with no fiber. The reason may be that the HCPMA specimen has a skeleton-gap structure and contains a high amount of coarse aggregates. The tensile strength and fracture energy mainly depend on the mastic adhesion properties, consisting of the HCPMB and filler. Due to the excellent rheological and mechanical properties of HCPMB in the original state, the HCPMA exhibited good raveling resistance and cracking resistance, and the mechanical enhancement of the polyester fiber can not be shown clearly. However, after short- and long-term aging, the polymer network in the HCPMB was destroyed, and the raveling and cracking resistance of HCPMA decreased significantly [20,21]. The HPCMA containing polyester fiber demonstrated much better raveling and cracking resistance due to the enhancement effect of polyester fiber. Thus, the performance evaluation of HCPMA enhanced with fiber should be conducted after long-term aging.

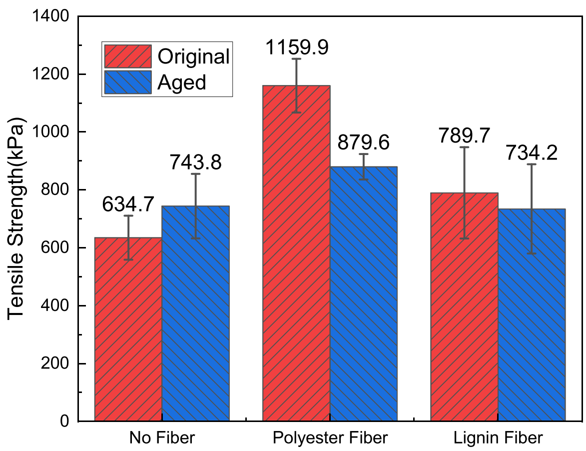


Fig. 6. Effect of fibers on tensile strength before and after aging in SCB tests.

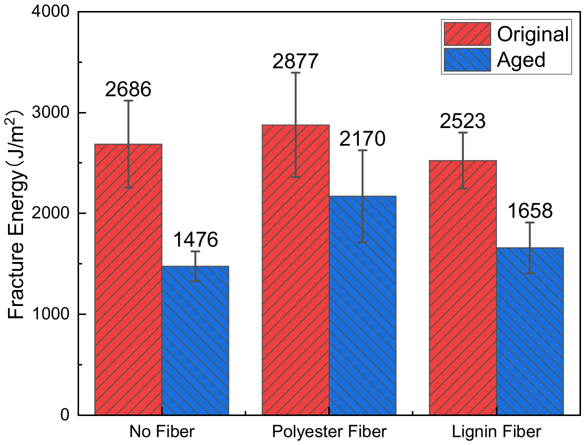


Fig. 7. Effect of fibers on fracture energy before and after aging in SCB tests.

4.3. *SCB Fatigue test results analysis*

The addition of fiber in the open-grade asphalt mixture can potentially improve the fatigue performance of the porous asphalt mixture [50,51]. In the research, SCB fatigue tests were conducted to determine the influence of fiber on the fatigue performance of HCPMA before and after aging, and the results can be seen in Fig. 8.

As demonstrated in Fig. 8, the addition of polyester fiber led to an increase in fatigue life, especially at the high-stress ratio, while the addition of lignin fiber led to a decrease in fatigue life. The addition of fibers has two effects: on the one hand, the fibers enhance the mechanical properties of the HCPMA. On the other hand, adding fibers reduces the bitumen film thickness, which leads to a decrease in

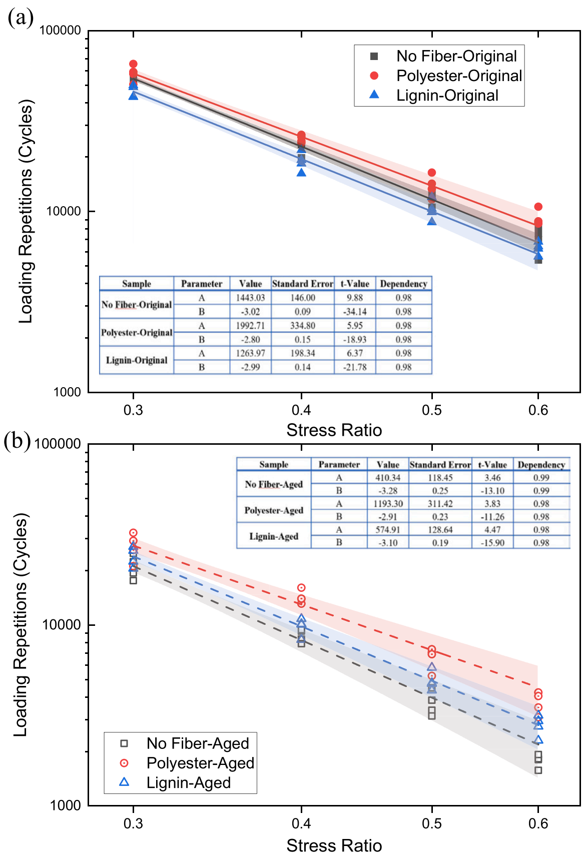


Fig. 8. Effect of fibers on fatigue life before and after aging in SCB fatigue tests.

the fatigue resistance of the HCPMA. The lignin fiber absorbs more bitumen and has a limited mechanical enhancement effect, which reduces fatigue resistance.

After short- and long-term aging, the fatigue resistance of HCPMA specimens without fiber decreased much more than that of HCPMA containing polyester or lignin fiber, which is consistent with the raveling and cracking resistance results. It indicates that adding polyester and lignin fiber decreased the aging susceptibility of the HCPMA. The reinforcement effect of polyester and lignin fibers was much more evident after aging.

To further analyze the SCB fatigue results, a function can be utilized to describe the relationship between the fatigue life and the stress ratio. The literature shows a linear relationship between stress ratio and fatigue life in double logarithmic coordinates [40,42]. Thus, the fatigue life can be described with Eq. (8) and Eq. (9). The expression between $\lg(N_f)$ and $\lg(\sigma_{ratio})$is a simple linear relationship. Based on the SCB fatigue results, the least squares equation can be obtained, and then the parameters A and B are determined correspondingly.

$$N_f = A(\sigma_{ratio})^B \tag{8}$$

$$\lg(N_f) = \lg A + B \times \lg(\sigma_{ratio}) \tag{9}$$

Where N_f is the fatigue life in the SCB fatigue test;.

σ_{ratio} is the stress ratio, which is the ratio between the loading stress in the SCB fatigue test and the peak stress in the SCB strength test;.

A is a regression parameter that describes the fatigue life of the specimen;.

B is a regression parameter that describes the stress sensitivity of the specimen.

After regression analysis of the SCB fatigue results, the parameters A and B of each HCPMA specimen were determined and demonstrated in Fig. 9 and Fig. 10. As shown in Fig. 9, adding polyester fiber resulted in a 38.1% increase in fatigue parameter A while adding lignin fiber led to a 12.4% decrease in fatigue parameter A. According to previous literature, the polyester fiber can form the three-directional network reinforcement that could stabilize the asphalt binders at high temperatures, resist the cracking propagation, prevent aggregate–asphalt interface sliding, reduce stress concentration, and improve the fatigue resistance of asphalt mixture [32, 46]. However, the improvement of lignin fiber in mechanical performance is limited [52,53].

After short- and long-term aging, the fatigue parameter A of HCPMA without fiber is reduced by 71.5%, indicating aging led to a severe decrease in fatigue resistance of the HCPMA. However, the aging process only resulted in a decrease of 40.1% and 54.5% in the fatigue parameter A for HCPMA with polyester and lignin fibers, respectively. In terms of fatigue parameter A, the addition of lignin and polyester fiber exhibited an advantage in aging resistance.

From the literature, fatigue parameter B indicates the stress sensitivity of the asphalt mixture, and lower fatigue parameter B indicates a higher stress sensitivity [40,42]. Fig. 10 showed that HCPMA with polyester fiber and HCPMA with lignin fiber were less stress sensitive than HCPMA without fiber, indicating that fibers have the function of decreasing the stress sensitivity during the fatigue test.

After aging, the fatigue parameter B of HCPMA without fiber decreased significantly, indicating the HCPMA specimens were more sensitive to stress after aging. It may be due to the increased stiffness of the HCPMB after aging. Meanwhile, the addition of polyester and lignin fibers still showed the function of decreasing stress sensitivity after aging.

4.4. HWT test results analysis

In order to investigate the influence of fiber on the rutting resistance of HCPMA before and after aging, the HWT test was conducted in water conditions at 60 ℃. The HWT loading-rutting depth curve and calculated creep slope of HCPMA specimens can be seen in

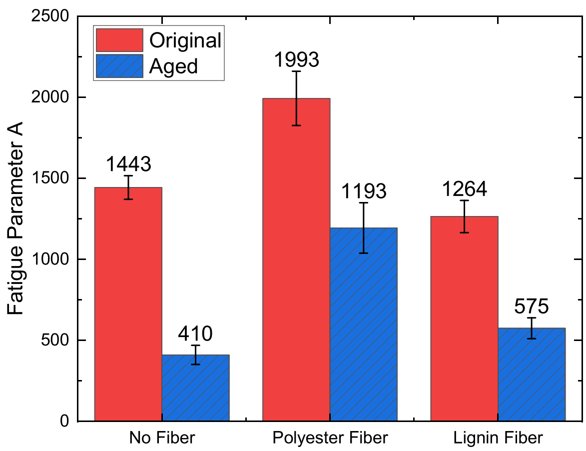


Fig. 9. Effect of fibers on fatigue parameter A before and after aging in SCB fatigue tests.

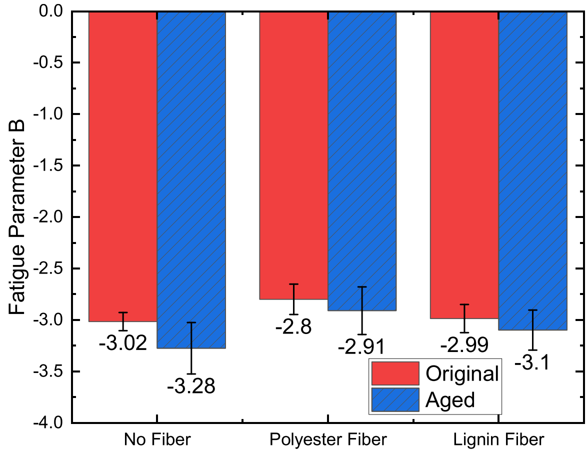
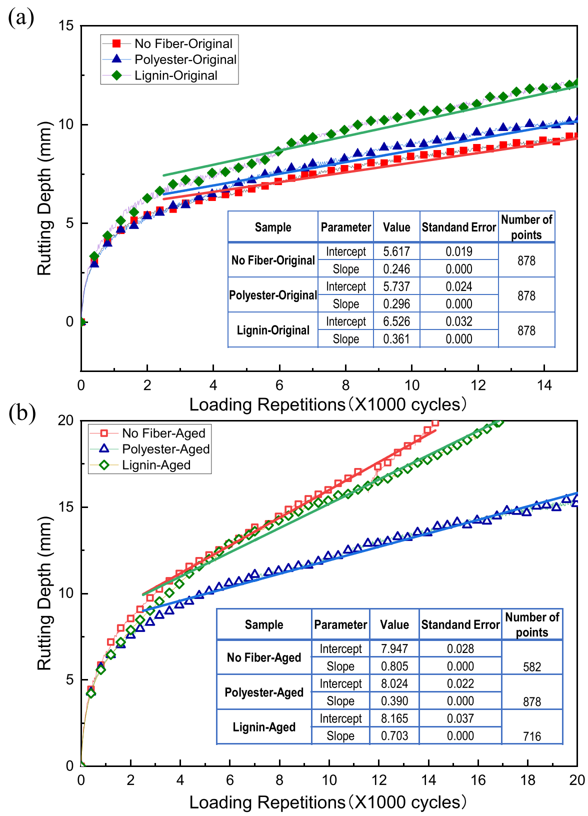


Fig. 10. Effect of fibers on fatigue parameter A before and after aging in SCB fatigue tests.



Sample	Parameter	Value	Standand Error	Number of points
No Fiber-Original	Intercept	5.617	0.019	878
	Slope	0.246	0.000	
Polyester-Original	Intercept	5.737	0.024	878
	Slope	0.296	0.000	
Lignin-Original	Intercept	6.526	0.032	878
	Slope	0.361	0.000	

Sample	Parameter	Value	Standand Error	Number of points
No Fiber-Aged	Intercept	7.947	0.028	
	Slope	0.805	0.000	582
Polyester-Aged	Intercept	8.024	0.022	
	Slope	0.390	0.000	878
Lignin-Aged	Intercept	8.165	0.037	
	Slope	0.703	0.000	716

Fig. 11. Effect of fibers on HWT testing curve before and after aging.

Fig. 11.

The HCPMA specimens only showed the significant post-compaction and creeping stages in the original state, without the significant stripping stage. The rutting depth and creep slope of the HCPMA with polyester fiber and HCPMA without fiber were close, which showed a slight advantage compared with that of HCPMA containing lignin fiber. This indicates that the addition of fibers has limited or even a slightly negative effect on the improvement of the rutting resistance of HCPMA.

After aging, the HCPMA specimens also did not show a distinct stripe phase, as the slope did not reach twice the slope of the creep phase. It indicated that HCPMA specimens did not demonstrate a severe problem in stripping resistance in moisture conditions even after long-term aging. The rutting depth of HCPMA without fiber and HCPMA with lignin fiber reached 20 mm (rutting limitation) at 14,200 cycles and 16,500 cycles, respectively. Meanwhile, their creep slope also increased to 0.805 and 0.703, respectively. However, the rutting depth and creep slope of the HCPMA with polyester fiber did not increase significantly after aging. It indicated that even when the rheological and mechanical properties of high content polymer modified bitumen deteriorated severely after long-term aging, the polyester fiber exhibited a performance enhancement effect and helped maintain the rutting resistance of the HCPMA.

Creep slope is the constant rate of increase in rut depth with the load cycle, which can be used to characterize the deformation that occurs primarily due to the viscous flow of the asphalt mixtures. In this research, the slope of the HCPMA specimen was calculated based on the creeping stage in the HWT testing curve, and the results can be seen in Fig. 12. Before aging, the creep slope of HCPMA without fiber was slightly lower than that of HCPMA with polyester fiber and lignin fiber, indicating that adding fibers has a slightly adverse effect on the rutting resistance.

After short- and long-term aging, the creep slope of HCPMA without fiber increased by 327.2%. Because of the severe deterioration of the SBS polymer network in HCPMB during the aging process, the rutting resistance of HCPMA decreased significantly. On the contrary, the creep slope of HCPMA with lignin fiber and HCPMA with polyester fiber increased by 31.7% and 94.7%, respectively. It indicates that adding lignin and polyester fibers positively affected aging resistance and significantly improved the rutting resistance of HCPMA after aging.

4.5. Comprehensive analysis of the influence of fiber on HCPMA

In order to comprehensively and quantitively analyze the influence of the fiber on the performance and aging behavior of HCPMA, the performance index (PI) and aging index (AI)were defined as Eq. (5) and Eq. (6).

$$\textbf{Performance Index} = \textbf{Parameter}_{(\textbf{with fiber})} \Big/ \textbf{Parameter}_{(\textbf{without fiber})} \times \textbf{\textit{100\%}} \quad (10)$$

$$\textbf{Aging Index} = \textbf{Parameter}_{(\textbf{Aged})} \Big/ \textbf{Parameter}_{(\textbf{Original})} \times \textbf{\textit{100\%}} \quad (11)$$

To comprehensively evaluate the influence of fiber on performance before and after aging, the performance indices of different performance characterization parameters were calculated and demonstrated in Fig. 13. When the PI of fracture energy, tensile strength, and fatigue parameter A(fatigue-life factor) is above 100%, and when the PI of Cantabro loss, fatigue parameter B (stress-sensitivity factor), and creep slope is below 100%, it indicates the addition of fiber had a positive effect on the performance of the HCPMA.

In the original state, the addition of polyester fiber had a positive effect on the tensile strength, fatigue parameters, and raveling resistance, while it had a slight adverse effect on the SCB fracture energy and creeping slope. The addition of lignin fiber had a slight positive effect on the tensile strength and a slight adverse effect on rutting and raveling resistance. These PI results supported the view that the addition of fibers had a very limited improvement or even adverse effect on mechanical performance in the original state.

After aging, adding polyester fiber had more significant positive effects on the PI of all the performance parameters, especially the fatigue parameter A. It indicates that the mechanical enhancement of the polyester fiber is more obvious after long-term aging. However, the addition of lignin fiber also exhibited a slight positive effect on cracking, raveling, and fatigue resistance. It revealed the enhancement of the polyester and lignin fibers mainly after long-term aging.

As illustrated in Fig. 14, when the AI of SCB fracture energy, SCB tensile strength, and fatigue parameter A (fatigue-life factor) is high, and when the AI of Cantabro loss, fatigue parameter B (stress-sensitivity factor), and creep slope are low, it indicated the HCPMA specimen had better aging resistance.

From the cracking resistance aspect, adding the polyester and lignin fiber showed a positive effect on fracture energy and a negative

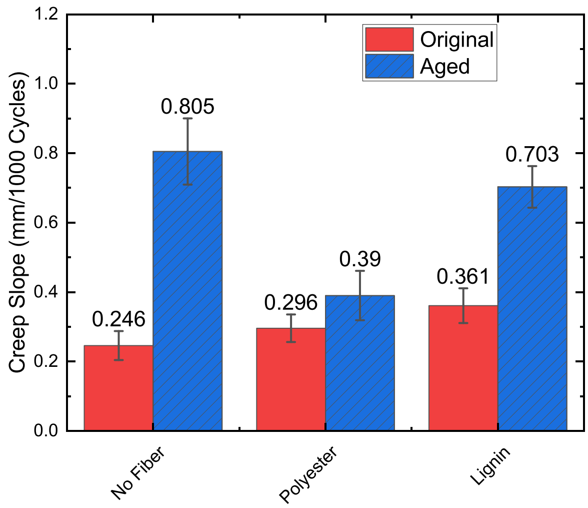


Fig. 12. Effect of fibers on creep slope before and after aging in HWT test.

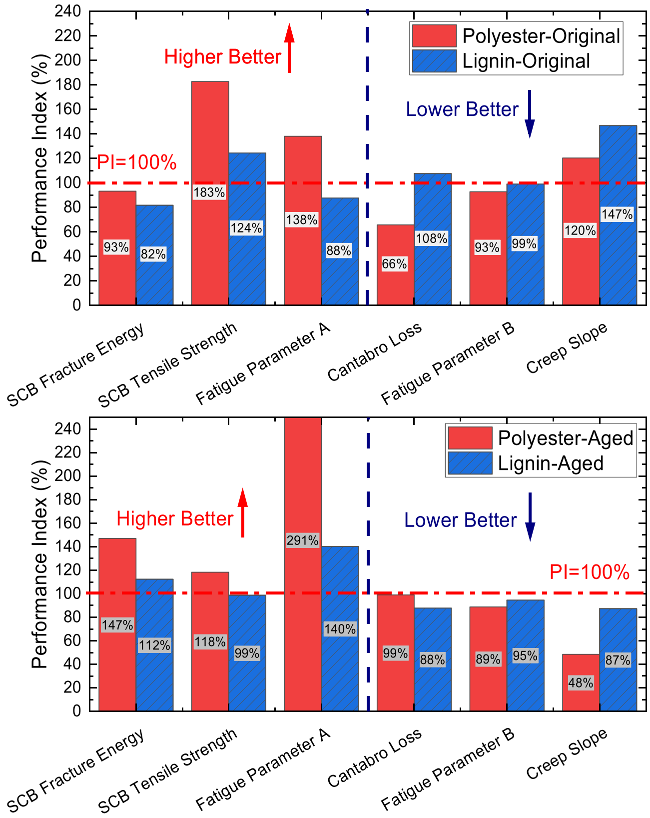


Fig. 13. Performance indices of different performance characterization parameters.

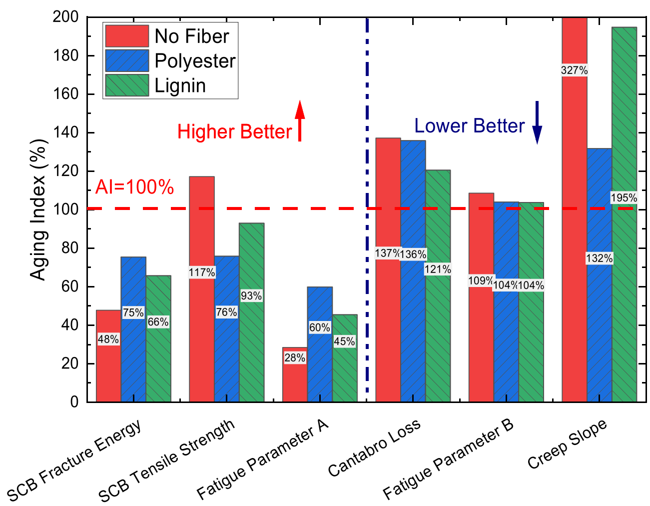


Fig. 14. Aging indices of different performance characterization parameters.

effect on tensile strength in the SCB test. The fracture energy indicates the work done for performing the fracture process, which is more representative of characterizing the cracking resistance of the asphalt mixture [39]. Thus, in terms of cracking resistance, the addition of lignin and polyester fiber had a positive effect on the aging resistance. Meanwhile, adding polyester and lignin fiber positively affected fatigue parameters A and B, which indicated that adding fiber had a positive effect on fatigue performance. As for the raveling and rutting resistance, the addition of lignin fiber and polyester fiber showed a positive impact on aging behavior. Especially in the creep slope in the HWT test, the addition of fibers significantly increased the rutting resistance after long-term aging. In summary, the addition of polyester and lignin fibers decreased the aging sensitivity of the HCPMA in terms of cracking, fatigue, and

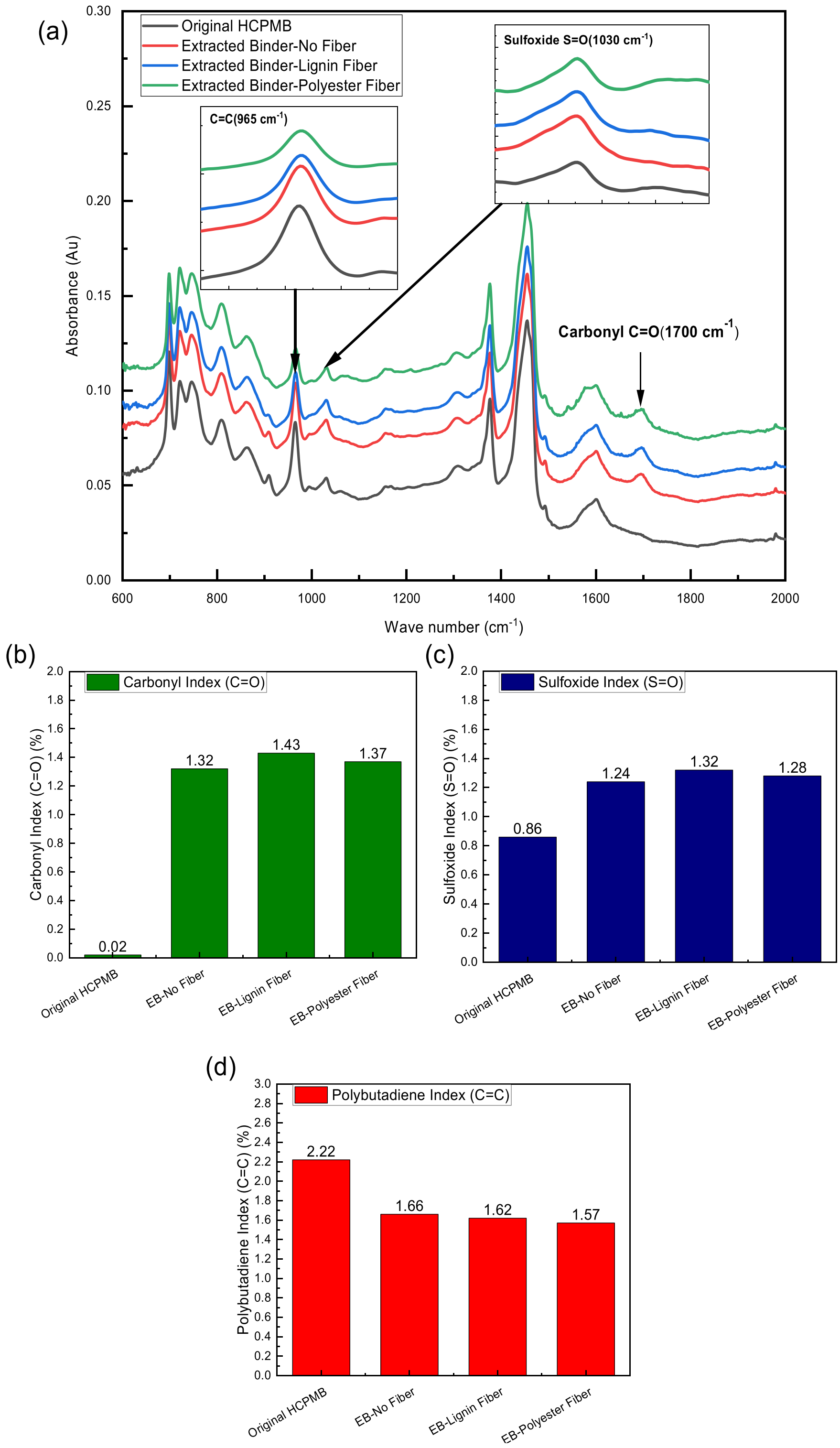


Fig. 15. FTIR results and indices of HCPMB: (a) FTIR spectrum of HCPMB binders, (b) carbonyl index, (c) sulfoxide index and (d) trans-polybutadiene index.

raveling resistance.

4.6. Chemical characterization of extracted bitumen binder

From the comprehensive evaluation of the asphalt mixture performance from the raveling, cracking, fatigue and rutting resistance, adding polyester and lignin fiber demonstrated very limited enhancement in the original state but a much more significant improvement for HCPMA after long-term aging. There are two possible hypotheses to explain these phenomena. One is that the addition of fiber decreased the aging degree of the bitumen binder. Another explanation is that the HCPMB has excellent cohesion and elastic properties, which showed a "masking" effect on the enhancement of the polyester and lignin fiber. After short- and long-term aging, the SBS polymer network in the HCPMB was severely destroyed, and the "masking" effect disappeared. In this way, the enhancement of the fibers is more pronounced, which significantly improves the raveling, cracking, fatigue, and rutting resistance.

In order to distinguish which hypothesis is correct, the bitumen binders from HCPMA specimens were extracted and recovered according to AASHTO T164 with trichloroethylene as the solvent. Extracted binders (EB) from HCPMA specimens without fiber, lignin fiber, and polyester fiber were labeled EB-No Fiber, EB-Lignin, and EB-Polyester Fiber, respectively. Afterward, the extracted and original HCPMB binders were characterized with FTIR to distinguish the aging degree of each binder. The results can be seen in Fig. 15.

As demonstrated in Fig. 14 (a), compared HCPMB in the original state, the functional group peak of trans-polybutadiene (965 cm^{-1}) of EB-No Fiber, EB-Lignin Fiber and EB-Polyester Fiber decreased significantly, which indicated the severe degradation of SBS polymer. Meanwhile, it can also be seen that area of the sulfoxide peak (1030 cm^{-1}) and carbonyl peak (1700 cm^{-1}) increased significantly during the aging, indicating the oxidation of the bitumen in HCPMB. To further quantitative analysis the aging degree of the extracted bitumen binder, carbonyl, sulfoxide and polybutadiene indices were calculated and demonstrated in Fig. 15 (b), (c) and (d). It was found that there was no significant difference in the oxidation of the bitumen phase and degradation of the polymer phase among the EB-No Fiber, EB-Lignin, and EB-Polyester Fiber. It indicates that the addition of fibers doesn't have a significant influence on the oxidation of bitumen and degradation of polymer for HCPMA.

Based on this observation, it can be inferred that hypothesis one is incorrect. The reason why specimens with fiber demonstrated more obvious performance enhancement after aging is not due to the anti-aging effect of adding fibers. The disappearance of the "masking" effect could partially explain this phenomenon. However, full proof of this hypothesis still requires further evidence and research. Due to the noticeable decrease in mechanical properties, it is strongly recommended that the performance evaluation and design of porous asphalt mixtures containing HCPMB should be based on the performance after aging.

5. Conclusion and recommendation

This research aims to evaluate the influence of lignin fiber and polyester fiber on the performance of HCPMA before and after aging. The raveling, cracking, fatigue and rutting resistance of HCPMA were evaluated with the Cantabro loss test, SCB strength test, SCB fatigue test, and HWT test, respectively. Based on the test results, the following conclusions can be drawn:

(1) In the original state, the addition of polyester fiber showed a slight enhancement, while the adding lignin fiber had very limited enhancement or even a slight adverse impact on the cracking, raveling, fatigue, and rutting resistance of HCPMA. After short- and long-term aging, the addition of polyester fiber and lignin fiber had a much more obvious enhancement impact on the cracking, raveling, fatigue, and rutting resistance compared with the HCPMA without fiber.

(2) According to the chemical characterization of HCPMB extracted from asphalt mixture samples, adding polyester or lignin fiber didn't significantly impact the oxidation of bitumen and degradation of the polymer.

(3) HCPMA may exhibit a "masking" effect in the original state and covers the enhancement effect of fiber. After long-term aging, the "masking" effect of HCPMA disappears, and the enhancement of fibers is more obvious. Thus, performance evaluation and design of open-graded asphalt mixtures containing HCPMB should be based on the performance after aging.

The limitation of this research is that it is based on the analysis of a single type of HHCPMB and one specific gradation, limiting the scope of its conclusions. Hence, future work should extend this research by testing various types of HCPMB and diverse gradations. Further investigation is also needed to fully comprehend the mechanism underlying the observed "masking" effect in HCPMA, which will help refine evaluation methodologies and broaden our understanding of the performance of HCPMA.

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CRediT authorship contribution statement

Xueyan Liu and Peng Lin conceived and designed the experiments; Peng Lin participated in the experiments and measurements; Jian Xu and Mingliang Li participated in the discussion of the results; Peng Lin drafted the manuscript. Monitoring and review were carried out by Peng Lin, Shisong Ren, Yi Li and Xueyan Liu.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors have participated in the research and preparation of the manuscript, and any relevant affiliations, sources of funding, or potential conflicts of interest have been disclosed. This study was conducted in adherence to the highest ethical standards and with the utmost integrity, ensuring the objectivity and transparency of the research process and results.

Data Availability

Data will be made available on request.

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